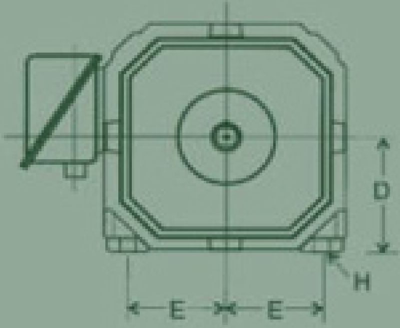
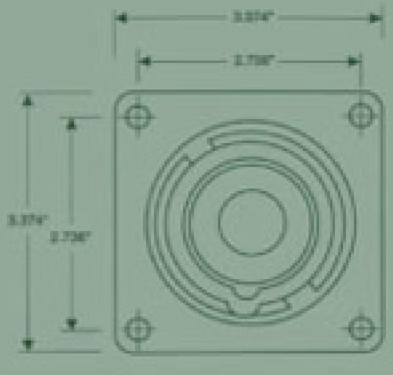
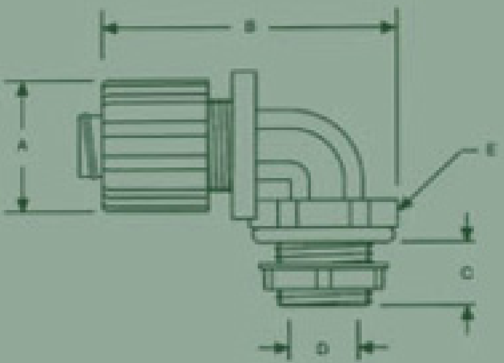


Neil Sclater
John E. Traister

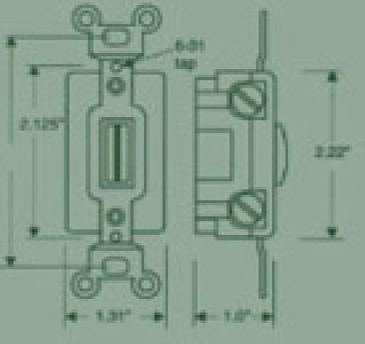


HANDBOOK OF ELECTRICAL DESIGN DETAILS

Second Edition



- EASY-TO-READ STYLE MAKES COMPLEX TOPICS UNDERSTANDABLE
- REFERENCES TO RELATED ARTICLES IN THE NATIONAL ELECTRICAL CODE
- A "MUST-HAVE" REFERENCE FOR THOSE WITH A NEED OR DESIRE TO GET "UP-TO-SPEED" ON THE ENTIRE SUBJECT OF ELECTRIC POWER
- COMPLETELY REVISED AND UPDATED



Copyright © 2003, 1997 by The McGraw-Hill Companies, Inc. All rights reserved. Manufactured in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a database or retrieval system, without the prior written permission of the publisher.

0-07-142579-9

The material in this eBook also appears in the print version of this title: 0-07-137751-4.

All trademarks are trademarks of their respective owners. Rather than put a trademark symbol after every occurrence of a trademarked name, we use names in an editorial fashion only, and to the benefit of the trademark owner, with no intention of infringement of the trademark. Where such designations appear in this book, they have been printed with initial caps.

McGraw-Hill eBooks are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please contact George Hoare, Special Sales, at george_hoare@mcgraw-hill.com or (212) 904-4069.

TERMS OF USE

This is a copyrighted work and The McGraw-Hill Companies, Inc. (“McGraw-Hill”) and its licensors reserve all rights in and to the work. Use of this work is subject to these terms. Except as permitted under the Copyright Act of 1976 and the right to store and retrieve one copy of the work, you may not decompile, disassemble, reverse engineer, reproduce, modify, create derivative works based upon, transmit, distribute, disseminate, sell, publish or sublicense the work or any part of it without McGraw-Hill’s prior consent. You may use the work for your own noncommercial and personal use; any other use of the work is strictly prohibited. Your right to use the work may be terminated if you fail to comply with these terms.

THE WORK IS PROVIDED “AS IS”. McGRAW-HILL AND ITS LICENSORS MAKE NO GUARANTEES OR WARRANTIES AS TO THE ACCURACY, ADEQUACY OR COMPLETENESS OF OR RESULTS TO BE OBTAINED FROM USING THE WORK, INCLUDING ANY INFORMATION THAT CAN BE ACCESSED THROUGH THE WORK VIA HYPERLINK OR OTHERWISE, AND EXPRESSLY DISCLAIM ANY WARRANTY, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO IMPLIED WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. McGraw-Hill and its licensors do not warrant or guarantee that the functions contained in the work will meet your requirements or that its operation will be uninterrupted or error free. Neither McGraw-Hill nor its licensors shall be liable to you or anyone else for any inaccuracy, error or omission, regardless of cause, in the work or for any damages resulting therefrom. McGraw-Hill has no responsibility for the content of any information accessed through the work. Under no circumstances shall McGraw-Hill and/or its licensors be liable for any indirect, incidental, special, punitive, consequential or similar damages that result from the use of or inability to use the work, even if any of them has been advised of the possibility of such damages. This limitation of liability shall apply to any claim or cause whatsoever whether such claim or cause arises in contract, tort or otherwise.

DOI: 10.1036/0071425799

CONTENTS

Preface *vii*

Chapter 1 Planning for Electrical Design *1*

Chapter 2 Power Generation and Transmission *37*

Chapter 3 Power System Equipment *57*

Chapter 4 Substations and Electrical Distribution *109*

Chapter 5 Service Entrance, Loadcenters, and Grounding *133*

Chapter 6 Wire, Cable, and Circuit Components *173*

Chapter 7 Branch Circuit Design and Device Wiring *243*

Chapter 8 Lighting, Lamps, and Luminaires *269*

Chapter 9 Telephone, Multimedia, and Alarm Systems *321*

Chapter 10 Electric Motors and Starters *345*

Chapter 11 Emergency and Standby Systems *379*

Chapter 12 Electrical Surges and Surge Protection *399*

PREFACE

This is the second edition of the *Handbook of Electrical Design Details* (HEDD), originally published in 1997. It is a well-illustrated reference book on electrical power and lighting—how it is generated, transmitted, distributed, and used. Considerable new information has been added in this edition but it is a smaller volume, making it more user-friendly and easier to keep on a desk or shelf. Among the topics new to this edition are computer-aided electrical drawing (CAD), basic switch and receptacle circuit wiring, outdoor low-voltage wiring, telephone and structured wiring, and electrical surge protection.

This book begins with a discussion of electrical drawing and symbols and the importance of specifications in electrical projects. The chapters that follow cover power generation, transmission, and distribution. Design details of generators and transformers and their role in delivering electric power to consumers' homes or buildings are included. Aerial and buried service entrances are explained and illustrated, as are main panels or loadcenters and the principles of earth grounding.

Properties of wire and cable are presented, and the dimensions and the details of basic electrical wiring devices are described and illustrated. The rules for installing branch circuit wiring are given along with an example of a load calculation and the reasons for load balancing. Extensive coverage is given to lighting, lamps, and indoor and outdoor lighting design. Other chapters explain telephone and structured wiring, electric motors, emergency and standby electrical systems, and the essentials of surge protection.

This edition of HEDD makes many references to the National Electrical Code® (NEC®)* on all topics governed by the code, such as wiring protection, wiring methods and materials, and standard equipment, where appropriate for reader guidance. In the chapters on wire, cable, and wiring devices, individual drawings represent whole classes of standard products such as switches, receptacles, and lamps, replacing the many repetitive catalog pages that appeared in the first edition.

Each chapter begins with a content summary called "Contents at a Glance" and an Overview of the chapter. In addition, there are separate glossaries of technical terms at the ends of the chapters on transformers, electrical service entrance, wiring, lighting, motors, telecommunications, emergency and standby systems, and surge protection, for handy reference and quick memory refreshing.

This second edition of HEDD has been written in an informal descriptive style, with minimal use of mathematics. The readers most likely to benefit from this book are electrical contractors, electricians, and instructors. Others who will find this volume helpful are those employed in the electrical industry in manufacturing, service,

---

*National Electrical Code and NEC are registered trademarks of the National Fire Protection Association, Quincy, Massachusetts.

1

PLANNING FOR ELECTRICAL DESIGN

CONTENTS AT A GLANCE

Overview
Electrical Drawing Objectives
Electrical Drawing Preparation
Computer-Aided Drawing
Electrical CAD Software
CAD Drawing Plotters
Drawing Sizes and Conventions
Drawing Reproduction
Drawing Line Widths and Styles
Electrical Graphic Symbols
Electronic Graphic Symbols
Drawing Schedules
Electrical Project Drawings
Electrical Product and Work Standards
What Are Electrical Specifications?

Overview

A successful electrical power and lighting project depends on effective planning in the form of drawings, schedules, and contract specifications. This contract documentation provides a concise picture of the objectives for the electrical project work to be done. It also serves as a record of intent for owners and as instructions and guidance for contractors, electricians, installers, and others performing the work. Contract documents, which might also include surveys and test data, are legal documents, and they can be used as evidence in court cases involving contractor malfeasance, or failure to comply with the intent of the drawings and specifications.

The present conformity to accepted formats for drawings and specifications is the result of years of practical experience reinforced by accepted national and international standards issued by government agencies and private standards organizations. The standards organizations are advised by experienced personnel from the ranks of manufacturers, contractors, and other interested parties. The intent of standards is to produce unambiguous documentation that is understandable by all project participants, from engineers and architects to contractors, project supervisors, electricians, and installers.

This chapter discusses the preparation of drawings and schedules and their reproduction. It also explains and illustrates typical standard electrical symbols used on plan-view, one-line, and schematic drawings for electrical construction, and identifies the principal government and industry agencies whose standards affect all phases of electrical work. Appendix A is a compilation of American National Standards Institute (ANSI) electrical symbols and National Electrical Manufacturers Association (NEMA) plug and receptacle and circuit wiring configuration diagrams. Appendix B contains the front matter and selected commonly used sections of a typical electrical specification, to show how a written specification is organized, its legal language, and its style.

Electrical Drawing Objectives

Drawing for an electrical project serves three distinct functions.

1. Describes the electrical project in sufficient detail to allow electrical contractors to use the drawings in estimating the cost of materials, labor, and services when preparing a contract bid.
2. Instructs and guides electricians in performing the required wiring and equipment installation while also warning them of potential hazards such as existing wiring, gas pipes, or plumbing systems.
3. Provides the owner with an “as-built” record of the installed electrical wiring and equipment for the purposes of maintenance or planning future expansion. The owner then becomes responsible for recording all wiring and equipment changes.

A typical electrical drawing consists of solid or dashed lines representing wiring or cables and symbols for luminaires, receptacles, switches, auxiliary systems, and other electrical devices and their locations on a scaled architectural floor plan of a home or building. The drawings also include title blocks to identify the project, the designers or engineers, and the owner, and change blocks to record any changes that have been made since the drawing was first issued.

In any given set of electrical drawing there are also specialized drawings such as one-line, elevation or riser, and electrical equipment installation drawings. There might be no drawing requirements for relatively simple electrical projects such as updating the amperage capacity of a home or extending branch wiring into a basement, attic, or extension. In these situations, all information needed can be included in a written proposal or other contractual agreement.

For commercial projects or new home construction, formal drawings are required to gain approvals from building inspectors and the local electric utility. A typical set will include several 24 × 36 in. architectural floor plans marked with the appropriate electrical graphic symbols. The set might also include drawings for telephone and multimedia structured wiring, outdoor wiring, or a security system.

By contrast, major large-scale construction projects such as shopping centers, high-rise office buildings, factories, hospitals, and scientific laboratories might require dozens of 24 × 36 in. (or larger) sheets, depending on the size and complexity of the project. These might include one-line drawings and manufacturer-furnished wiring diagrams for installing equipment. For complex projects, special instructions and installation schedules will also be included.

Electrical Drawing Preparation

The preparation of electrical drawings for updating an existing electrical system or constructing a new one is the responsibility of a consulting architect, engineer, or designated experienced employee in an architectural or consulting engineering firm. The actual drawing could be performed by on-staff electrical engineers or designers, or it could be subcontracted out to consultants specializing in electrical power and lighting design.

However, consulting engineering firms are usually retained to design and supervise the construction and electrical work in major commercial, industrial, and government projects. These firms employ registered professional electrical, mechanical, structural, and civil engineers as well as specialists in writing specifications and drafting for large-scale projects. Some engineering firms also employ registered professional architects who are experienced in building design. All of these specialists might participate in the preparation and approval of electrical drawings and specifications, because close coordination between these disciplines will help to avoid mistakes or oversights that are costly and time-consuming to correct in the field.

If a project is to include custom-made electrical-powered equipment such as machine tools, generators, conveyors, escalators, or elevators, the project manager will request generic drawings of that equipment from qualified vendors for estimating and planning purposes. These drawings will show floor space and ceiling height requirements for the installation of the equipment, the relative positions of any necessary auxiliary equipment, and the recommended positions of all piping and wiring required. The drawings will also show the correct orientation of the equipment to assure sufficient space for operators and maintenance personnel to move around the equipment to gain access to all removable panels or hatches and to provide for the swing radius of any hinged doors. If the equipment is large, measurements for minimum space requirements to move the equipment into the building will be included.

These measurements will be useful in sizing entryways or scheduling the installation before the walls are covered.

In some cases large units such as machine tools, furnaces, or elevators will require the preparation of special concrete foundations, and construction drawings will be provided by the manufacturer. This work must be completed prior to the delivery of the equipment.

Generic drawings will be replaced by drawings of the actual custom-built equipment after it has been ordered. These drawing might be accompanied by installation, operation, and maintenance manuals prepared specifically for the project. These will later become part of the owner's engineering documentation.

The electrical contractor might have his or her own staff designers prepare supplementary electrical drawings if they are needed to clarify certain aspects of the installation, help to avoid mistakes, speed up the work, or provide extra guidance for the field supervisors.

Computer-Aided Drawing

Most large engineering consulting and architectural firms in the United States have made the transition from manual to computer-aided drawing (CAD). These companies have had to purchase computer workstations, applications software, and plotters, as well as pay for personnel training in CAD. The dedicated workstations and off-the-shelf high-performance desktop computers now available are capable of supporting the most sophisticated commercial CAD software available. The pricing for both is far lower today than it was only a few years ago, making CAD affordable even for small design firms and individual professional consultants.

The acronym CAD also stands for computer-aided design, but this is a misnomer. CAD programs do *not* do design work; that must still be done by skilled draftspersons, designers, or engineers with sufficient technical knowledge and training to perform professional-level work.

CAD drawing can be learned on the job, in trade and technical schools, or at training facilities set up by software vendors. However, the training in a software vendor's classes focuses on teaching the company's proprietary software and might not include instruction in the use of competitive or alternative software.

An experienced electrical designer or drafter might require months of on-the-job practice with specific CAD software to become proficient enough in its use to do professional work on the workstation more cost-effectively than it could be done by traditional manual drawing.

The software needed for electrical power and lighting design work typically consists of two components: a general purpose two-dimensional (2-D) CAD software package and supplementary applications-specific electrical design software. While it is possible to do professional electrical drafting with basic off-the-shelf 2-D CAD drawing software, the addition of the supplementary electrical design software will relieve the user of the onerous task of creating custom files of symbols and other design elements specific to electrical construction.

The supplementary applications-specific software is expected to pay for itself within a short period of time and increase drawing productivity. This software typically contains a complete library of electrical symbols, which can be selected from a menu and dragged into position on the workstation screen for proper placement on the architectural or one-line drawings. Most electrical drawing software permits the user to modify the industry standard symbols or create new ones for specific devices or equipment.

Many corporate clients of architectural or engineering consulting firms as well as U.S. government agencies have their own drafting style guides, which must be followed in the performance of contract work. They might, for example, have their own specialized symbols or make specific selections in cases where two or more alternative symbols are approved and accepted by the industry. All drawings produced for the bidding process and later construction phases must be drawn in accordance with these guidelines.

Some CAD programs are capable of producing the proper forms and making the necessary calculations to produce material lists and cost estimates based on the number and type of symbols placed on the drawing.

The benefits of CAD electrical drawing are the following.

- Saving time in the preparation of all types of electrical drawings.
- Eliminating the tedious tasks of lettering and drawing uniform lines and symbols.
- Permitting the transfer of large sections of drawings prepared originally for one project to be reused on a different project.
- Providing databases of “families” of master digitized drawings that can be modified for reuse on other projects or become de facto templates for new drawings.
- Making rapid changes on completed and approved drawings to reflect field changes such as the substitution of different equipment.
- Making rapid corrections of mistakes or oversights that have been discovered.
- Reproducing corrected drawings rapidly for use in the field, eliminating concern that work might be done against obsolete drawings, necessitating costly rework.
- Permitting work to be done on a specific drawing by two or more persons at separate workstations within the same office or miles apart, because data can be transmitted over networks to a master workstation. This permits two or more persons to participate in the design work in real time.
- Reducing the space required to store completed drawings, because digital data can be stored on a centralized server, computer disks, or CD-ROMs.
- Accelerating the distribution of drawings to all concerned parties: owners, contractors, equipment manufacturers, and suppliers. The drawing data can be transmitted over computer networks and printed out by the recipient, saving time and delivery cost.
- Providing a secure backup for all master drawings files if the drafting offices are destroyed by fire or flood, saving the time and expense needed to reconstruct the drawings from alternative sources.

Electrical CAD Software

Some software publishers specialize in electrical design CAD software for both electrical drafting and estimation. These software packages typically supplement the capabilities of AutoCAD, a recognized proprietary brand of general-purpose CAD software. AutoCAD can be adapted to many different technologies, but it does not contain coding for either electrical drawing or estimation.

The basic AutoCAD software has a menu structure that permits drawing lines, circles, arcs, rectangles, polygons, spline curves, and hatching. It also permits the generation of text, scaling, and dimensioning. The modifying commands include erase, copy, mirror, stretch, and array. It also permits the creation of blocks and templates.

The electrical drafting software builds on these capabilities and contains a library of hundreds of standard electrical symbols as well as a collection of easily modified detail diagrams, schedules, and title blocks. The default symbol library included in the software can be customized to accommodate all user or client drawing standards that are different.

The electrical software permits the designer to make accurate measurements of all circuit routings, regardless of the scale of the drawing. It also contains an architectural drafting "toolkit" that permits the drafter to modify a building's architectural floor plan to include any desired electrical work that cannot be accommodated in the original design. For example, a wall location might be moved to allow more space for the installation of a flush-mounted electrical cabinet or the installation of structured wiring bundles.

Logic inherent in the software monitors the use of the symbols and indicates possible errors. Electrical drafting software typically includes the following functions.

- Multiple user interfaces: mouse-driven, on-screen, and digitized template formats. These menu systems are designed to be intuitive, to save the draftsperson's time in calling up desired functions.
- Automatic graphics and text sizing to adjust to required drawing scales.
- Customizable layer management that accommodates all layering procedures required where interconnected electrical circuits exist on two or more floors.
- Modular riser symbols for quick assembly of single-line diagrams. Symbols and connecting feeders can be put together quickly in building-block fashion.
- Automatic labeling features for circuitry, feeders, special raceways, cabling, fixtures, and equipment, with various line-breaking routines and branch or feeder markings.

ELECTRICAL COST ESTIMATION SOFTWARE

CAD software revolutionized the drafting process and eliminated the drudgery of manual drawing by permitting engineering drawing to be made on computer screens, speeding up the entire design process. It was later found that the digital data accumulated in the preparation of CAD drawing could serve double duty by taking the drudgery out of cost estimation of electrical projects, a task that must be performed as part of the bidding and overall project cost estimation process.

Some estimation software has the ability to keep track of the number and kind of electrical devices and wiring placed on a CAD drawing, either during its preparation or after the drawing is completed, to produce the desired estimation documentation automatically.

CAD Drawing Plotters

Special plotting equipment is required to print out drawing sizes larger than about 8.5 × 14 in., the upper limit of most standard office inkjet or laser printers. Today there are many different models of inkjet plotters capable of printing out drawings up to 42 in. wide on rolls of paper, vellum, or film that permit drawing lengths that are proportional to their widths. The printing can be done on any of eight different types of media, including five different kinds of paper and two different kinds of film. These plotters use the same thermal inkjet printing technology as standard off-the-shelf desktop inkjet printers. The cost of plotters depends on such factors as

- Width of drawings they can print (typically from 24 to 42 in.)
- Print quality in dots per inch (dpi)
- Ability to print in color in addition to black
- Ability to send and receive digitized drawing data over networks

Table 1-1 lists the range of features and capabilities found on commercially available inkjet plotters. Basic inkjet plotters that print only in black on media up to 24 in. wide with acceptable 600 × 600 dpi print quality are now priced under $1500. However, top-of-the-line plotters are priced up to $8000; they can also print in color on media up to 42 in. wide, offer print quality of 1200 × 600 dpi, and include a hard-disk drive and circuitry for sending and receiving digitized drawing data over computer networks.

Drawing Sizes and Conventions

Most electrical drawings are drawn on 18 × 24 in. to 24 × 36 in. paper, but some measure as large as 30 × 42 in. From small to large they are sized A through D.

DRAWING TITLE BLOCKS

Electrical drawings typically contain a *title block* in the lower right-hand corner to identify both the intent and the source of the drawing. The contents of title blocks have generally been standardized so that all persons having access to the drawings and a need to use them can find the information they want in the same location, regardless

TABLE 1-1 CHARACTERISTICS OF THERMAL INKJET PLOTTERS (Based on Available Commercial Models)

Media sizes (1)	8.3 × 8 in. to 42 × 600 in.
Print length (max.)	50 ft
Print technology	Thermal inkjet
Print quality (black best)	600 × 600 dpi to 1200 × 600 dpi
Print color (2)	Black (cyan, magenta, yellow optional)
Print languages	HP-GL/2, HP-GL, HP-RTL, HP-PCL3-GUI
Media types	Bright white inkjet paper (bond), translucent bond, natural tracing paper, vellum, clear film, matte film, coated paper, gloss photo paper
Memory (3)	4 MB RAM to 96 MB RAM
Connectivity, opt. (4)	Centronics parallel, IEEE-1284-compliant, USB1.1 (Windows 98 and 2000)
Dimensions (W × D × H)	40 × 9 × 13 in. to 49 × 19 × 14 in.

NOTES:
(1) For engineering applications drawing sizes A, B, C, D, and E.
(2) Colors standard on some models.
(3) High-end models include hard-disk drive.
(4) Applies only to network-compatible models.

of the origin of the drawing. Uniformity in drawing style, format, and typefaces can eliminate time wasted and frustration in searching for needed information.

Title block size is generally proportional to both drawing size and the extent of information needed in it. A typical drawing block contains all or most of the following information:

- Name of the project and its address
- General description of the drawing
- Name and address of the owner or client
- Name and address of the organization that prepared the drawing
- Scale(s) of the drawing
- Approval block containing the initials of the drafter, checker, and design supervisor who approved the drawing, all accompanied by initialing dates for accountability
- Job number
- Sheet number

The objective of the initialing process is identify all of the persons who participated in the drawing process and provide a paper trail to assure accountability for the accuracy of the drawing. Some drawings also include the signature, initials, or professional stamps or seals of the responsible architect or consulting engineer, and some also include the initials of the project owner or representative.

DRAWING REVISION BLOCKS

Revision blocks are lists of changes accompanied by the dates of those changes and the initials of the person who made them. This information is contained within a lined and bordered block adjacent to the title block. The initial change entry is made just above the lower margin of the drawing, and all subsequent changes are listed in date order ascending from the first entry. This means that the latest change entry is always at the top of the revision block so that the history of changes can be read in top-down order.

Drawing Reproduction

Most of today's engineering drawing standards were adopted when engineering drawings were drawn manually and lettered with pencil or ink on translucent vellum sheets. Those drawings were made on translucent cloth media so that they could be reproduced by placing the master drawing on photosensitive paper and passing it through a reproduction machine. The underlying photosensitive paper was exposed to light that passed through the drawing. It was then "developed" by a chemical process.

The blueprint process (white lines and features on a blue background) predominated until the middle of the last century. The Ozalid diazo blueline process (blue lines and features on a white background) has superseded blueprinting as the preferred method for reproducing drawing. It can be used to reproduce CAD or manually prepared drawings.

The cost of Ozalid process reproduction of drawings is less than that for blueprints or direct printout on a plotter, and it is faster than either of the other processes. Moreover, blueline prints, like black-on-white inkjet printouts, are easier to read than blueprints.

The Ozalid printer is contained in a long metal bench-mounted box containing a conveyer-belt system and an ultraviolet lamp. The conveyer moves the master drawing, paired with light-sensitive diazo paper, past an ultraviolet light tube that extends the length of the machine. These machines are capable of reproducing drawings in sizes up to 30 × 42 in.

The inkjet plotter has not eliminated the need for the Ozalid machine. The Ozalid process is still used to reproduce earlier manually prepared file-drawing masters, and it can reproduce CAD drawings that have been printed on translucent vellum by an inkjet plotter.

Drawing Line Widths and Styles

Line widths and styles convey different kinds of information on engineering and architectural drawings. For example, dashed lines have one meaning and dotted lines another. Center lines of alternating short and long segments divide drawing elements, and dashed lines with uniform segments and spaces show physical connections between drawing elements. Technical details on drawings are indicated by graphic symbols combined with lines. However, there is no uniformity in the use of lines that appear on architectural, mechanical, electrical, electronic, and civil engineering drawings.

Line widths on manually prepared engineering drawing were obtained by inserting graphite “leads” of different thickness in holders and shaping their ends as wedges to be dragged along the drawings. Alternatively, if the drawings were inked, the spacing between the blades of ruling pens was adjusted to the desired spread with a small thumb screw and India ink was inserted between the blades, where it was retained by capillary action. As the pen was dragged along the drawing media, the ink flowed out in the desired width. However, the drafter had to manually set the lengths of dashes and spaces on straight and curved lines, a tedious task that required high concentration.

CAD has eliminated the chore of manually drawing lines of uniform width and uniform dashes and spaces between them. The draftsperson can select the appropriate line width and style from a menu on the workstation screen. The lines selected can be drawn horizontally, vertically, or at any desired angle.

Electrical engineers have generally agreed on the line conventions that represent wires, cables, conduit, and wiring within conduit, as illustrated in Fig. 1-1. For example, branch circuit power wiring is represented as a solid line, while both switched and control wiring are represented by broken lines. Abbreviations inserted within breaks in the lines, such as “EM” for emergency and “CT” for cable tray, identify their functions. Home runs from electrical devices to panels are represented as lines with arrowheads.

However, there is no enforcement of generally acceptable line drawing standards within the industry. Unless the draftsperson is required to follow a company style or style is mandated by the client, there are many possible variations of the line samples shown in the figure. For example, some drawings show branch circuit wiring as heavy lines and control wiring as fine lines.

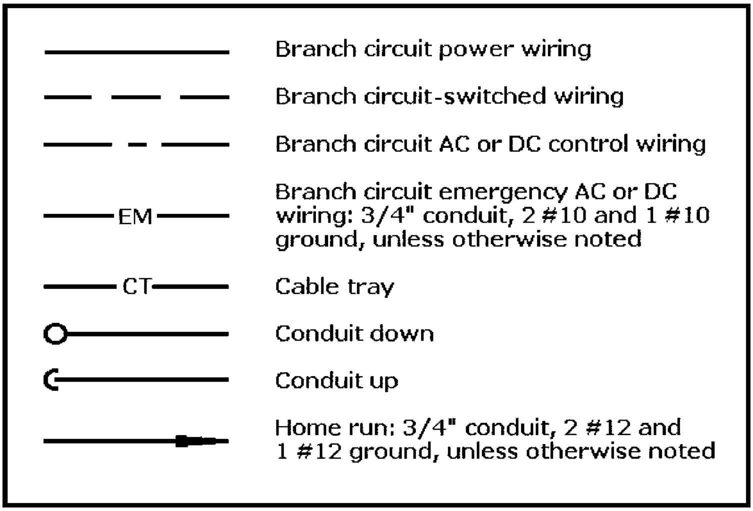


Figure 1-1 Lines used to indicate wiring on electrical drawings.

Also, in some drawings the number of wires in a cable or conduit is indicated by short diagonal slashmarks made through the line. This convention might be followed only if there are more than three wires. In other schemes, wire gauge is indicated by numbers positioned above or below the slashmarks.

A properly prepared drawing will include a *key of symbols* that explains the meanings of all of the lines and symbols. Reference should always be made to this key to verify the meanings of lines and symbols before trying to interpret the drawing.

Electrical Graphic Symbols

Electrical engineers and designers generally follow accepted standards for the basic electrical and electronic symbols. These electrical symbols can be classified as those used on *connection and interconnection diagrams* and those used on *elementary or schematic diagrams.*

Connection and interconnection symbols represent complete electrical devices such as switch outlets, receptacle outlets, lighting fixtures or luminaires, and auxiliary systems. These symbols take the form of relatively simple geometric shapes modified with lines and letters inside or outside of them. The intent was to create a kind of technical shorhand that could be easily learned. They were kept simple to reduce the time and expense of preparing drawings, particularly those used in the field for installation of common off-the-shelf electrical components.

Figure 1-2 includes a selection of electrical connection and interconnection symbols recommended by the American National Standards Institute (ANSI) for use on architectural drawings. These symbols, or modified versions of them, are widely used on electrical drawings in North America. Appendix A also includes a page of these symbols.

CAD electrical drafting software has eliminated the chore of reproducing these symbols. The software contains a library of symbols that can be accessed from a menu, downloaded, and dragged into position on the face of the screen as needed. The basic symbols can be modified to fulfill special requirements or identify devices not listed in the standard symbol list. In the past, symbols were usually drawn by the draftsperson tracing around the inside of geometric cutouts in templates made of sheet plastic.

As with line conventions, the motivation for using standardized symbols is to eliminate the time involved in trying to interpret drawings that include unfamiliar proprietary symbols. It is important that the symbols be easily recognized by all parties involved in an electrical project, from the designer to the electricians doing the work. As a result, the chances of making costly mistakes in interpretation are lessened.

Moreover, large architectural and consulting engineering firms with national and international clients approve of symbol standardization because of the many people of different backgrounds, languages, and cultures who could be using the drawings. This is especially true of large-scale new construction projects such as hospitals, power stations, and industrial plants involving many different contractors.

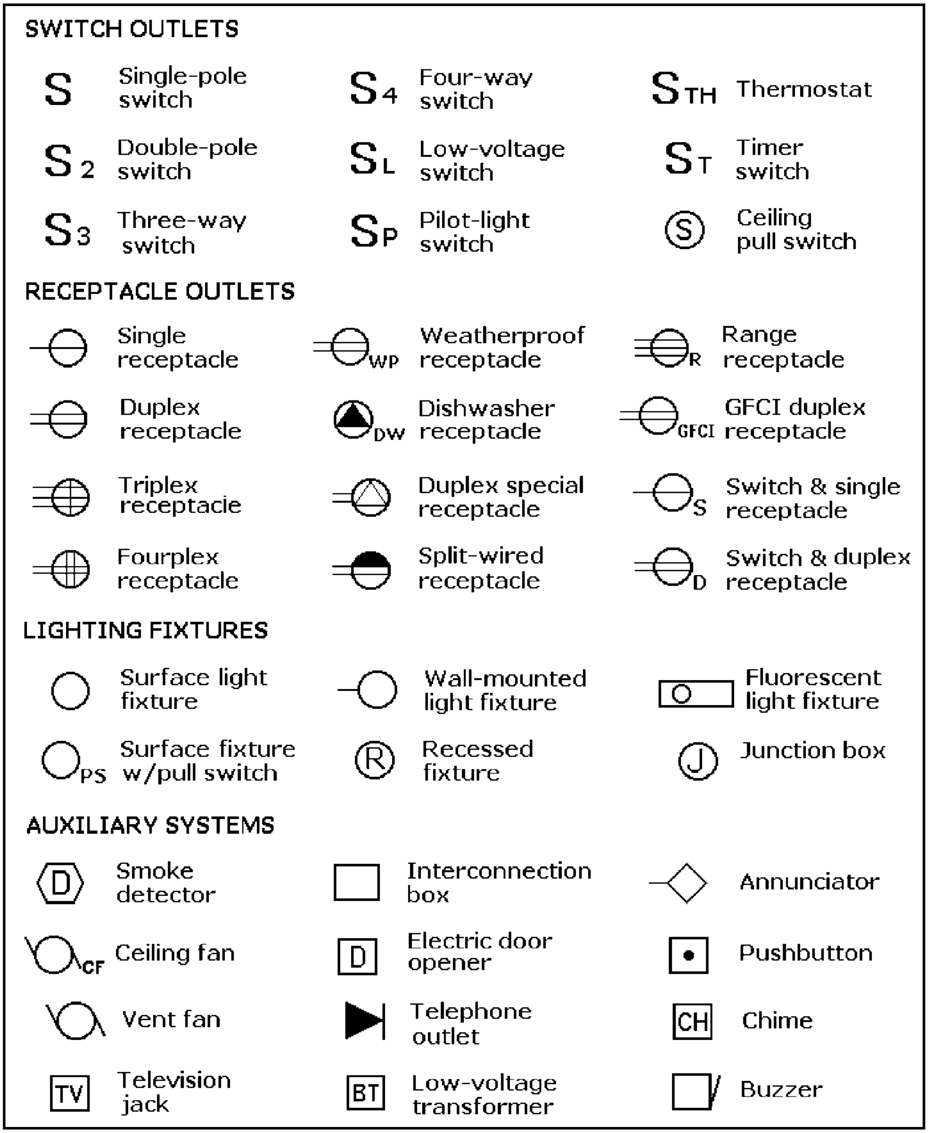


Figure 1-2 **Graphic symbols for electrical wiring diagrams.**

As a condition of accepting a contract, many government agencies and large corporations require that drawings and specifications meet their standards. They provide architectural and engineering design firms and eligible contractors with copies of their documentation and drawing standards before any work is done. U.S. government agencies including the Department of Defense (DoD), the National Aeronautics and Space Administration (NASA), and the National Security Agency (NSA) each issue their own drawing and specification standards.

ELECTRICAL CONNECTION AND INTERCONNECTION SYMBOLS

It can be seen in Fig. 1-2 that the basic symbol for the single-pole switch classed under "switch outlets" is the letter "S," but the symbol can be modified to represent other switches by adding number or letter subscripts to indicate switch outlets such as double-pole, three-way, and four-way, or functions such as pilot light, thermostat, timer, and ceiling pull switch.

A circle intersected by a horizontal line is the symbol for a single grounded receptacle in the "receptacle outlets" category. By adding additional lines to represent the number of outlets, the single-receptacle symbol becomes the symbol for duplex, triplex, and fourplex receptacles. Also, by adding letter abbreviations for special functions such as range, and ground-fault circuit interrupter (GFCI), symbols for other receptacles are obtained. If the receptacles are ungrounded, they are followed by the letters "UNG."

In a similar manner, the basic symbol for a luminaire in the "lighting outlets" category is a plain circle, but adding a short line projecting to the left makes it a wall-mounted luminaire. Here again, letters within the circle, such as "X" or "J," represent functions such as exit and junction.

Most of the symbols in the "auxiliary systems" or "residential occupancies" category are based on the square, but some are based on circles. Here again, letters can be used within the symbol, such as "TV" to represent a television jack and "CH" to represent a chime. Other symbols in this group include those for bells, buzzers, smoke detectors, telephone outlets, pushbuttons, and ceiling fans.

In the case of luminaire symbols, schedules either on the drawing or within the written specifications provide supplementary information about that luminaire, including the name of the manufacturer, its catalog number, the type of lamp to be installed, voltage, finish, and mounting method.

Symbols for many of the objects are drawn in sizes that approximate the size of the actual object drawn to the same scale as the architectural floor plan. They are accurately located on the floor plan with respect to the building configuration, walls, doors, windows, etc. Where extreme accuracy is required in locating outlets, luminaires, or electrically powered equipment, exact dimensions are given from reference points on the floor plans, such as height above the finished floor line or distance to the nearest finished wall.

The key of symbols previously mentioned identifies the symbols and all included internal letters or letter and number subscripts. There are also graphic symbols for distribution centers, panelboards, transformers, and safety switches not shown here. Unless mandated by contract requirements, the designer is free to modify standard symbols as desired, provided that they are identified in the key of symbols or other contract documentation. A detailed description of the service equipment on a project is usually given in the panelboard schedule or in the written specifications. However, on small projects the service equipment might be identified only by notes on the drawing.

Appendix A includes a compilation of these ANSI architectural symbols.

ELECTRICAL SCHEMATIC SYMBOLS

Another group of symbols, called elementary or schematic symbols, is used on electrical one-line and schematic drawings. A selection of these symbols is shown in Fig. 1-3. Electrical schematic symbols are used in drawing circuits such as those for motor starters or the wiring inside appliances or building service equipment.

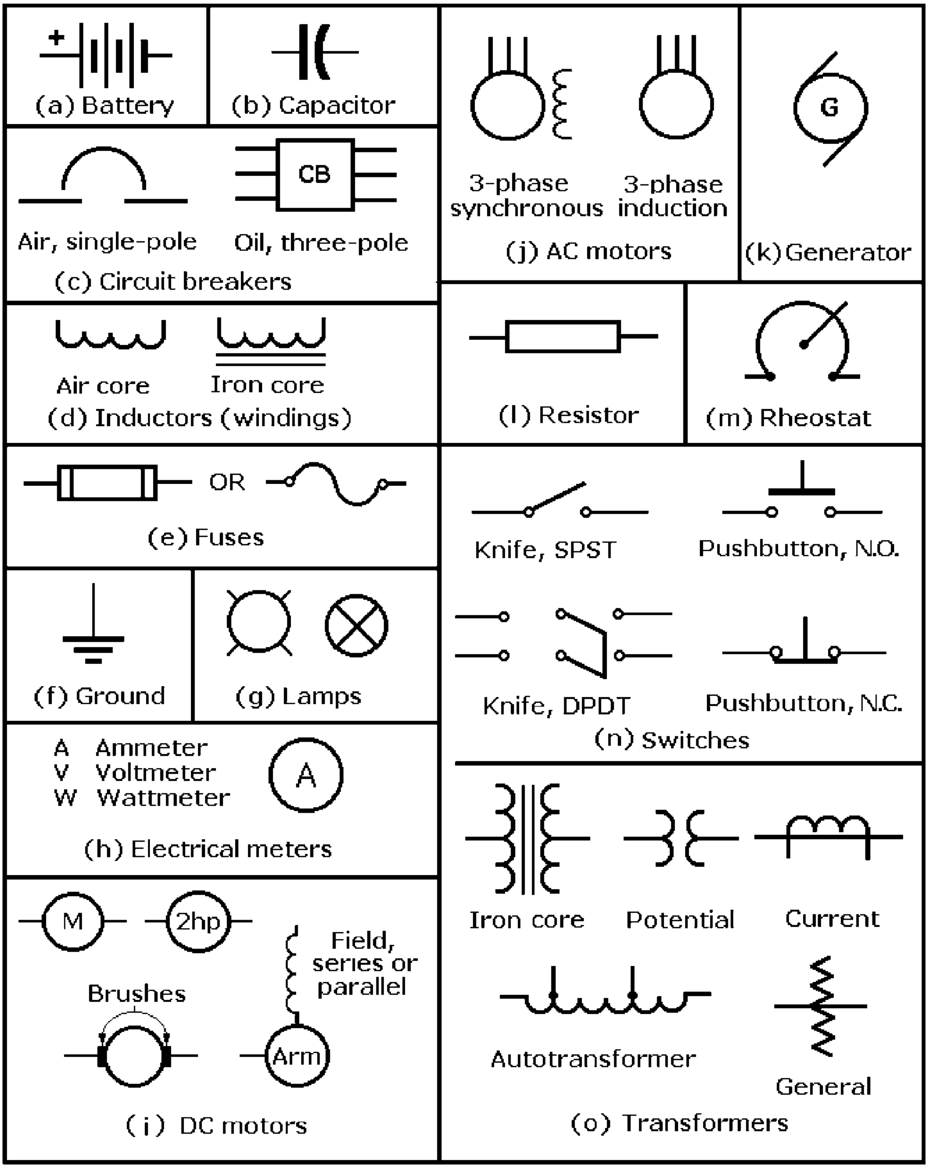


Figure 1-3 Graphic symbols for electrical schematics, Part 1.

Electricians installing equipment in the field might work with electrical schematic diagrams if it is necessary to make specific connections inside an appliance or to hook up a motor for a furnace, hot water heater, fan, compressor, pump, or other machine.

There are graphic symbols for all of the basic components in an electrical circuit, such as capacitors, fuses, motors, meters, resistors, switches, and transformers. These symbols are generally pictorial representations of the electrical *functions* performed by the components. Most of these symbols were first used near the end of the nineteenth century, well before electronics was considered a separate technology, but the set of standard symbols has been modified over the intervening years.

During World War II the U.S. Navy and War departments ordered the simplification of some of the symbols to speed up the manual preparation of drawings for military procurement. These were later made standards by the U.S. Department of Defense. For example, the loops in the symbols for windings or coils that were standard on prewar electrical drawing for inductors and transformers were replaced by easier-to-draw scalloped lines. However, these obsolete symbols can still be seen in some textbooks and equipment manufacturers' catalogs. There is less uniformity in the depiction and use of standard electrical schematic symbols in manufacturers' catalogs and installation and maintenance diagrams because many of the older, well-established electrical equipment manufacturers still favor the traditional symbols.

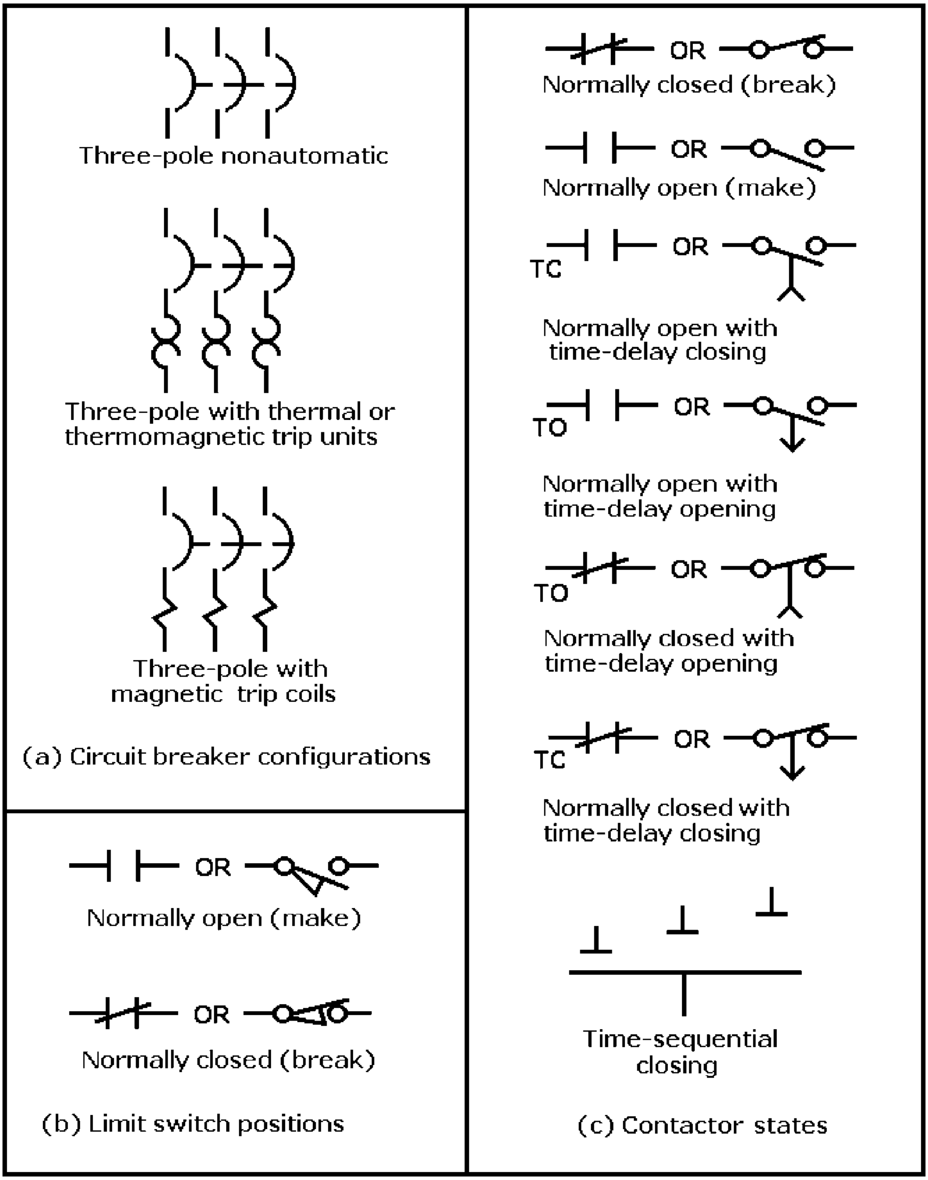
Some of the basic symbols are described below.

- *Battery:* The multicell battery symbol is a set of long thin and short thick parallel line segments representing poles, as shown in Fig. 1-3*a.* It is used on both electrical and electronic schematics in North America. The plus sign next to the long segment identifies the positive pole.
- *Capacitor:* The capacitor symbol used in both electrical and electronic schematics is a straight line segment next to a curved line segment, as shown in Fig. 1-3*b.*
- *Circuit breakers:* The symbol for both thermal and thermal-magnetic circuit breakers rated for less than 600 V is a semicircle positioned over a gap between the ends of two conductors, as shown in Fig. 1-3*c.* The symbol for higher-rated circuit breakers, such as the oil-immersed units in distribution substations, is a square containing the letters "CB," also shown in the figure.
- *Inductors or windings:* The modern symbol for an inductor or winding is a scalloped line used to signify a single winding, as shown in Fig. 1-3*d.* If the inductor has a ferromagnetic core, two parallel lines are drawn next to the scalloped line, as shown in the same figure. However, some one-line electrical diagrams still use zigzag lines as symbols for inductors.
- *Fuses:* In electrical drawings, the fuse symbol is either a rectangle with bands at each end, as shown in Fig. 1-3*e,* or a sine-wave curve, also shown in the figure. The latter symbol, however, is more commonly seen on electronic schematics.
- *Ground connection:* Three parallel line segments of diminishing length intersected by a vertical line representing the conductor, as shown in Fig. 1-3*f,* is the symbol for an earth ground. This symbol is also used on electronic schematics.
- *Lamps:* The schematic symbol for a lamp can be a circle with four radiating line segments 90° apart, as shown in Fig. 1-3*g.* These could include a "W" for white or an

"R" for red, with the designation "PL" for pilot light. An alternative is a circle with a cross inside.

- *Meters:* The basic meter symbol is a circle; an "A" inside represents an ammeter, a "V" a voltmeter, and a "W" a wattmeter, as shown in Fig. 1-3*h.*
- *DC motors:* There are many different symbols for motors, the most basic being a circle representing the frame and the letter "M" inside. The type of motor must be determined from the context of the drawing. Common variations for DC motors include circles with marks representing brushes or circles with the horsepower ratings within the circle, as shown in Fig. 1-3*i.* DC motors have also been represented by a circle with the letters "Arm" inside to designate an armature, with the symbol for a series or field winding attached.
- *AC motors:* The basic symbol for a single-phase AC motor is a circle with two projecting line segments, while a three-phase motor symbol is a circle with three line segments. The symbols for three-phase synchronous and induction AC motors are shown in Fig. 1-3*j.*
- *Generator:* The generator symbol is a circle with a "G" inside and two tangent lines representing brushes, as shown in Fig. 1-3*k.*

  Note: It is common practice to provide additional information on motors and generators in a schedule on the drawing. This includes identification of the manufacturer, type, and horsepower rating for a motor or output voltage rating for a generator.
- *Resistors and rheostats:* A rectangle with line segments projecting from each end, as shown in Fig. 1-3*l,* is the most commonly used symbol for a resistor on electrical schematics. The symbol for a rheostat, variable resistor, or potentiometer on electrical schematics is shown in Fig. 1-3*m.* It represents a movable contact or wiper on a curved resistive element.
- *Switches:* Four different switch symbols commonly used on electrical schematics are shown in Fig. 1-3*n.* The *single-throw knife switch* symbol is a line representing a pole connected at one end to a conductor and offset so that when closed it will bridge the gap to complete the circuit. The *double-throw knife switch* symbol is two single-throw switches in parallel, with their poles connected. The *normally open (N.O.) pushbutton switch* symbol is an inverted T-shaped pole above a gap between two conductors, and a *normally closed (N.C.) pushbutton switch* has its pole bridging the gap between two conductors, completing the circuit. These symbols are also used on electronic schematics.
- *Transformers:* The basic electrical symbol for a transformer is a parallel pair of scalloped lines representing windings, but the symbol for a transformer with an iron core (or steel laminations) has two parallel lines between the windings, as shown in Fig. 1-3*o.* Other symbols in the figure are those for current and potential or voltage transformers. However, the zigzag symbol is still widely used on electrical one-line drawings to represent a transformer. An *autotransformer* or single-winding transformer is represented as a single winding with several taps, as shown in the figure.
- *Circuit breaker configurations:* Two or more circuit breaker poles can be organized to open or close simultaneously, as shown in Fig. 1-4*a.* Circuit breakers with thermal trip units (thermal overloads) are represented as having conjoined C-shaped



(a) Circuit breaker configurations

(b) Limit switch positions

(c) Contactor states

Figure 1-4 Graphic symbols for electrical schematics, Part 2.

elements connected to one conductor, and those with magnetic trip coils (protective relays) are represented as Z-shaped elements connected to one conductor.

- *Limit switch positions:* Limit switch symbols are drawn as parallel lines or as modified switch symbols, as shown in Fig. 1-4*b*. Both "normally open" (N.O.) and "normally closed" (N.C.) limit switch symbols are illustrated.

- *Contactor states* (for limit switches and relays): The parallel line symbol for a contactor, as shown in Fig. 1-4*c*, is widely used in electrical schematic drawings and logic diagrams. A gap between the lines indicates that they are normally open (N.O.), but a diagonal line across the symbol indicates that they are normally closed (N.C.). The letters "TC" adjacent to the symbol indicate "time-delay closing," while the letters "TO" indicate "time-delay opening." Alternative symbols for contactors with equivalent meanings shown here are modifications of the standard knife switch symbol.
- Contactor symbols on schematic drawings are usually accompanied by the symbol for a coil, a circle enclosing a letter "C."

Electronic Graphic Symbols

Before the turn of the twentieth century the electrical industry was engaged in the manufacture and installation of equipment for DC and AC power generation and lighting, and transmission, and distribution, is still very much its role today. At that time there were also separate telegraphy and telephony industries. The Atlantic Cable was functioning, and there were practical telegraph systems and telephone companies in the advanced Western countries. However, about that time experiments demonstrated that wireless telegraphy was practical, and after Guglielmo Marconi sent a wireless signal across the Atlantic in December 1901, the radio industry was born.

The early radio industry focused on the design and manufacture of components and equipment for transmitting and receiving radio signals. Although it was a spinoff of the electrical power industry and depended on the same electrical laws and measurement instruments as well as many of the same components, it developed as a separate industry with no links to the power, telephone, or telegraph industries.

After World War II the radio industry evolved into what is now known as the electronics industry, which has expanded to include computers and computer science. From its origins in the development of vacuum tubes and their application in rectifiers, detectors, amplifiers, and radio transmitting and receiving equipment, it went on to produce semiconductor devices and integrated circuits.

It was not long before the benefits of electronics in terms or reliability, low power consumption, and versatility attracted the attention of the electrical power industry, which began to incorporate electronic devices and circuits into its equipment. This brought the electrical power and electronics industries closer together.

Soon electromechanical rectifiers were replaced by solid-state rectifiers, electronic instruments replaced moving-coil instruments, and in many applications solid-state electronic relays began to replace electromechanical relays.

Today the electronic/computer industry has a close cooperative relationship with the electrical power industry. Electronic ballasts are replacing magnetic ballasts for fluorescent lamps, and solid-state circuits have made possible such products as dimmers, GFCI circuits, occupancy sensors, and surge protectors. Microcontrollers have also replaced banks of relays for the control of a wide range of appliances, machines, and motion controllers.

Despite this close tie between electronics and electrical power, it is still possible for an electrician or electrical contractor to perform his or her work without training in electronics; however, that situation is fast changing, due in large part to deregulation of both the telephone and electrical power industries. A working knowledge of electronics is now considered to be an essential part of the training for electrical contractors and electricians as well as electrical equipment and maintenance personnel.

As discussed earlier, many of the original electrical symbols have been adopted by the electronics industry for use on electronic schematics. They include symbols for the battery, capacitor, earth ground, lamp, and transformer. However, a new set of specialized radio (and later television) symbols had to be developed to represent components not found in electrical power circuits. These include antennas, cathode-ray tubes, headphones, speakers, radio-frequency coils, crystals, and receiving tubes. Later, new symbols were developed for thyratrons, magnetrons, klystrons, traveling-wave tubes, solar cells, transistors, and integrated circuits.

Figure 1-5 illustrates some of the more commonly used electronic symbols that are likely to appear on schematics for the rectification, amplification, and control of power. Electronics schematics identify each symbol with an alphanumeric code and rating information near the symbol. For example, batteries are rated in volts, capacitors in microfarads, inductors in microhenries, and resistors in ohms.

- *Batteries:* The multicell battery symbol shown in Fig. 1-5*a* is common to both electrical and electronic drawings. The symbol for a single cell (also called a battery) is more commonly found on electronic schematics. Batteries are identified on electronic schematics as B1, B2, etc.
- *Capacitors:* Electronic schematics distinguish between various types of capacitors, as shown in Fig. 1-5*b*. The symbol for the variable capacitor has an arrow through it, and the symbol for the electrolytic capacitor has a plus sign above it to indicate its polarization. Capacitors are identified on electronic schematics as C1, C2, etc., and their values in microfarads (μF) are usually given.
- *Inductors:* Electronic schematics use the same symbols for windings, coils, or inductors as electrical schematics, as shown in Fig. 1-5*c*. Inductors are identified on electronic schematics as L1, L2, etc.
- *Diodes:* The diode symbol in electronic schematics is an arrowhead pointing to the flow of conventional current, as shown in Fig. 1-5*d*. Electronic schematics include many different variations on this basic symbol to represent zener diodes, light-emitting diodes (LEDs), and thyristors. The outward-directed arrows on the LED symbol represent emitted light. Diodes on electrical schematics are identified as D1, D2, etc., but LEDs are identified as LED1, LED2, etc.
- *Fuses:* The electronic symbol for a fuse is a sine-wave shape, as shown in Fig. 1-5*e*. Fuses are identified on electronic schematics as F1, F2, etc.
- *Ground:* Electronic schematics use the same ground symbol as electrical schematics, as shown in Fig. 1-5*f*.
- *Integrated circuits (ICs):* The symbol for an integrated circuit is a rectangle with the projecting lines representing its pins, as shown in Fig. 1-5*g*. It is a pictorial

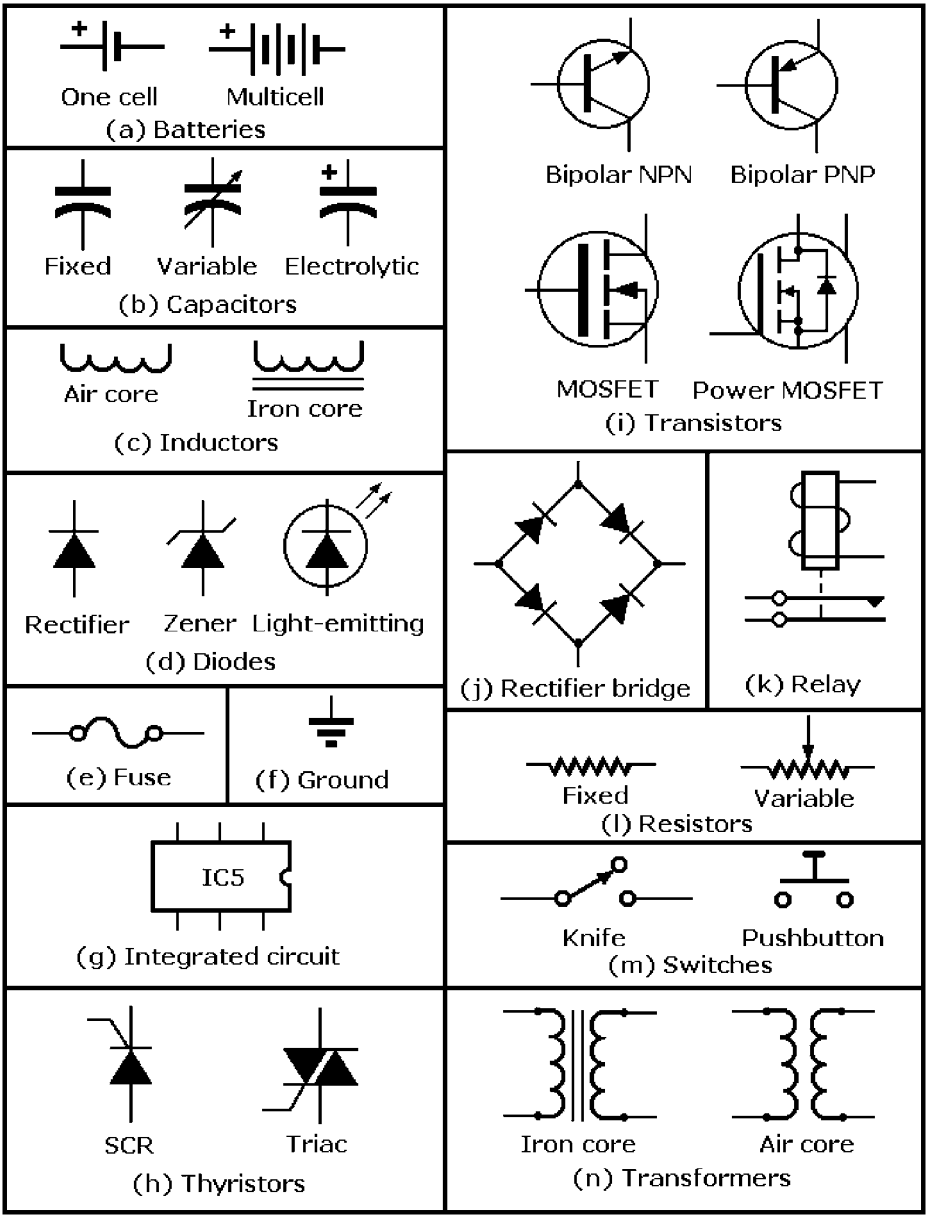


Figure 1-5 Graphic symbols for electronic schematics.

representation of a rectangular IC package as viewed from the top. The notch at one end indicates the starting point for pin numbering. The first pin is on the upper right corner and numbering continues counterclockwise around the device, with the last pin at the lower right corner. This information is important for orienting the IC correctly in a circuit. ICs are identified as IC1, IC2, etc. They might also be identified with industry standard type numbers such as 555 or 7447, or a manufacturer's numerical designation such as CD4040. The most advanced and fastest microprocessors are also represented by this symbol, but they will have many more pins than most ICs.

- *Thyristors:* The symbol for the most common half-wave thyristor, the SCR (for silicon controlled rectifier), and the triac are shown in Fig. 1-5*h.* They are three-terminal variations on the basic diode symbol.
- *Transistors:* Figure 1-5*i* shows the symbols for typical discrete power transistors that are widely used in electrical control systems. Other symbols have been developed for various field-effect transistors (FETs). The MOSFET and power MOSFET symbols are shown here. On electronic schematics transistors are identified as Q1, Q2, etc. They are also marked with an industry standard number or the manufacturer's proprietary designation.
- *Rectifier bridges:* A configuration of four rectifier diodes, as shown in Fig. 1-5*j,* is called a bridge. Bridges are widely used in electrical equipment for rectifying full-wave AC. Bridges are identified on electronic schematics as BR1, BR2, etc.
- *Relay:* The electronic schematic relay symbols shown in Fig. 1-5*k* are more detailed than the relay symbols shown on electrical schematics. The rectangle above the relay contacts represents a solenoid. In this example the contacts are normally open (N.O.). When the solenoid is energized, the contacts will close. Relays are identified on electronic schematics as RY1, RY2, etc.
- *Resistors:* The zigzag line symbol in Fig. 1-5*l* is the one accepted for U.S. electronic schematics. The variable resistor or potentiometer symbol is the resistor symbol with an arrow at right angles to indicate a movable contact. Resistors are identified as R1, R2, etc., and the value in ohms is usually given.
- *Switches:* The electronic symbols for switches shown in Fig. 1-5*m* are the same as those used on electrical schematics. Switches on electronic schematics are identified as S1, S2, etc.
- *Transformers:* The symbols for transformers, as shown in Fig. 1-5*n,* are basically the same the same as those used on electrical schematics. Transformers are identified on electronic schematics as T1, T2, etc.

Drawing Schedules

Drawing schedules are systematic listings of equipment in tabular form accompanied by identification notes. They provide information about the components and equipment shown as symbols on the drawings. Schedules typically are placed on one-line drawings, wiring diagrams, and riser drawings.

Schedules on drawing sheets are more convenient for the use of field supervisors, electricians, and installers than separate specification pages that could be easily lost or misplaced in the field, and they save time required to find the information on separate pages. Also, when the schedules are on the related drawings, the draftsperson is better able to coordinate the symbols with the supporting information. This simplifies making changes and assures data accuracy without having to cross-reference other sources.

A luminaire schedule, for example, typically lists the luminaire number, type, manufacturer, catalog number, and mounting method. It might also include a symbol key to identify the luminaire symbols on the drawing.

The information in schedules might also be duplicated in the written specifications for contract management and supervision purposes, but these specifications are not always available on the job site. Other schedules frequently found on electrical drawings include *connected load, panelboard, electric heat, kitchen equipment,* and *receptacle.* These schedules are placed on drawings for homes, offices, and small commercial businesses. However, many other kinds of equipment schedules appear on drawing sets for high-rise buildings, factories, shopping centers, and other more complex projects.

Electrical Project Drawings

ELECTRICAL WIRING DIAGRAMS

The most common electrical drawings are *wiring diagrams* or *wiring plans.* In these drawings the electrical lines and symbols are superimposed on an architectural floor plan, as shown in Fig. 1-6. The drawing scale must be large enough to permit symbols and line conventions to be drawn legibly. Floor plans for new homes, office buildings, and large industrial, commercial, or government projects are drawn by architectural drafters to a scale appropriate to the floor area of the building or project. The scales selected are typically from ¼ in. equals 1 ft to 1 in. equals 1 ft, and depend on building size. The electrical designer marks the symbols for the electrical devices such as switches, receptacles, and luminaires and lines representing wires or relationships on a copy of the floor plan.

Some electrical design CAD software includes code for making changes in the architectural drawing if that becomes necessary. For example, it might be necessary to relocate a wall to provide enough space behind it to run cable bundles or permit deep electrical panels to be flush-mounted. The electrical designer might make those changes based on his or her knowledge of building construction and the space requirements for the cables or panels to be placed behind the walls.

Figure 1-6 is a one-sheet electrical wiring diagram for a two-bedroom private home. It contains many of the same elements that would be found on wiring diagrams for larger commercial or industrial buildings. This diagram contains a *key of symbols* and a *list of branch circuit ratings* to guide the electricians or installers in the field.

Wiring diagrams are important because they are required for obtaining work permits from local building inspectors and approval by the local power utility. The wiring diagram gives the building electrical inspector an overview of the scope of the work to be performed and later serves as a guide for the inspector during the work in progress and after the work is completed. In situations where the project involves new or updated connections to the power line, the local power utility must be informed and may ask for a copy of the wiring diagram.

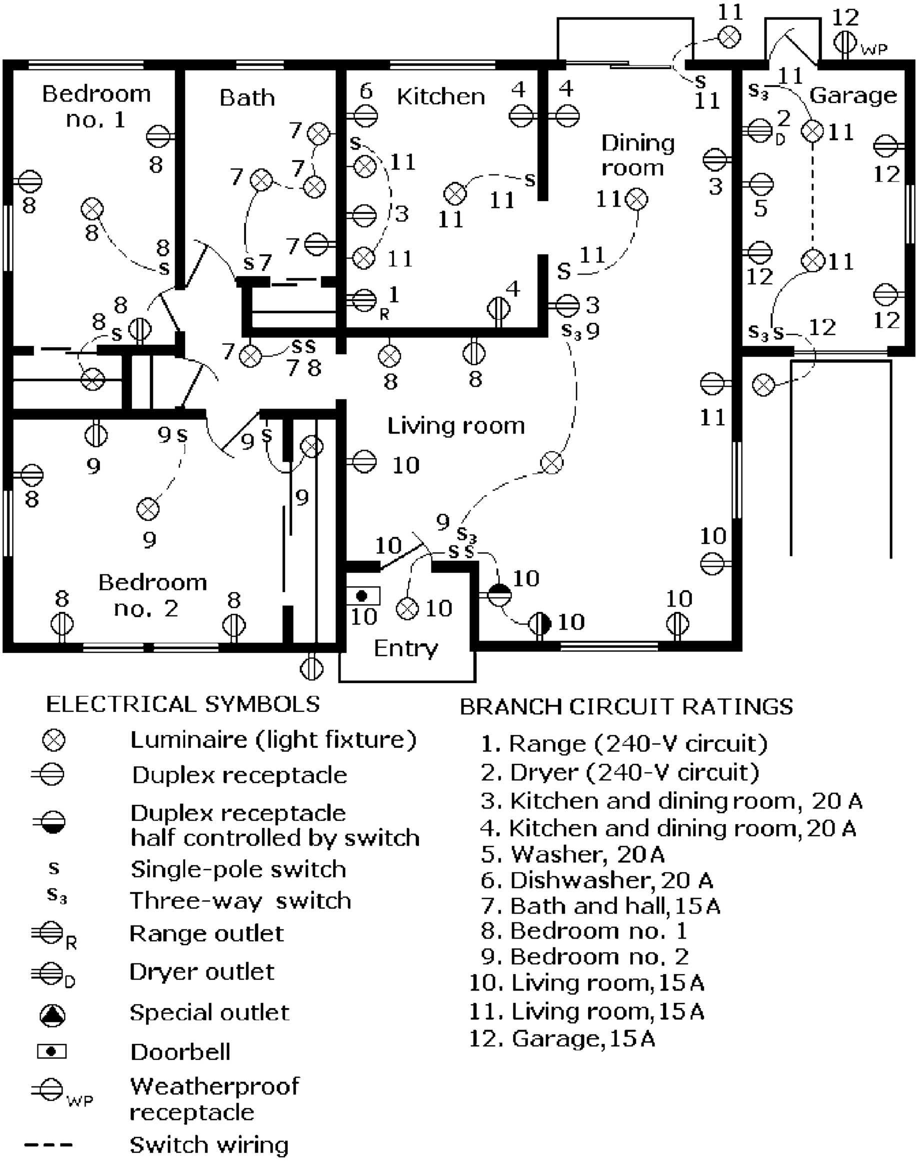


Figure 1-6 Electrical system drawing for a two-bedroom home. The dashed lines match the luminaires to the switches that control them.

The wiring diagram is also a major source of information for preparing lists of materials, and it also serves as a guide for sizing cable lengths and scheduling the installation of electrical devices and building services. A properly prepared wiring diagram should be comprehensible to those who are familiar with the symbols and conventions used in preparing it.

Because wiring diagrams are two-dimensional floor plan drawings, they do not include information about the heights of switches, receptacles, and luminaires above the floor. With the exception of ceiling fixtures, which are obvious from the diagram, the heights of receptacles and switches above the floor and their separation distances are dictated by the *National Electrical Code*® (*NEC*®)* and local building codes. In most cases the local codes will be keyed to the *NEC*, but they may be more specific about certain details based on local experience. For example, where soil conditions are typically dry a more elaborate grounding system might be required, or more provisions for protection against lightning strikes might be required in parts of the country where there is a high incidence of lightning. Any exceptions to the *NEC* requirements for device placement must be noted on the diagram. For example, switches and receptacles might be placed at more convenient heights for the handicapped occupants or those in wheelchairs.

Nevertheless, it is possible for a homeowner without formal training or experience in electrical wiring to prepare an acceptable wiring diagram if all of the rules and procedures are followed. A basic requirement, however, is familiarity with all of the relevant sections of the *NEC*, with emphasis on chapters 1–4. All submissions of wiring diagrams should be accompanied by a copy of a list of materials and a symbol key.

Some basic rules for the preparation of an acceptable wiring diagram are as follows.

- Draw or obtain a scaled architectural drawing of the floor area to be wired showing walls, doors, windows, plumbing pipes and fixtures, and heating and cooling ducts.
- Determine the floor area by multiplying the room length by width and then deduct any floor areas occupied by closets and storage areas. Indicate this figure on the diagram.
- Mark the location of switches, receptacles, luminaires, and permanent appliances such as ranges, microwave ovens, heat exchangers, and attic fans with standard electrical symbols.
- Draw in cable runs between wiring devices, indicating approved cables by type designation, wire gauge, insulation type, and branch circuit amperage. If conduit is used, size and location should be given.
- Identify the wattages for luminaires, permanent appliances such as ranges and air-conditioning systems, building service equipment such as furnaces and hot water heaters, and the type and size of each electrical box.

ONE-LINE DIAGRAMS

One of the most important drawing types for the design of a new electrical system or modernizing an existing system is the one-line drawing. It uses single lines and standard symbols to show electrical wiring or busbars and component parts of an electric circuit or system of circuits. The one-line drawing differs from the wiring diagram in that it does not specify device (receptacle, switch, luminaire, etc.) locations or switch locations for controlling those devices.

The one-line diagram in Fig. 1-7 gives an overview of a complete system and how it works. For example, a three-phase load requires three wires, and each wire has its own

---

* *National Electrical Code* and *NEC* are registered trademarks of the National Fire Protection Association, Quincy, Massachusetts.

pole of a control switch and one overcurrent device. It is not necessary to repeat this information three times on the diagram; one line shows what happens to all three wires.

General rules must be followed in preparing one-line diagrams. Compliance with these rules helps to ensure a complete, accurate, and easily interpreted diagram.

- *Indicate relative positions of components* in a building or factory. For example, distinguish between those parts of the system that are inside or outside a building. This makes the drawing easier to interpret because components are properly located with respect to each other.

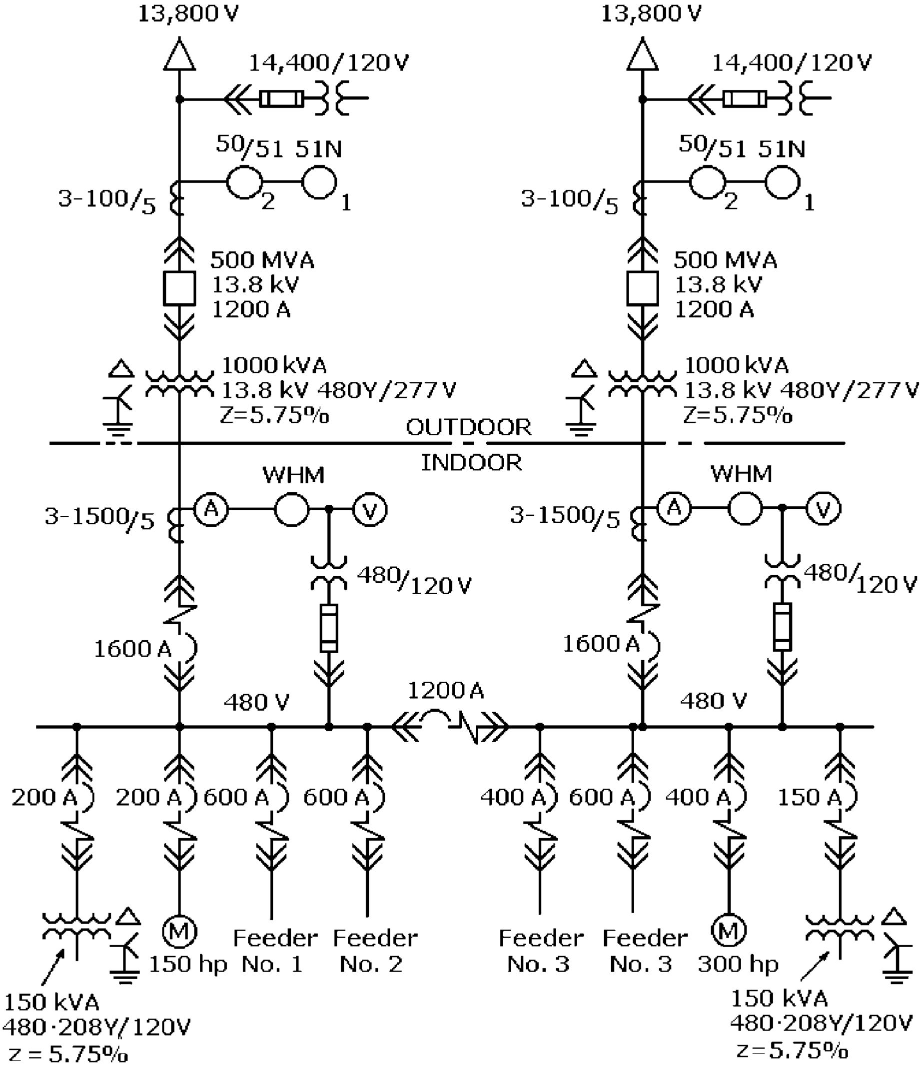


Figure 1-7 Typical one-line electrical diagram.

- *Avoid duplication of lines symbols, figures, and letters.* A one-line drawing is a precise form of technical communication, and every line, symbol, figure, and letter has a definite meaning. Unnecessary duplication will make interpretation more difficult.
- *Use standard electrical symbols* for the more common wiring devices. The use of alternative or modified symbols for common wiring devices leads to confusion and detracts from the correct interpretation of symbols for unusual or special components.
- *Allow for future expansion,* either on the drawing or with explanatory notes.
- *Include correct title data.* Assign titles with care to be sure that they identify each component correctly, eliminating confusion with other components in the system.
- *Include all pertinent technical information.*

The following checklist will be helpful in avoiding the omission of important technical information.

- Manufacturers' designations and ratings of all machines and power transformers included in the project
- Ratios of current and voltage transformers, taps to be used on multiratio transformers, and connections of dual-ratio current transformers
- Connections of power transformer windings
- Circuit breaker ratings in volts and amperes, interrupting ratings, and type and number of trip coils on circuit breakers
- Switch and fuse ratings in volts and amperes
- Any special features of fuses (current limiting, dual element, etc.)
- Functions of relays
- Size and type of conductors
- Voltage, phase, and frequency of incoming circuits; indicate wye and delta systems, and show whether they are grounded or ungrounded

POWER RISER DIAGRAMS

Power riser diagrams are single-line diagrams showing electrical equipment and installations in elevation. Figure 1-8 is an example drawn for a combined office and warehouse. It shows all of the electrical equipment and the connecting lines for service entrance conductors and feeders. Notes identify equipment, the size of conduit necessary for each feeder, and the number, size, and type of conductors in each conduit.

ELECTRICAL SCHEMATIC DIAGRAMS

Electrical schematic drawings are usually prepared by equipment manufacturers to show the electrical connections that must be made by the electrician or installer. They are also used for testing, troubleshooting, and maintenance of the equipment. As an example of an electrical schematic diagram, Fig. 1-9 shows an across-the-line starter for a three-phase motor powered from a three-phase, three-wire supply.

It can be seen from the diagram that the motor starting equipment is housed in two separate enclosures. This starter would normally be shipped by the manufacturer with

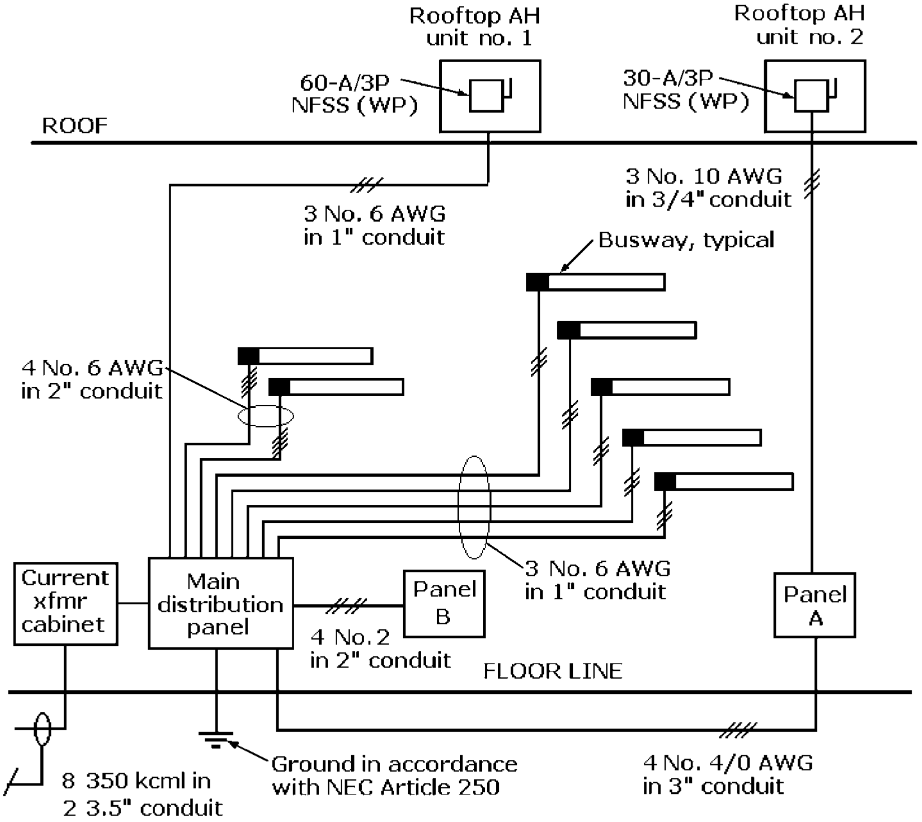


Figure 1-8 Power riser diagram for a combined office-warehouse building.

the motor it will control. The contactors, overcurrent protective devices, transformer, and operating coil are in one enclosure, and the start/stop pushbuttons are in a separate enclosure so that they can be mounted some distance from the motor.

In this schematic each component is represented by a graphic symbol, and each wire is shown making individual connections between the devices. However, multiple wires could appear as one line on the drawing. As on this drawing, each wire is usually numbered to indicate where it enters the enclosure, and those numbers are repeated for the same wires connected inside the enclosure.

The three supply wires are identified as L1, L2, and L3; the motor terminals are designated T1, T2, and T3; and the normally open line contactors controlled by the magnetic starter coil C are designated as C1, C2, and C3. Each contactor has a pair of contacts that open or close for control of the motor.

The remote control station consists of the stop and start pushbuttons connected across lines L1 and L2 by the primary of an isolation control transformer. The transformer secondary in the control circuit is in series with the normally closed overload contactors (OC) and the magnetic starter coil (C). The stop button is also connected in series with the starter coil, and the start button is connected in parallel with the starter coil.

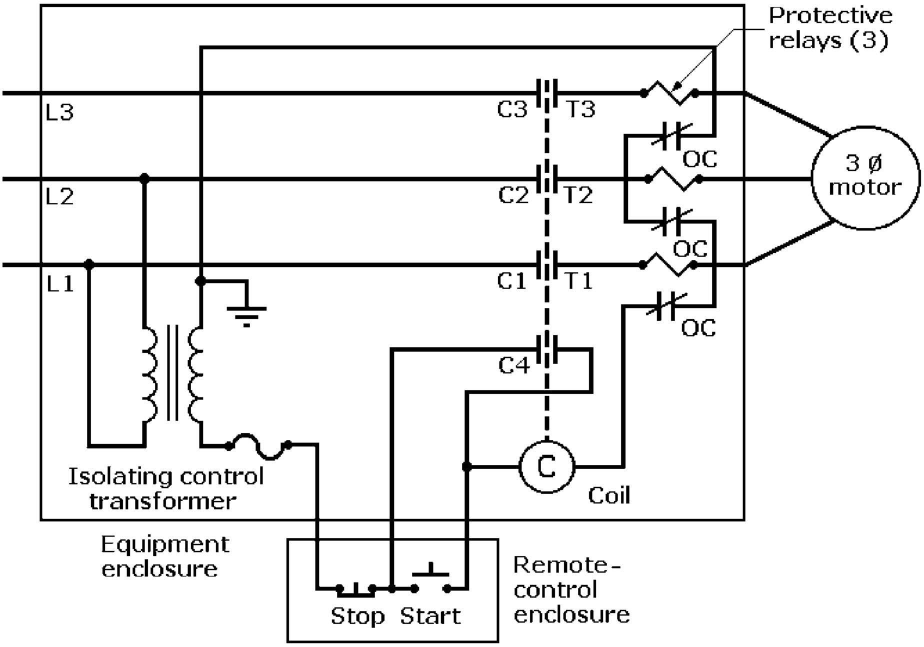


Figure 1-9 Schematic diagram for an across-the-line motor starter.

In this circuit, the control transformer isolates the control circuit and prevents it from responding to any ground faults that could cause the motor to start accidentally. The isolating transformer can have its primary winding identical to its secondary winding so that input voltage equals output voltage, or it can step the motor circuit voltage down to a lower level as an added safety measure for the control circuit.

ELECTRICAL DETAIL DRAWINGS

Electrical detail drawings are prepared as separate sheets to give the installer more complete details of a specific, nonstandard installation requirement. Figure 1-10 is a detail drawing of a section through the wall of an office warehouse. It provides details of how and where hanger fittings and boxes are to be placed between a column and insulation to support a run of bus duct.

Any set of electrical drawings might require additional “blowup” drawings of certain technical details that are not clearly indicated on small-scale drawings, particularly plan views. In this example, it is an elevation view of a section wall shown on a plan view. It includes both mechanical and architectural details. Other drawings might show section views of special foundations or footings, or suspension systems for electrical equipment.

These detail drawings might be drawn by the consulting architectural or engineering firm on complex projects, but they might also be supplied by the manufacturer of the equipment or hardware to be installed. The consulting firm will collate these drawings into the related set with appropriate sheet numbers.

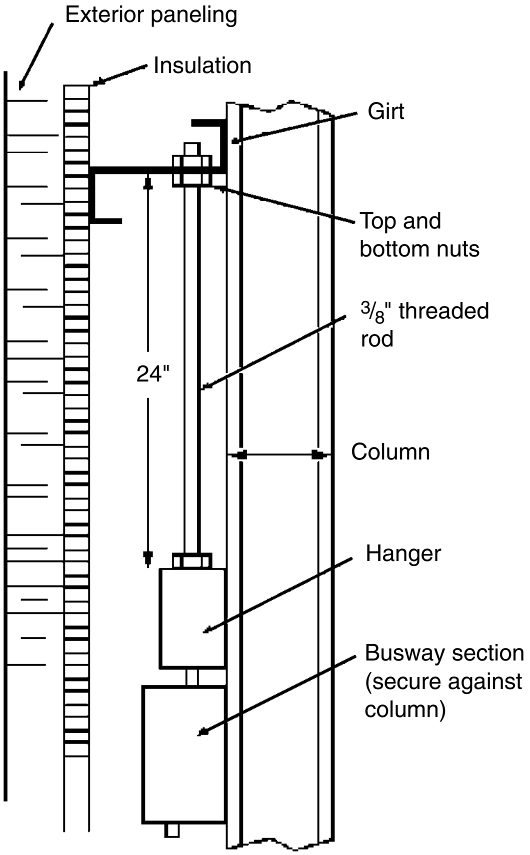


Figure 1-10 Electrical construction detail for hanging a busway.

SHOP DRAWINGS

Many items of electrical equipment such as motors and motor control cabinets are standardized by the manufacturer, and the outline and footprint dimensions are included in their catalogs. However, large, costly electrical equipment such as high-voltage switchgear, transformers, motor control centers, HVAC (heating, ventilating, and air conditioning) systems, and elevators are usually custom made for each project. Project shop drawings for this equipment are usually drawn by the manufacturer and furnished prior to the delivery of the equipment. They might also include installation and maintenance manuals custom-prepared for the specific project.

The architect/engineer requires dimensional outline information to lay out the location of the equipment on the elevation drawings and check for any possible interference conflicts that could develop. For example, the equipment must be positioned to provide, safe easy access to the equipment for routine maintenance. Allowance must be made for the swing radii of all doors, and adequate space must be allowed for maintenance personnel to gain access to the equipment through removable cover panels as well as enough room to work.

In some cases, special concrete footings must be prepared with specified lag bolts for anchoring the equipment before it is delivered. This work must be completed and the concrete must be sufficiently cured to accept the load when the equipment arrives on the site.

Shop drawings also are helpful for the contractor responsible for installing heavy equipment, so any required cranes or other heavy moving equipment will be on the site prior to the delivery of the equipment. In addition, the contractor must make sure that any existing openings in the walls or doorways are wide and high enough to provide adequate clearance for the entry of the equipment. Advance information will give the contractor enough time to install any conduit, cable trays, or plumbing that would be difficult or excessively costly to install after the equipment is in place.

As-built drawings that include detailed “factory-wired” connection diagrams will assist the installer in performing any “field wiring.” Later they will be important if any commissioning procedures or final acceptance testing is required. These drawings will then become part of a maintenance file to assist the maintenance personnel in the performance of any troubleshooting that might be required at a later date, after the equipment is operational. These drawings and any operation and maintenance manuals are essential documents of record that will be useful for making any later additions to the facility.

Electrical Product and Work Standards

The generation, transmission, and distribution of electrical power are now deregulated, but many rules, regulations, and standards still apply to the manufacture of electrical equipment, the job site, and the installation of electrical systems. Many of these standards are focused on safety issues, such as the elimination or avoidance of hazards in working with or using electricity.

The installation of any inferior wiring devices or equipment, substandard workmanship, or inadequate test and maintenance procedures could be the cause of fires or explosions and result in the creation of electric shock hazards. There is a need for standards that, when adopted, will serve as a basis for proper inspection and supervision. There are regulatory standards, national consensus standards, product standards, installation standards, and international standards.

The consensus standards include the National Electrical Code (NEC), the National Electrical Safety Code (NESC), National Fire Protection Association (NFPA) 70B and 70E, and other NFPA standards, as well as American National Standards Institute (ANSI) and the Institute of Electrical and Electronic Engineers (IEEE) standards. Interested persons with requisite education, training, and background experience volunteer their time and expertise to develop these standards. Some might be employees of electrical product manufacturers, and others might be consultants or engineering professors.

Some standards were developed specifically for electrical applications. These include the National Electrical Code (NEC) (officially NFPA 70) and the National

Electrical Installation Standards (NEIS). In addition, the National Electrical Manufacturers Association (NEMA) standards cover equipment design and construction, while the Underwriters Laboratories Inc. (UL) standards cover safety provisions in the manufacture of electrical devices, products, and accessories.

The National Fire Protection Association (NFPA), publisher of both the NEC and NESC, has also developed standards related to electrical work including:

- NFPA 79 Industrial Machinery
- NFPA 780 Lightning Protection
- NFPA Static Electricity

The NFPA has also developed standards for fire prevention, installation of sprinklers, stacking materials, and a standard building code. The following organizations have also developed standards that have a bearing on electrical work:

- ACS: American Chemical Society
- ACGIH: American Conference of Governmental Industrial Hygienists
- AIChE: American Institute of Chemical Engineers
- ASME: American Society of Mechanical Engineers
- ASTM: American Society for Testing and Materials
- ASSE: American Society of Safety Engineers
- AWS: American Welding Society
- CGA: Compressed Gas Association
- CMA: Chemical Manufacturing Association
- CMAA: Crane Manufacturer's Association
- GSA: General Services Administration Federal Supply Services
- NSC: National Safety Council
- OSHA: Occupational Safety and Health Administration

Individuals or organizations with a professional or business interest in these standards can join these organizations to help support them and gain access to their newsletters so that they can stay informed on any changes within the standards.

Standards-making organizations may make changes to their standards between normal cycles that are not included in the printed text of the original issue of the standard. The NFPA, for example, does this in the form of a Tentative Interim Amendment (TIA). Additionally, changes may take place without a formal notice of change, so it is important to stay current with any given standard. Interested parties can communicate with these standards organizations and suggest changes or revisions in standards.

It is the responsibility of all electrical contractors, electricians, and installers in the field to know which standards apply to any project taking place within any given location or job site. It is also important to remember that not all standards that might apply to every job site or location actually apply. A hazard assessment by the project supervisor or licensed electrician must determine which standards apply at each workplace and that they are followed.

The contractor has the responsibility for assuring that a workplace is free from recognized hazards and is a safe place for electricians and installers to work. This could apply to such factors as the quality of ladders or scaffolding at the site or the need for safety goggles or face masks when performing certain kinds of work. For example, eye protection should be worn during any grinding or cutting operations that could result in flying chips of metal, and proper face masks should be worn by anyone performing burning or welding that could result in the release of toxic gases.

Designers, engineers, contractors, electricians, or equipment installers and all other persons whose work is governed by one or more standards should be familiar with and know how to apply the rules found in all of the applicable standards. These are the rules that relate to design, including safety considerations, for a particular project or task.

What Are Electrical Specifications?

Electrical specifications for buildings or projects are written legal descriptions of the work to be performed by the electrical contractor, subcontractors, and electric power utilities and the responsibilities and duties of the architect/engineer, general contractor, and owner. Electrical specifications and electrical drawings are integral parts of the contract requirements for the performance of electrical work.

Because specifications are a significant part of a legally binding contract, typically involving expenditures of thousands or even millions of dollars, it is important that they be mutually compatible with the drawings and as free as possible of errors or discrepancies. It has long been known that even minor errors in wording or intent or the presentation of incorrect data or measurements can result in expensive repairs or replacements of hardware, lost time in the completion of the schedule, and serious project cost overruns due to delays and the need for additional labor and supervision.

In most engineering and architectural firms, regardless of size, specifications writers are skilled persons with technical backgrounds who report to a responsible project supervisor. The preparation of an error-free specification is a time-consuming task calling for the writer's patience and the ability to deal effectively with complex technical details. The process might call for many drafts and revisions following the review, comments, and corrections made by persons within the architect/engineering organization with specialized knowledge and experience in each of the trades involved in the project. As with drawings, all responsible reviewers are expected to sign the final version that is released for bid.

Nevertheless, this does not relieve specifications writers of their responsibilities, because they are expected to have sufficient knowledge of the project to make them capable of finding and resolving any discrepancies between the specifications and the drawings. Discrepancies are most likely to occur when

- A generic master or prototype specification is used without making all of the modifications necessary to reflect what is actually shown on the working drawings.
- Revisions that should have been made in a previously prepared drawings are indicated only by a note in the revision block, leaving the drawing unchanged.

- Revisions in items that are listed both in schedules on the drawings and in the written specifications are made on only one of these documents.

For example, there is a discrepancy if the specification calls for one loadcenter but the drawing has been revised to show two loadcenters and this change is not reflected back to the specifications. Such a discrepancy could result in unnecessary costs, unless caught in time. For this reason, it is not good professional practice to duplicate the same information on both specifications and drawings. It is preferable that the required information be placed on the document on which it is most logically found to assure compliance, with perhaps a reference to its location on the other document.

If for some reason duplication of information occurs in both drawings and specifications, and it is not practical to delete it from one of the documents, the project supervisor should add a note to the contract before it is put out for bid stating whether the specifications or drawings take precedence.

THE MASTER ELECTRICAL SPECIFICATION

Appendix B is a sample master electrical specification edited specifically for electrical work to be done in a new residence or small office. It is intended for educational purposes only and should not be used as the basis for an actual contract specification unless reviewed and approved by a licensed electrical contractor or specialist in electrical power and lighting specifications.

A master specification, regardless of its source, is a generic prototype or template that functions both as a check-off list and repository of useful paragraphs from which a specifications writer can pick and choose to prepare a working specification. Those paragraphs that do not relate to the project can be deleted and new or revised paragraphs can be added.

The master specification is written in a quasi-legal style with words such as *shall, will,* and *may* having very specific meanings. *Shall,* for example, indicates that the party named must carry out the specified activity; *will* indicates that there is certainty that the party named will perform the specified action; and *may* means that permission can be granted for the party named to take a specific action. Some phrases widely used in specifications to convey specific meaning are *or equivalent, as approved,* and *unless otherwise specified.*

The master specification might be the result of years of accumulated experience of an engineering or architectural firm, or it could be a document prepared by an industry-sponsored institute based on the collective experience of its members. Regardless of the specification's origin, it is the specifications writer's task to modify or "tailor" it to fit a specific project. After all of the applicable general paragraphs have been selected, they are supplemented with the additional information required to identify the desired materials, equipment, products, and devices, and perhaps even specify the methods or procedures required for the performance of the work.

It necessarily follows that implementing a master specification requires specialized technical knowledge in the interpretation of drawings and practical experience or training in a specific trade. Experience is also needed in knowing the optimum locations for presenting certain kinds of information, either on the drawings or in the specification.

For many straightforward projects such as modifying or updating the electrical system in a residence, small office building, or retail shop, a simple one-page specification or description of the work to be done may be sufficient to describe the scope of the work. However, it might also have one or two working drawings attached, if necessary. By contrast, large-scale commercial or industrial projects might require hundreds of pages of specifications and hundreds of working drawings.

Master specifications are also prepared for the work of other trades such as masonry, carpentry, structural steel work, plumbing, and machine or mechanical equipment installation. Each of these divisions in a general specification is organized in a manner similar to the electrical division with certain provisions and special conditions common to all. They also include paragraphs covering such topics as the type and quality of materials to be used, the equipment to be furnished, workmanship, and testing.

The general specification must deal with situations where the work of various trades overlaps or is interdependent. This calls for precise definitions of work boundaries and the responsibilities among subcontractors. It might also involve precise scheduling to minimize worker downtime in one trade while the work of another trade is performed.

Master electrical specifications are typically organized in sections such as the following.

General Provisions sections consist of a group of considerations and regulations that apply to all sections of the division. Topics covered might include the scope of work, electrical reference symbols, codes and fees, and tests to be performed.

Basic Electrical Material and Methods sections identify type and quality of materials, equipment, and devices specified for use such as wiring and cable, conduit, boxes, cabinets, loadcenters, switches, receptacles, motors and starters, and overcurrent protective devices. They might also specify methods for installing certain kinds of equipment.

Power Generation sections cover equipment used for emergency or standby power generation that would take over essential electrical service during a utility power outage. They usually include installation requirements for emergency circuits, generator sets, storage batteries, controls, and distribution switches.

Medium Voltage Distribution sections cover the installation of high-voltage (over-600-V) transmission and distribution facilities required for large government or industrial facilities, work that would not be performed by publicly held electric utilities because it does not relate to their system operation. The equipment specified in these sections is usually rated for more than 2.4 kV, and includes substations, switchgear, transformers, rectifiers, converters, power factor-correction capacitors, and instrumentation.

Service and Distribution sections cover the distribution of power under 600 V for residential, commercial, and light industry projects including service entrances, metering, grounding, branch circuit loadcenters, and branch circuits including the size and number of conductors, wiring devices, circuit protection devices, and installation methods.

Lighting and Luminaires sections cover interior and exterior luminaires and lamps. Schedules identify luminaire types and locations and the ratings, types, and number of required lamps. These sections cover the requirements for indoor lighting, including such topics as track and recessed lighting, emission colors of lamps, and types of ballasts. They can also cover outdoor floodlighting and even street lighting, poles, and standards.

Special Systems sections cover a wide variety of special systems related to or dependent on electrical power. Examples include lightning and surge protection, battery chargers, outdoor low-voltage lighting systems, and door chimes.

Communications sections cover such systems as fire alarm, burglar alarm, surveillance, multimedia, public address, and intercommunication, as well as wiring for telephone systems and cabling for cable and satellite TV systems.

Heating, Ventilation, and Air Conditioning sections cover the installation and wiring of electric heating, ventilating, and air-conditioning equipment. Examples include ranges, microwave ovens, washing machines, dryers, baseboard heaters, exhaust fans, and wall-mounted air-conditioning units. The work of these sections requires cooperation between mechanical equipment and appliance installers and the electrical contractor.

Controls sections cover controls and instrumentation installed on a project. Examples include recording and indicating devices, interior low-voltage lighting control systems, thermostats, and remote HVAC controls.

PREPARING A WRITTEN SPECIFICATION

The preparation of an accurate and complete electrical specification is the responsibility of the architect/engineer and is an integral part of the project contract documentation. The specification must be coordinated with the project electrical drawings, and failure to do so can result in significant costs and lost time for making corrections.

The electrical specification for a project might refer to hundreds of products, parts, and components as well as numerous items of equipment and systems. By agreement between the owner and the architect/engineer, these items can be specified in different ways. They can be approved only if they are the products of a single manufacturer and are identified by a part or model number. Alternatively, the citation of one manufacturer and model number can become the standard for quality and specification grade (hospital, industrial, commercial, or residential) if the phrase "or equivalent" is added. Yet another option is simply the statement in the specification that a material or product shall conform to a specific commercial, federal, or military standard or comply with certain codes and tests.

In some specifications, especially those calling for the procurement of equipment or systems, a summary of critical performance characteristics and perhaps outline dimensions is included to define the desired products. This information can be obtained from the catalog data obtained from a number of manufacturers whose products have been approved as meeting the specification requirements. By using this approach, procurement is opened to competitive bidding from a wider base of qualified suppliers. This can lead to more favorable prices and delivery schedules.

GENERAL AND SPECIAL CONDITIONS AND PROVISIONS

The *General Conditions* section of written specifications consists of a selected group of regulations that apply to the general contractor as well as all subcontractors (electrical, mechanical, structural, plumbing, etc.). The General Conditions are usually presented as a formal standard document entitled *General Conditions of the Contract for Construction.*

Among the subjects covered in General Conditions are the bid, the required contract, and performance bonds and insurance payments, as well as the identification of those responsible for such duties as removing rubbish and providing temporary electrical service. All of these subjects are of concern to the electrical contractor. The electrical specification writer must make certain that nothing in the electrical specification conflicts with these General Conditions.

Some project specifications include *Supplementary General Conditions and Special Conditions*. These are inserted after the General Conditions, and they normally apply only to the general contractor. However, if there is a requirement for Supplementary General or Special Conditions that apply to only one trade, they are usually inserted in the division of the specification that applies to that trade.

Electrical specifications typically include a *General Provisions* section that applies only to that division. It is intended to remind those using the electrical specification that the General and Special Conditions apply because they are also a part of the specification.

The General Provisions section typically includes paragraphs entitled Temporary Power; Electrical Drawing and Symbols, including the requirement that a symbol list appear either on the drawings or in the written specification; Work Included; Work Not Included; and Codes and Fees. The Codes and Fees section states that the electrical contractor must comply with all applicable codes, federal laws, state and local ordinances, industry standards, electric utility specifications, and fire insurance requirements. It also includes a penalty clause to be invoked against the electrical contractor for noncompliance.

Some electrical specifications include only a *General Description of the Work* or *Scope of the Work* on the assumption that this will be sufficient because more detailed information will follow in subsequent pages.

The sample master specification in App. B contains both Work Included and Work Not Included sections. The latter section identifies the electrical equipment to be

- Furnished, installed, and wired by others.
- Furnished and installed by others, but wired by the electrical contractor.
- Furnished by others, but installed and wired by the electrical contractor.

2

POWER GENERATION AND TRANSMISSION

CONTENTS AT A GLANCE

Overview
Energy for Electricity Generation
North American Power Grid
Single- versus Three-Phase Power
Power Generating Stations
AC Generators
Auxiliary Power Station Equipment
Generator Synchronization
Wye- and Delta-Connected Loads
AC Transmission Systems
Transmission Towers, Poles, and Frames
High-Voltage DC Transmission

Overview

The first commercial power plant was opened in San Francisco in 1879. It was followed in 1882 by the opening of Thomas Edison's Pearl Street station in New York City, which delivered direct current (DC) electric power. In 1893 alternating current (AC) generation and transmission were displayed at the Chicago Worlds Fair. By 1896 an AC transmission line had delivered power generated by a Niagara Falls hydroelectric plant some 20 miles to Buffalo, New York. After a contentious battle between Thomas Edison and other proponents of DC power, the advocates of AC power such as Nikola Tesla and George Westinghouse prevailed. Alternating current became the accepted national power standard. Demonstrations had proven that AC transmitted over long distances sustained lower power losses than DC transmitted over the same distances.

Over the next hundred years a North American power grid, a major development in power generation and transmission, evolved from the consolidation of separate AC power generation and distribution networks. This grid now stretches across the country from New York to California, with parts extending into Canada and Mexico. More recently, computer-controlled switching systems with advanced software have been introduced into the power grid.

Meanwhile, electric power generating capacity has fallen behind the ever-increasing demand for electricity in North America. The power shortage has been traced to the complications brought on by deregulation, a shortfall in the construction of new power plants, and strong environmental activism that has inhibited new plant construction.

The deregulation of the electric power industry in the 1990s has resulted in immense changes in the industry since that time. While traditional electric utilities still generate, transmit, and distribute electricity much as they did before deregulation, many others have taken advantage of deregulation to divest themselves of their power generation facilities, which had long served their local areas. Of these utilities, some acquired newer, more efficient generation plants in other locations, while others abandoned generation altogether. Some utilities that gave up on generation claimed that they wanted to concentrate their resources on transmission, distribution, and improving customer service, but others admitted that they just wanted to be free from the constant public complaints about the air pollution produced by their power stations.

As a direct result of deregulation, the electric power industry has seen the entry into the market of small and independent power producers, so-called merchant generators, and power marketers. Moreover, there has been a significant increase in mergers and acquisitions within the industry, along with the entry of some power utilities into other, more lucrative commercial enterprises. The objective of some of this diversification has been the formation of integrated energy services.

Power marketers act as independent middlemen who buy and sell electricity in the wholesale market at market prices. Most of this power is traded in the growing electricity commodity market. In the past, power marketers did not own electric generation, transmission, or distribution facilities, but recently even this has changed. They are now acquiring generation plants under various ownership and leasing arrangements.

Electric utilities now bid for electricity from various generation plants in two auctions, one that occurs every day before the power is scheduled for use and another that happens an hour before use.

The U.S. electric power industry today is a complex mix of organizations consisting primarily of shareholder-owned, cooperative-owned, and government-owned utilities engaged in power generation, transmission, and distribution. There are, however, other participants classed as nonutility producers and suppliers. As one of the nation's largest industries, the revenues generated by the U.S. electric power industry surpass those of the telecommunications, airline, and natural gas industries.

Demand for electricity in the United States has historically been closely correlated with economic growth. Since the end of World War II, electric power demand has matched the growth in the gross domestic product (GDP), the indicator of economic health. The reasons for this increasing demand for electricity include the population expansion, the surge in the use of electrically powered labor-saving machines, tools, and appliances, wider acceptance of air conditioning in all parts of the country, and the popularity of home entertainment electronics and computers.

Newer models of TVs, stereo systems, and computers consume more power than their predecessors, and the Internet has attracted nearly around-the-clock home computer operation. Deregulation introduced competition and the price of electricity with respect to the cost of living index has fallen, encouraging even more consumption.

The electric power industry recognizes three major customer groups: residential, commercial, and industrial. As one might expect, the number of residential customers far exceeds the number of commercial and industrial customers. The commercial customer base includes retail stores, hotels, offices, and restaurants, but the ratio of customers to the total sales of electricity is relatively small. The customer base in the industrial sector is the smallest, accounting for less than 1 percent of all electric utility customers. The sector consists primarily of large corporations engaged in manufacturing, mining, and the processing of oil, chemicals, metals, and food.

Surprisingly, each of these groups buys about one-third of the total power generated in the United States. However, there is yet another smaller group of customers, not classed among the big 3 because it consumes less than 3 percent of all electricity generated. This group includes railroads, national, state, and local government agencies, and the state and municipal authorities that pay for street and highway lighting.

Energy for Electricity Generation

More than 85 percent of all electric power generated in North America is produced by AC generators that are driven by steam turbines. Of this amount, more than 65 percent of the steam is produced by burning of fossil fuels, primarily coal and natural gas. The pie chart Fig. 2-1 illustrates the distribution of energy sources for electrical power generation in the United States. The proportions hold for North America and many European countries as well.

Coal is the dominant fossil fuel consumed to produce steam, accounting for more than 50 percent of all energy consumed. Despite its reputation as a constant threat to its neighbors, nuclear energy accounts for only about 20 percent of the energy consumed for electric power generation. The nuclear reactors function only as steam generators.

Natural gas is in third place among energy sources for steam generation. Oil is also a fossil fuel accounting for only about 3 percent of the energy consumed for electric generation, but most of it is used to power gas turbines in turbine generators or as fuel for the diesel engines in engine–generator sets.

Coal remains the dominant fuel worldwide for producing the steam required for electric power generation, despite efforts toward using the so-called renewable resources: water power, wind power, and solar power. Coal retains its importance because it is plentiful and relatively inexpensive and because many industrialized countries have

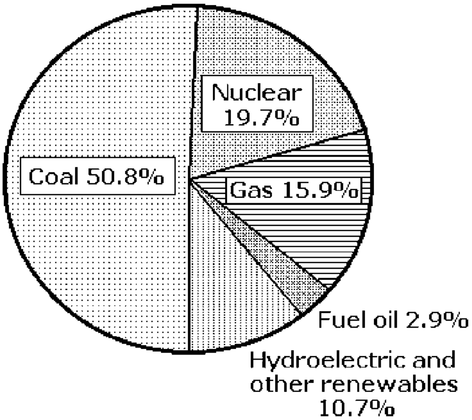


Figure 2-1 The use of different energy sources to generate electrical power in the United States.

adequate domestic sources. The United States, for example, does not have to depend on foreign sources for coal.

The burning of coal, oil, and natural gas provides 85 percent of the world's commercial energy and 80 percent of all human-caused carbon dioxide emissions. Energy demand has nearly doubled in the past 30 years, and it is expected to increase another 60 percent by 2020. At present only about 10 percent of the world's total energy is supplied by renewable energy, although in some countries its use is said to be growing rapidly. This figure is comparable to the approximately 10 percent figure for North America.

Hydroelectric power dominates among the renewable sources, but such alternative sources as wind turbines, solar cells, biomass fuels, and hydrogen fuel cells still account for only a few percentage points. Nevertheless, some studies have predicted that renewable energy sources could provide half the world's energy needs by 2050.

The burning of fossil fuels has been identified as the source of most of the world's pollutants—sulfur dioxide, nitrogen dioxide, particulates, and ozone. These emissions have been blamed for air pollution, smog, and acid rain, and they have been identified as a major cause of death and serious health problems. However, motor vehicles produce far more of these pollutants than electric power plants.

Because it is easier to focus on power plants than vehicles, citizen groups, environmentalists, and health professionals have demanded more government regulations to control and possibly eliminate objectionable emissions from power plants. Despite the fact that the electric power industry has done much to reduce its emissions over the past 20 years, primarily as a result of new plant construction, friction between the government and the industry still exists.

Some power plant owners have argued that some pollution control regulations are excessive, impractical, and too costly to implement in older plants. They say that compliance would be so expensive that they would either have to shut down the plants or raise electric rates. They add that by shutting down the plants they would deprive many people living nearby of a reliable local power source, and that low-income families would be unable to pay the higher rates.

Some have said that the obvious solution is to build more nuclear power plants because they do not produce pollutants, but this argument does not seem to be a viable option. Nuclear power plants have long been controversial because they pose a threat to public safety and health due to the possibility of nuclear accidents caused by equipment failure or operator error. This hazard was amply demonstrated by the well-publicized reactor meltdown at Chernobyl in the Ukraine and the many casualties it caused.

More recently, the public has become alarmed over the accumulation of spent nuclear fuel at existing nuclear power plants and the hazards that are presented by transporting large quantities of radioactive waste material from those sites over the nation's highways to a storage facility in the Nevada desert.

Another serious consideration has been the security at commercial nuclear plants, because of the threat of terrorist attacks on the reactors that could release radioactive materials into the air. All of these factors have led to more legal constraints on the operation of existing nuclear plants and any construction of new ones, along with pressure to decommission more existing plants.

As a result of all of this controversy, natural gas is reemerging as the fuel of choice for new power plants in the United States because its combustion by-products are lower in polluting gases and particulates than coal-fired plants. This means that the scrubbing and filtering systems need not be as comprehensive as those required for coal-fired plants.

Federal laws prohibiting the use of both natural gas and petroleum products as fuels for power generation were passed during the energy crisis of the 1970s. That prohibition was only lifted years later, in 1987. Many of the new power plants being built or planned will be capable of generating steam from either natural gas or coal. The choice will depend on the price and availability of natural gas.

Despite high hopes for the renewables, the most important of these sources, hydroelectric generation, has proven to be unreliable in times of drought. Moreover, environmental concerns about the damming of bodies of water large enough to produce electric power reliably and cost-effectively have led to public protests against new dam construction. Here again, there is pressure to decommission many existing dams to improve the water flow in rivers and restore now submerged lands to a natural condition.

Complaints about the unsightly appearance of wind turbines and the threats they present to migrating birds have cast a shadow on that technology. Hopes for economical power generation from large arrays of solar panels have been dashed, and research into power generation by ocean waves and tides has yet to prove its viability.

Coal-fired, hydroelectric, and nuclear power plants remain the most economical sources for electric generation on an hourly basis for 24-hr periods. Because oil-fueled turbine and diesel engine generators have a higher hourly cost, their operation is reserved for peak periods or as backup when other power plants are offline for repairs.

Newer technologies have been introduced to correct the pollutant emissions from existing coal-fired power plants. Improved fabric filters and electrostatic precipitators are removing particulates, the dust and smoke that affect air quality. An electrostatic charge is applied to the particulates in precipitators, and the particulates are then passed through an electric field where they are attracted to collecting electrodes. The electrodes are then mechanically jolted, causing the particulates to drop into collecting hoppers.

Various flue-gas desulfurization (FGD) processes including lime/limestone wet scrubbers and dry scrubbers are being installed to remove sulfur dioxide, the industrial pollutant that forms acid rain. In addition, catalytic reduction systems (SCRs) are reducing the emission that reacts with sunlight to create ground-level ozone, or smog.

North American Power Grid

The North American power grid consists of interconnected grids of generating plants, transmission lines, and distribution facilities that blanket the United States and extend into both Canada and Mexico. Transmission lines link generators to substations that distribute electricity to local customers throughout this vast region. These grids provide electric utilities with alternative power paths in emergencies, and allow them to buy and sell electricity from each other and from other power suppliers.

The U.S. power grid consists of three networks: the large Eastern and Western, and the smaller Ercot within Texas. Essentially independent, they are connected by high-voltage DC lines in only a few locations. In emergencies, power can be transferred from one connection to another, but power failures cannot spread between them.

There are more than 700,000 mi of high-voltage transmission lines in the three interconnected networks of the grid. Each of the three networks in the grid produces and distributes AC, but they are connected by DC links, which are easier to control. Today 138 control areas monitor the grid with computers that predict energy flow and anticipate reactions to power failures. Within each of these networks, the amount of electricity consumed must equal the amount of electricity produced at all times.

The Eastern grid covers the entire East coast from Maine to Florida and extends westward to the Continental Divide and northward into Canada. The Western grid covers the western states from the Continental Divide to the Pacific coast, also extending into Canada and Mexico. The Ercot grid covers eastern Texas.

Each grid is composed of a tangle of transmission lines operated by a diversified group of owners from regulated utilities to government agencies and private power marketers. A disparate set of state, regional, and federal regulators governs the operation of the networks. Far from a perfect system, it still requires that restraints be applied to avoid overloading; consequently, it has been called a “work in progress.”

Transmission operators in strategically located control substations monitor:

- Electricity flowing from their own regional networks
- Changes in customer demand
- Transfers of electricity between the grids
- Power from transfers flowing through their own grids

A computerized system permits the operators to:

- Control the network
- Find alternate sources when generation plants are offline
- Verify that power transfers follow orderly procedures

The transmission lines within the networks operate at voltage levels of 765, 500, 345, and 230 kV. The ever-increasing demand for power in the United States has not been matched by the construction of needed extensions to the existing transmission infrastructure. To remedy this shortcoming, engineers have turned to computer science and electronics for controlling the grids and making them work faster and more efficiently.

The development of specialized high-power silicon thyristors has made it possible to switch high levels of power faster than could be done earlier, compensating, in part, for the lack of needed transmission line extensions. Thyristors, like transistors, can turn the flow of electrons ON and OFF, but they can handle larger power loads more effectively than transistors because of their higher electrical ratings. Moreover, once turned ON, thyristors stay ON. This characteristic allows energy to flow continuously.

However, stock thyristors are unable to switch electrons as rapidly as transistors, which are orders of magnitude faster. This has limited their capabilities for high-speed power switching in the grid. This was overcome with the development of the *insulated-gate bipolar transistor* (IGBT), a four-layer discrete power transistor that combines the characteristics of a power MOSFET and a thyristor. MOSFET transistors open and close the thyristor's latch electronically. These devices have also been used to control electric motors and low-power generators.

The IGBTs make the grid less vulnerable to voltage sags, surges, and noise in the power signal. Without electronic control of high-power transmission, power-line loads must be limited to as little as 60 percent of their rated *thermal capacity*, the temperature at which overheated wires sag into trees or onto the ground, and short out.

Computer-based controllers can bypass surges or sags automatically and much more quickly than would be possible with the manual adjustment of transformers or dependence on automatic circuit breakers that sense a disturbance and simply "trip" a transmission cable offline. That action can send surges of power through neighboring circuits, tripping them as well, leading to massive regional outages.

The efficient operation of the North American electrical grid now depends on computers, software, and solid-state power electronics capable of handling heavy current loads. These systems have improved the reliability of power distribution throughout North America. They have also made it possible to increase the efficiency of existing power plants while reducing the urgency for the construction of the thousands of power plants that will be needed in the United States alone in the near future.

It is expected that electronic controls will eventually be located throughout the nation's power grids. Integrated network controls could synchronize all of the system's electronics to optimize flow over the entire grid. The Electric Power Research Institute estimates that integrated control could boost the overall transmission capacity of the existing infrastructure by 30 to 40 percent.

Single- versus Three-Phase Power

The principal elements of an electric power system are the generating stations, the transmission lines, the substations, and the distribution networks. The generators produce the electricity, the transmission lines move it to regions where it is consumed, and the substations transform it for industrial, commercial, and residential use. Finally, the distribution networks carry the electricity to the customers.

Most AC power is generated as three-phase power. Both three-phase and single-phase devices can be powered from a three-phase supply. A three-phase circuit is a combination of three single-phase circuits. The current, voltage, and power relations of balanced three-phase AC circuits can be studied by applying the rules that apply to single-phase circuits.

The sine waves of three-phase voltage are separated by 120 electrical degrees because they are generated by three separate sets of armature coils in an AC generator. These three sets of coils are mounted 120 electrical degrees apart on the generator's armature. The coil ends could all be brought out of the generator to form three separate single-phase circuits, but they are conventionally interconnected so that only three or four wires are actually brought out of the generator.

Single-phase AC voltage with zero power factor has both voltage and current sine waves in phase, so they cross the zero line together twice in each cycle. Similarly, a plot of three-phase voltage sine waves, also with zero power factors as shown in Fig. 2-2, has all three voltage and current waves crossing the zero line twice each cycle together. Each of its three phases, V1, V2, and V3, is separated by 120 electrical degrees.

Power supplied to each of the three phases of a three-phase circuit also has a sinusoidal waveform, and the total three-phase power supplied to a balanced three-phase circuit remains constant. As a result, there are two practical reasons why three-phase power is superior to single-phase power for many applications.

1 Three-phase machines and controls can be smaller, lighter in weight, and more efficient than comparable single-phase equipment. More power is supplied to them in the same period than can be supplied by a single-phase power circuit. However, the trade-off for this advantage is that three-phase machines and controls are more complex and expensive.

2 Only about 75 percent as much copper wire is required for distributing three-phase power as is required for distributing the same amount of single-phase power.

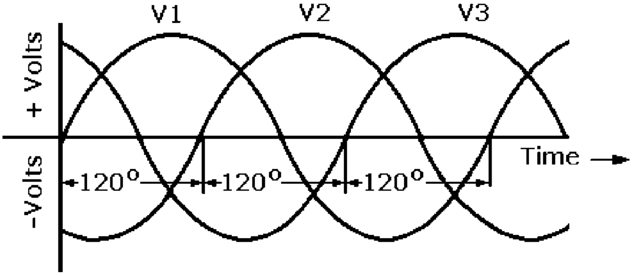


Figure 2-2 Three-phase voltage waveforms are separated by 120 electrical degrees.

Power Generating Stations

A power generating station contains one or more AC generators capable of generating power at predetermined voltage levels. As discussed previously, the mechanical power for spinning most generator shafts is obtained from steam, and most of the steam is produced by boilers heated by burning fossil fuels or nuclear reactors. The steam spins turbines, which in turn drive the generator. In the case of hydroelectric generation, a hydraulic turbine driven by water falling through a dam penstock drives the generator.

Gas turbine or diesel engine generators, either sharing space in conventional power stations or in separate buildings, generate the additional power required for peak load periods or emergencies.

The capacities of power generating stations are rated in megawatts (MW). The largest coal-fired station now in service produces 1100 MW, but three recently constructed coal-fired stations produce 650, 800, and 950 MW. Many of the new fossil fuel-powered stations planned for construction within the next few years will produce power only in the range of 80 to 750 MW. By contrast, most nuclear power stations in the United States produce from 1150 to 1300 MW.

Some of the new power stations are intended primarily to supplement the generating capabilities of existing larger stations in different parts of the country. Natural gas is now the favored fuel for these new power plants, but some of these will be designed as dual-function plants: Natural gas will be the primary fuel, and oil will be the backup fuel if gas price increases make its use uneconomical or the gas supply is disrupted.

The smaller-capacity gas turbines and diesel engine generating stations for use during periods of peak load or emergencies are typically run for only a few hours each day. Because they are rated for up to 100 MW, some power stations have installed as many as six of these to achieve capacities of 500 MW.

AC Generators

AC generators are synchronous machines capable of generating AC electric power. The interactions between the multipole magnetic fields of the stators (armatures) and rotors of synchronous generators generate the electrical power. The interaction is called *synchronous* because when the generator is running, the stator and rotor magnetic fields turn at the same speed.

A single small generator might have a rating of a few hundred watts, but the largest single machines have ratings that exceed a billion watts. All synchronous generators have wound armatures and rotors, but the armature is wound on the stator rather than on the rotor, and the field winding is wound on the rotor. Figure 2-3 is a cutaway view of a synchronous AC generator with a solid cylindrical-wound rotor that permits it to turn at high speed without self-destructing.

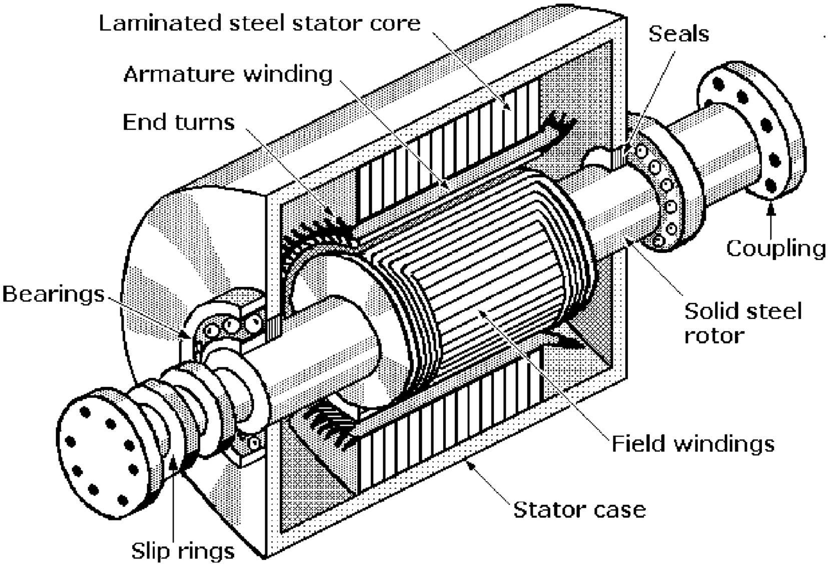


Figure 2-3 **Cutaway view of a synchronous AC generator with a solid cylindrical rotor capable of high-speed rotation.**

The organization of a utility AC generator is opposite that of most DC generators and both AC and DC motors. If these machine have armatures, they are wound on their rotors; if they have field windings, they are wound on their stators.

The construction of AC generators is reversed to eliminate the complexities of slip-ring mechanisms for obtaining the AC power and to provide more stable mechanical support for the stator windings. With more rigid support, the stators eliminate vibrations that create centrifugal forces which degrade the quality of the AC output.

The armature windings are fitted tightly into slots on the inner surface of the stator formed by stacking magnetic sheet steel laminations. The field coils are then wound in axial slots in the outer surface of the solid cylindrical magnetic steel rotor. The rotor and stator together form the magnetic circuit. Most utility AC generators have a three-phase armature winding.

The insulation of the AC generator is simplified by having a revolving field and stationary armature. As the poles move under the armature conductors on the stator, the field flux cutting across the conductors induces an alternating voltage. It is alternating because poles of opposite polarity pass successively by a given stator conductor. The alternating voltage appears at the stator windings and is brought out directly through insulated leads from the stationary armature.

Because most utility AC generators run at constant speed, the voltage generated depends on field excitation. The rotating field is supplied with 120 or 240 V DC from a separate small DC generator called an *exciter* through two slip rings and brushes. This arrangement permits the generated voltage to be controlled by adjusting the amount of field excitation supplied to the exciter. The field excitation, in turn, is controlled by varying the excitation voltage applied to the alternator field.

The exciters that provide DC field excitation are usually connected directly to the generator or driven by a belt from the generator. However, some generators have separate motor-driven exciters.

The rotor and stator of a synchronous machine must have the same number of poles, because power generation is the result of the magnetic interaction between a succession of north–south magnetic-field pole pairs.

AC FREQUENCY GENERATION

The frequency of the generator's output voltage depends on the number of field poles and on the speed at which the rotor is turning. In a given coil, one complete voltage cycle is generated when a pair of rotor poles (north and south) is moved past the coil. The AC output frequency f of the generator is related directly to the number of poles p, and the mechanical speed of the rotor is N. The frequency f in hertz is found by

$$f = \frac{pN}{120}$$

where p is the number of poles and N is the number of revolutions per minute (rpm).

It can be seen that the product of p and N must be a constant to obtain either a 60- or 50-Hz output frequency. The standard power frequency in North America is 60 Hz. Most electrical utility AC generators have two poles and are driven by fossil-fueled steam turbines. From the equation above, it can be determined that with two poles, rotor speeds must be 3600 rpm for 60 Hz and 3000 rpm for 50 Hz AC.

By contrast, AC generators driven by steam turbines with the steam produced by nuclear reactors have lower speed requirements. They are typically four-pole machines with rotor speeds of only 1800 rpm for 60 Hz or 1500 rpm for 50 Hz AC.

From the equation it can be seen that all AC generators driven at slower speeds must have more poles to obtain the 50- or 60-Hz output. For example, an AC generator that is to be driven by a diesel engine with a shaft speed of 400 rpm must have nine poles.

AC GENERATOR ROTORS

Synchronous AC generators are fitted with one of two different rotor designs depending on their intended rotational speeds.

- *Round rotors* are solid steel cylinders with the field winding inserted in slots milled into the surface or the rotor. They usually have two or four poles. Round rotors can withstand the stresses of high-speed rotation.
- *Salient-pole rotors* have multiple pole pieces (typically six) mounted to the rotor structure, and the field winding is wound around the pole pieces. Because of their more complex construction and larger diameter-to-length ratios, salient-pole rotors cannot withstand the stresses of high-speed rotation.

Electric utility steam-turbine–driven generators designed for 50- or 60-Hz AC output voltage have round rotors with two poles because they can withstand the stresses of speeds of 3000 and 3600 rpm. Hydroelectric, diesel, and natural-gas engines have far lower shaft speeds than steam turbines, so the generators they drive usually have six or more pole rotors, requirements usually met with more complex salient-pole rotors.

Three-phase AC generators have a winding that is made up of three separate stator windings, each displaced from the other two by 120 electrical degrees. The three windings can either be *wye-* or *delta*-connected. The wye connection is more common because it is better suited for direct high-voltage generation.

BUS VOLTAGE GENERATION

When a steam turbine or other driver has brought the generator rotor up to its required speed, its field is excited from the DC supply, as shown in the single-line diagram Fig. 2-4. As stated earlier, most AC generators run at constant speed, so voltage generation depends on field excitation. The generator field is energized by the main exciter. A voltage of 13.8 kV is generated by the generator shown, and it is stepped

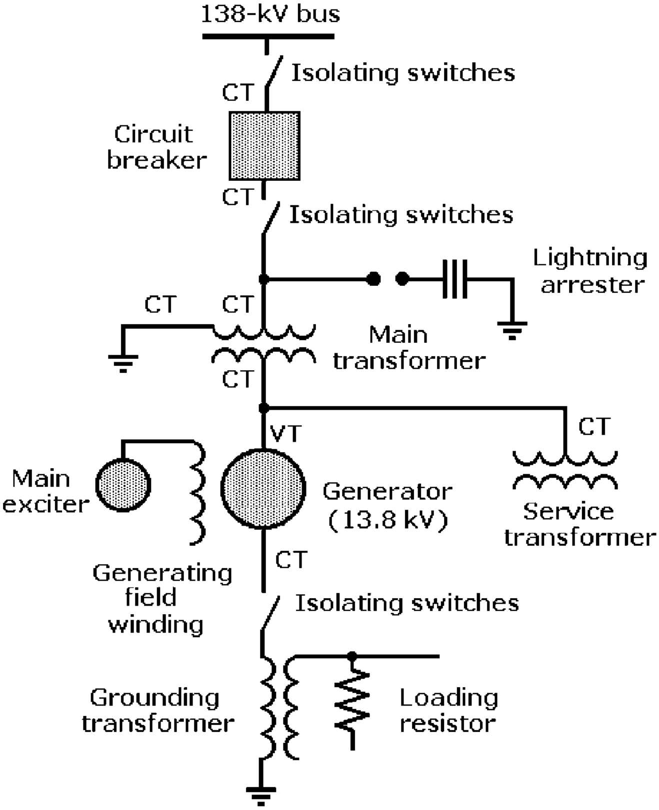


Figure 2-4 Single-line diagram of a power station AC generator. CT = location of a current transformer; VT = location of a voltage transformer.

up to 138 kV by the main transformer. It is then passed through the circuit breaker and isolating switches before being applied to the 138-kV bus.

The generator is grounded through a grounding transformer. Current transformers, whose positions are indicated by the "CT" abbreviations, are positioned on both sides of the generator, the main transformer, and the circuit breaker. There is also one located at the service transformer. They provide power for the measuring instruments and relays.

A voltage or potential transformer indicated by the "VT" abbreviation on the output side of the generator provides the necessary voltage for voltage regulation, relays, and instrumentation. The service transformer provides voltage for the power station's auxiliary equipment, and a lightning arrester protects the generator. The main transformer's neutral point is grounded by another current transformer.

Auxiliary Power Station Equipment

The operation of a generating station requires many different subsystems and accessories for the control of its vital functions. For example, there are controls for the steam and water pressure to the turbines, the excitation field of the exciter, the rotational speed of the generator armatures, and the voltage at the input to the step-up transformers.

Other important services in a power station are auxiliary electrical power generation to provide for the station's heating, lighting, and cooling requirements as well as the operation of measuring instruments and internal and external communications equipment. The electric power needed for the proper operation of power station service equipment can range from 5 to 10 percent of the total power output of the generators.

Instruments monitor boiler temperature, turbine temperature, shaft speeds, generator voltages and currents, power output, phase synchronization, and load. Fossil-fuel power plants must also control the effluents from their cooling systems, and smoke and fly ash from their stacks. Power station communications equipment includes telephone and radio links for internal plant operation and telephone, radio, and data links for maintaining constant contact with other parts of the electrical system outside the station.

Generator Synchronization

When a generator is connected to a three-phase transmission bus in a system, it is important that its frequency be synchronized with the frequencies of other generators supplying power to that bus as well as the frequency of the voltage in the bus. A synchronizer or synchroscope indicates whether the generator and the bus are in synchronism. This instrument can be a rotating pointer on an electromagnetic instrument or can show up as a pattern on an instrument with a cathode-ray tube.

The three-phase generator is connected to the high-voltage three-phase bus through disconnecting switches and a circuit breaker. One step-down voltage transformer is connected to one phase of the generator, and a second step-down transformer is connected to the same phase on the bus. The secondaries of the transformers are connected to a synchronizing bus.

A voltmeter can indicate either the actual voltage of the transmission bus or the generator, depending on how it is connected to the synchronizing bus. The generator voltage is applied to one terminal of the synchroscope and the transmission bus voltage is applied to the other terminal. If the two voltages are not in phase, an indicator will show the need for synchronization.

Wye- and Delta-Connected Loads

Wye and delta connections for generators are also used for other loads such as motor windings, lamps, and transformers. The same current, voltage, and power relations that apply for generators also apply for other three-phase load connections.

Figure 2-5 illustrates the wye and delta connections for either load or source, where E_L = load voltage, I_L = load current, E_P = phase voltage, I_P = load current, and Z_P = load impedance.

Figure 2-5*a* is the schematic diagram for the wye connection and its various voltage and current relationships, and comparable information for delta connections is given in Fig. 2-5*b*. A discussion on the use of wye and delta connections for transformers is given in Chap. 3.

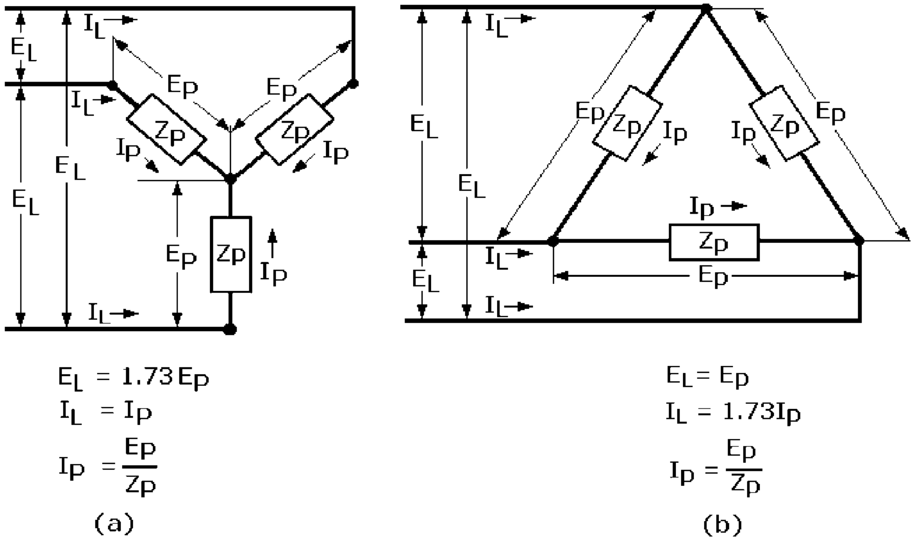


Figure 2-5 Three-phase connections for a load or source: (*a*) wye; (*b*) delta.

AC Transmission Systems

After electrical power is generated by a power station at voltages from 1000 to 26,000 V (1 to 26 kV), it is fed to transformers that step the voltage up to higher values more suitable for transmission over long distances. These transformers step voltages up to values that include 110, 138, 230, 345, 500, and 765 kV. Of these, all but 110 and 138 kV are transmitted over the North American power grid.

Transmission lines can span distances as long as hundreds of miles and provide electric power to large geographic regions. The ability to transmit electric power from one location to another with minimal voltage loss was made possible by the invention of the transformer. The *step-up transformer* increases the AC generator voltage from the primary winding to the secondary winding, but it also steps down the current.

The step-up transformer at the power station produces an extremely high voltage with low current, which flows through the high-power transmission lines strung on tall steel, aluminum, or wooden towers and poles located across the country. These power lines connect to *step-down transformers* at local substations. Step-down transformers reduce voltage from the primary winding to the secondary winding, but step up current. Transformations occur many times throughout the transmission path across the country to urban, suburban, and rural areas.

The reliability, security, and stability required of transmission systems are assured by the transmission substations. These substations include switching, high-voltage transformers, and control equipment. High-voltage switchgear protects against line faults, contains disconnect switches for maintenance purposes, and might also include the equipment for connecting two transmission lines and synchronizing their voltages.

The selection of operating voltage depends on the amount of power to be carried and the distance to be covered. The permissible power loading of a circuit depends on such factors as the thermal limit of the conductors, their clearances above the ground, the voltage drop between the transmitting and receiving ends, reliability considerations, and the power requirements needed to keep the generating stations in synchronism.

Maximum AC transmission voltages rose from 500 to 765 kV, now the highest AC voltage in commercial use. Some 2000 mi (3200 km) of 765-kV lines are now in service in the United States. While problems associated with insulating the lines to withstand lightning have been overcome, insulating them adequately against voltage surges caused by circuit breaker operation still remains problematic.

Research and test lines have experimented with voltages as high as 1500 kV, but it is unlikely that voltages much higher than 765 kV will be used in North America because of existing environmental and political considerations. These include public challenges based on audible noise or “hum” levels, the need for wider rights-of-way, and concern for the possible adverse effects of high voltage on persons and animals in the immediate vicinity of the transmission lines. Moreover, many people would object to the intrusive visual impact caused by the taller transmission towers and higher cables that would be required.

TRANSMISSION CABLES

The conductors for high-voltage transmission lines are typically made from copper, aluminum, copper-clad steel, or aluminum-clad steel. These lines are suspended from many different kinds of supporting structures by strings of porcelain insulators. The most common of these structures are the self-supporting steel towers or poles. The construction of these towers and poles has permitted significant increases in the distance between supporting structures, and has helped to reduce the cost of transmission. Transmission towers are modified structurally to withstand the stresses involved when they are used to change the directions of entering conductors to different outgoing angles. Modern high-voltage transmission lines that traverse essentially straight paths can have as few as six towers per mile.

UNDERGROUND/UNDERWATER AC POWER TRANSMISSION

High-voltage underground cables have been installed in response to adverse public response to the visually offensive high-rise transmission towers in or close to populated communities. Underground cables rated for voltages as high as 500 kV have been developed. They were first placed in service in the United States in 1976. Traditionally, underground cable systems have been installed in cities and other heavily populated areas, where open high-voltage lines present a safety hazard. They have also been installed where overhead lines were not practical, in locations such as airport approaches because of aircraft safety issues, or water crossings where overhead lines are not feasible because of interference with water traffic. For crossing large bodies of water, trenches are dug or dredged to depths related directly to the voltage being carried by the cable, and the crossings are marked near the shore lines.

Extruded dielectric cables have become the U.S. standard for voltages to 161 kV. Low-pressure cables have hollow cores for the circulation of oil under low pressure. The oil provides temporary protection of the enclosed wires from water damage should the cable sheath develop a leak. High-pressure oil-filled pipe-type cables are commonly installed for 230- and 345-kV applications in the United States.

Oil is circulated in the pipe under high pressure (14 kg/cm^2 or 200 psi). Most new cable installations make use of extruded dielectric, but pipe-type cables account for 75 percent of the approximately 2400 circuit miles now in service. From 15 to 20 percent of the cable is extruded dielectric, and most of the remainder is self-contained fluid-filled cable.

Transmission Towers, Poles, and Frames

Structures are built to support single, double, or multiple circuits. Structures for supporting single or double circuits are generally used for transmission lines in rural areas, where rights-of-way are inexpensive. High right-of-way costs generally rule them out in congested urban and suburban areas. Three or more circuits can be supported in heavily populated areas to transmit large blocks of power over one line. Many different kinds of structures are used to support transmission-line conductors. These include:

- *Steel structural towers:* rigid self-supporting, semiflexible, and guyed
- *Steel tubular poles:* self-supporting and semiflexible
- *Aluminum structural towers:* rigid self-supporting and guyed
- *Wood poles and H frames*
- *Concrete poles*

The optimum transmission-line supporting structure depends on such factors as:

- Location of the line
- Funds allocated for its construction
- Cost of maintenance
- Availability of material

The three basic kinds of rigid towers used for supporting single- or double-circuit lines are used for different economic and engineering reasons:

- *Tangent suspension towers* support normal line spans with no changes in direction.
- *Angle suspension towers* support normal line spans with small-angle turns.
- *Angle suspension towers* support normal line spans with large-angle turns.

Steel towers are widely used to carry high-voltage transmission lines over distances of hundreds of miles with stretches that might be over rugged terrain. Wide conductor spacing is required to assure adequate clearance for the electrical phases and their insulators even during high wind or tornado conditions. The tower must be high and strong enough to maintain safe conductor sag distances above the ground even when the conductors expand during exposure to ambient temperatures in excess of 100°F. At the same time, the tower structure height must be reasonable. The size and form of the tower depends on

- Nature of the terrain traversed
- Voltage carried
- Combined weight of both the insulators and conductors
- Turns in the direction of the line

The “spotting” or spacing of these towers also depends on the path to be followed by the transmission line and the terrain traversed. Tower spacing can be wide if the terrain is essentially flat and the path between them is essentially straight point-to-point. However, long spans are also required if the lines cross ravines, lakes, rivers, or mountainous areas.

Self-supporting towers offer the advantages of long life with minimum inspection and maintenance costs. They are widely used to support three-phase transmission lines carrying voltages up to 765 kV. The basic parts of towers are the base or footing, the main tower structure, the bridge or crossarm members, ground wires, insulators and vibration dampeners, and the tower's grounding system.

Figure 2-6 shows a conventional tangent self-supporting steel tower capable of carrying 500 kV. It is designed to support a bundle-conductor line with three 971.6-kcmil aluminum-clad steel wire conductors per phase. The spacing between the three conductors in the bundle is 18 in., and the spacing between the three phases is 40 ft. Two overhead ground wires consisting of seven No. 9 strands of aluminum-clad steel wire are suspended and insulated from the tower with distribution-type guy strain insulators. These ground wires are also used to transmit carrier-current communications channels. Each ground-wire insulator has a spill-over gap to protect it during lightning discharges. The legs are spaced 36 ft apart in a square configuration.

If the towers are to be located on sloping ground, the towers will have legs of different length to compensate for the angle of slope. Towers that support lines that turn are reinforced to take the additional load, and offset cross-arms to support the insulators that will offset from vertical to support the turning conductors. The wider the angle of turn, the more pronounced will be the offset of both the crossarms and insulators.

The horizontal spacing between phases of lines carrying 500 kV will be 30 to 40 ft, and the cross-arms will be about 80 ft wide. However, if 765 kV is being carried, phase spacing is increased to about 45 ft and crossarm lengths can exceed 120 ft.

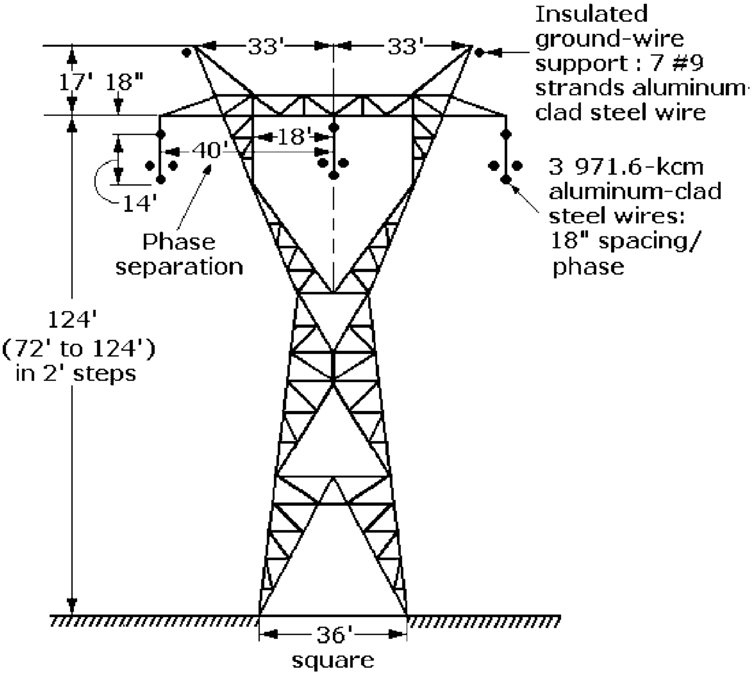


Figure 2-6 A 500-kV steel self-supporting transmission tower.

Semiflexible self-supporting towers are useful for voltages up to 500 kV. They have narrower leg spacing at right angles to the line direction and require less structural steel. To compensate for the narrower tower bases, ground wires are strung more tightly to take up unbalanced loads and become part of the structural system. Some self-supporting towers also have crossed guy wires between legs of the tower to increase lateral strength.

Guyed towers overcome the weakness of semiflexible towers in line with the line. They can be built with two narrower legs spanning a fixed distance at right angles to the line, while guy wires between and outside of the legs make the structure rigid. The guy wires are securely anchored in the ground. Another kind of guyed tower has two thin structural legs supporting the cross-bridge, which converge at a single hinged point at the base to form a V-shape. Guy wires in the direction of the line and at right angles to it provide the required rigidity.

Although steel towers predominate, the demand for high-strength *aluminum-alloy towers* is increasing. They can be built to the same structural designs as steel towers, but the use of aluminum calls for an engineering trade-off. While aluminum offers better resistance to corrosive atmospheres, it is more expensive than steel and lacks its rigidity. Aluminum is commonly used in the construction of guyed towers.

Tubular steel poles are being used for voltages up to and including 345 kV along railroad rights-of-way and other locations where space for running transmission lines is restricted. The conductors and supporting insulators are suspended vertically in the same plane from arms or booms projecting from the steel poles. These poles are usually tapered and about 100 ft high. For 230 kV, the arms are about 9 ft long, so they hold the insulators and conductors about 9 ft away from the pole; vertical phase separation is about 18 ft. These towers are normally spaced about 300 ft apart.

H-frame structures with wood pole legs and laminated wood crossarms can support 345-kV lines. They can be constructed for considerably less cost than metal towers. Figure 2-7 shows an H-frame structure with a trussed crossarm used on 345-kV lines. The line has two 795-kcmil aluminum-clad steel conductors per phase with18-in. bundle spacing and 28-ft phase spacing. The insulation hardware is not grounded, so the structure takes full advantage of the impulse insulation of its laminated wood crossarm. Lightning flashovers could occur between the conductors and ground wires on the poles, but they are not expected to follow the insulator string and crossarm. The height of the legs can vary from 75 to 100 ft, as required for the site. The poles and timbers are made from Douglas fir treated with pentachlorophenol.

High-Voltage DC Transmission

Many years of experience with extra-high-voltage DC (EHVDC) transmission lines has demonstrated that DC voltages as high as 800 to 1000 kV could be sent cost-effectively over long distances with minimal line losses. It was also found that EHVDC can overcome some problems that restricted the use of alternating-current systems over the

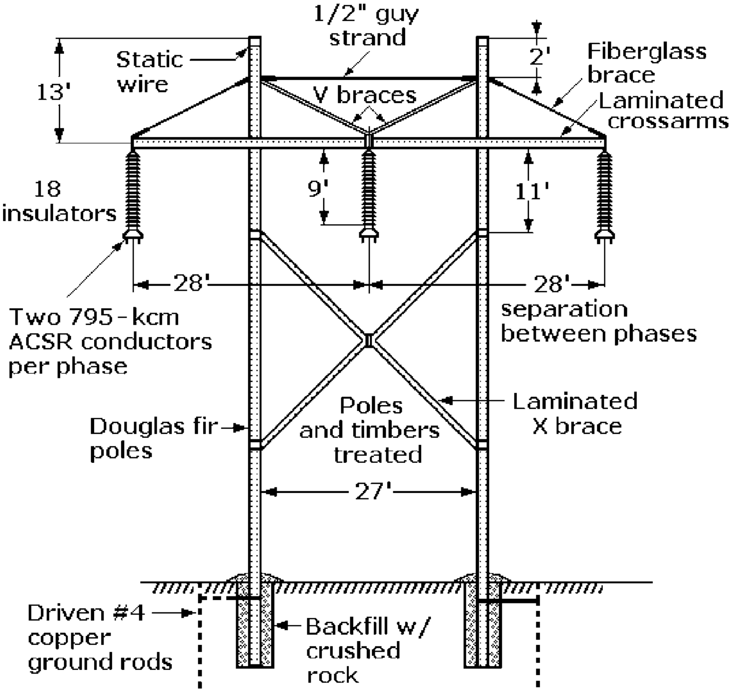


Figure 2-7 A 345-kV wood H-frame transmission tower.

same route. In the United States 800-kV HVDC systems are now operating, but a 1000-kV system is operating in Sweden.

The greatest disadvantage of EHVDC is the need for costly AC-to-DC conversion equipment to convert incoming AC power to DC power and later reconvert it to AC for distribution to consumers at useful voltage levels. The development of solid-state rectifiers has made overhead HVDC economical for distances of more than 400 mi (650 km), but underground HVDC transmission lines are a far shorter 25 to 30 mi (40 to 50 km).

3

POWER SYSTEM EQUIPMENT

CONTENTS AT A GLANCE

Overview

Transformers, General

Transformer Characteristics

Glossary of Transformer Terms

High-Voltage Circuit Breakers

Circuit Switchers

Reclosers

Interrupter Switches

Voltage Regulators

Power Factor

Primary and Secondary Power Capacitors

Kilovarmeters

Synchronous Condensers

Phase Converters

Power Semiconductor Devices

Overview

This chapter covers the functions performed by high-voltage power transmission and distribution equipment in the electrical power industry. Basic transformer theory is discussed here to highlight the similarities in construction and operation of all transformers, whether they are low-power units or high-voltage transformers used in transmission and distribution. The transformer configurations used in single-phase and three-phase applications are discussed. In addition, the more specialized voltage and current transformers for high-voltage instruments as well as autotransformers are explained. The transformer section of this chapter includes a glossary of transformer terms for ready reference.

The circuit breakers discussed in this chapter are rated for more than 600 V. They operate on different principles than the more familiar low-voltage units and have different distinguishing features. (Residential low-voltage circuit breakers are discussed in Chap. 5.) The functions of high-voltage circuit switchers, reclosers, interrupter switches, and voltage regulators in power transmission and distribution systems are explained.

To make the most effective use of AC power, it is important that inductive reactances be minimized to bring the voltage and current waveforms into a closer phase relationship. The subjects of power factor and power factor correction are discussed, and the role of power capacitors in power factor correction is explained. The use of the kilovarmeter to monitor power factor and capacitive reactance during typical 24-hr periods is discussed.

The way in which rotary or static phase converters convert single-phase to three-phase power is explained. Power semiconductors are playing an increasingly important role in power rectification and control. The semiconductor devices most widely used in the performance of those functions are identified and explained.

Transformers, General

A transformer is a static electrical component with no moving parts that is used for stepping voltage up or down or isolating one circuit from another. Transformers have the ability to convert low-voltage, high-current AC to high-voltage, low-current AC, or vice versa, with minimal energy losses. Minimizing energy losses is critical in all power generation, transmission, and distribution systems. Transformers work only with AC in accordance with the physical laws of magnetic induction, and they are inherently low-loss components. The simplest low-voltage transformers can be made by winding separate coils of insulated wire around a ferromagnetic core, typically a stack of steel laminations.

When one coil or winding, called the *primary* or *input coil,* is energized, the core is magnetized so that the resulting magnetic flux induces a voltage in the second winding, called the *secondary* or *output coil.* The change in voltage (voltage ratio) between the primary and secondary coils depends on the number of turns in each winding.

Transformers are widely used in electrical power and lighting circuits as well as many low-voltage electronic products. The large transformers in power generation stations step up the output voltage of AC generators to higher values for more efficient transmission over transmission lines while also reducing the current values. Somewhat smaller transformers at electrical substations step the transmitted voltage down to the values more useful for regional and local distribution to customers while also stepping up the current.

Some of the smallest commercial transformers are found in the AC-to-DC converters that convert line AC voltages to the low DC voltages required for powering electronic products including cordless telephones, notebook computers, and cellular telephone battery chargers. However, transformers are the largest and heaviest components in the stand-alone linear power supplies for industrial, military, and commercial applications. The 60-Hz transformers built into TV sets and stereo systems are also large and heavy, but the high-frequency switching transformers in desktop and laptop computers are considerably smaller and lighter.

Transformers can also isolate circuits, suppress harmonics, and regulate line voltage between distribution substations and consumers. Zigzag grounding transformers, for example, derive neutrals for grounding and a fourth wire from a three-phase neutral wire. They can be operated at voltages below their nameplate ratings, but they should not be operated at higher voltages unless they have taps intended for that purpose. However, when a transformer is operated below its nameplate rated voltage, its kVA output is reduced correspondingly.

Single-phase transformers rated 1 kVA and larger and three-phase transformers rated 15 kVA and larger can be reverse-connected without a loss of kVA rating. This is possible with high-power transformers because their turn ratios are the same as their voltage ratios. The turns ratio compensation on a low-voltage winding of a single-phase transformer rated below 1 kVA rules this out, because the low-voltage winding has a higher voltage than is indicated by the nameplate at no load. Although the transformer will not be harmed, its output voltage when reverse-connected will be lower than is stated on its nameplate.

TRANSFORMER CLASSIFICATION

Transformers are classified in many different ways: dry- or liquid-insulated, single-phase or polyphase, step-up or step-down, and single-winding or multiwinding. In addition, they are classified by application. For example, there are voltage or potential transformers (VTs) and current transformers (CTs) that are used step high voltage and current down to safe levels for the measurement of voltage, current, and power with conventional instruments. The transformers discussed in this chapter are

- Autotransformers
- Auto zigzag grounding transformers
- Buck-boost autotransformers
- Current transformers
- Distribution transformers
- Substation transformers
- Voltage transformers

In addition to the many different kinds of transformers, there are many different ways to connect them. These include delta-to-delta, delta-to-wye, wye-to-delta, and T.

NEC TRANSFORMER REQUIREMENTS

NEC 2002 Article 450, *Transformers and Transformer Vaults (Including Secondary Ties),* states the requirements for the installation of transformers. It covers overcurrent protection for transformers rated for more or less than 600 V, autotransformers rated for 600 V or less, grounding autotransformers, secondary tiers, parallel operation, guarding ventilation, and grounding. Specific provisions apply to different types of transformers such as dry-type and liquid-insulated for both indoor and outdoor installation. Transformer vault location, construction, ventilation, and drainage requirements are also given.

The NEC has defined a *secondary tie* as a circuit operating at 600 V or less between phases that connect two power sources of power supply points, such as the secondaries of two transformers.

SUBSTATION TRANSFORMERS

Power is transmitted at high voltages because less current is required to transmit a given amount of energy at a higher than a lower voltage. Consequently, electrical energy can be transmitted with less I^2R or line loss when high transmission voltages are used. Transmission voltages as high as 500 kV can only be obtained from step-up transformers at power stations, because AC generators cannot generate voltages at those values.

Step-down transformers in distribution systems reduce the high transmission voltages to the values needed by industrial, commercial, and residential consumers. Large power transformers rated at 35 kV or more can reach efficiencies of 99 percent at full load.

Figure 3-1 shows a primary or secondary open substation transformer that can transform transmission voltages to useful levels. Both three-phase and single-phase substation transformers can be constructed in this configuration. They are made from a wide range of steel cores and winding conductors to meet specific substation requirements.

The transformers can be either wound-core or shell-type (these are discussed later). Their core and coil assemblies are placed in steel tanks that are filled with either electrical-grade mineral insulating oil or another suitable dielectric coolant. These transformers can be self-cooled or forced-air-cooled. In addition, they can be built specifically for indoor or outdoor installation.

Transformer Characteristics

Figure 3-2 is a diagram of a conventional (core-type) single-phase transformer. It shows two independent coils or windings, the primary and secondary, wound on a closed-ring core made from a stack of laminated sheet steel.

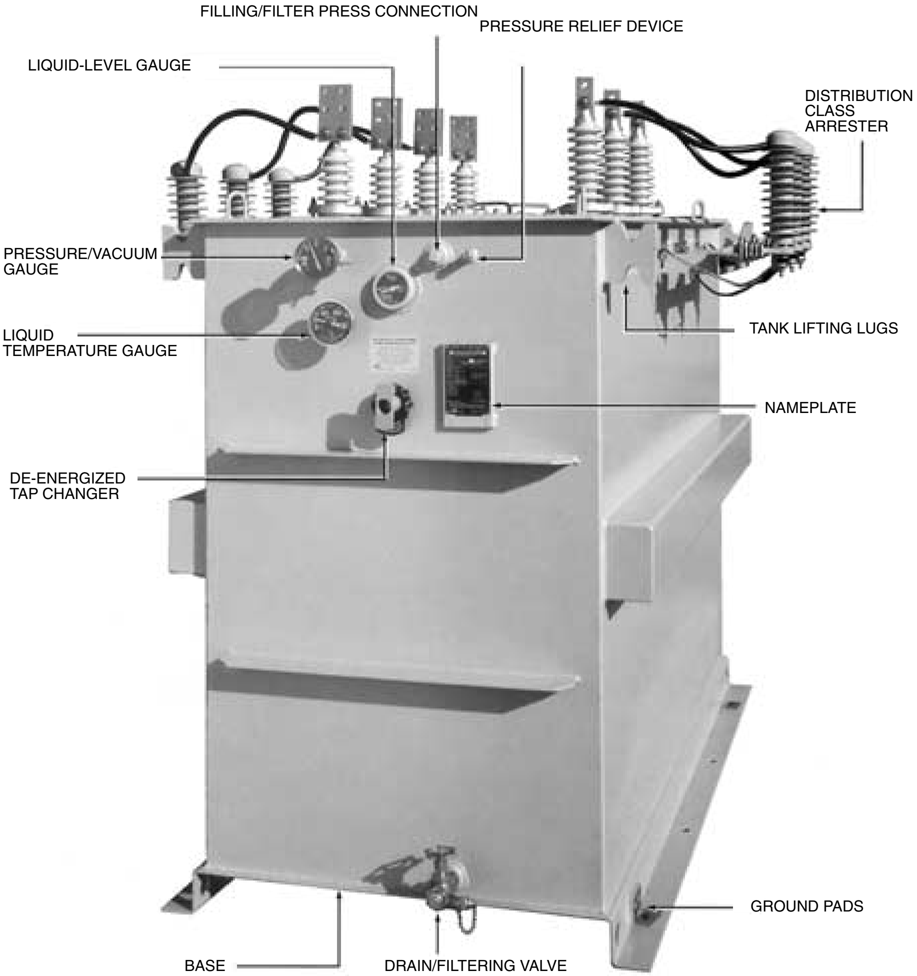


Figure 3-1 **Secondary open substation transformer.** *Courtesy Cooper Power Systems*

If an AC voltage is applied to the primary winding of the transformer, an electromagnetic field or flux forms around the core and expands and contracts at the input frequency. This changing flux cuts the wires in the secondary winding and induces a voltage in it. Because the turns of both windings are cut by the same magnetic flux, the voltage induced in each turn of both windings is the same. Thus the voltages across the windings of a transformer are directly proportional to the turns in each winding:

$$\text{Primary ampere-turns} = \text{secondary ampere-turns}$$

From this expression, it can be determined that the ratio of the currents in a transformer is inversely proportional to the ratio of the turns. The voltage that appears

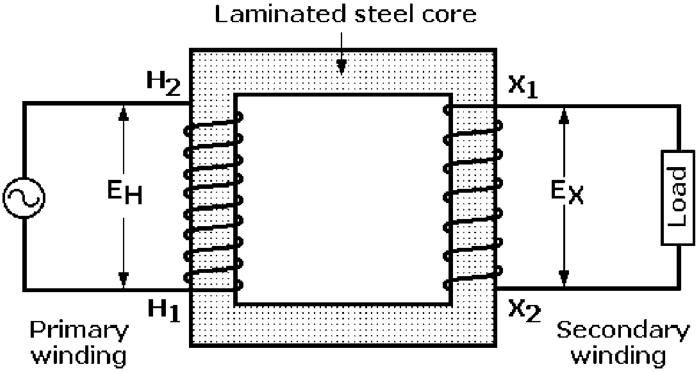


Figure 3-2 Schematic diagram of a basic transformer.

across the secondary winding depends on the voltage at the primary winding and the ratio of turns in the primary and secondary windings.

Transformers obey the *law of conservation of energy,* meaning that the product of voltage and current (power) in the primary winding equals the product of voltage and current (power) in the secondary winding, except for losses. For example, if the voltage at the secondary terminals is twice the voltage at the primary terminals, the current at the secondary terminals must be half that at the primary terminals to keep the product of voltage and current constant.

A *step-up transformer* has more turns in its secondary winding than in its primary winding, so the voltage across the secondary winding will be higher than the voltage across the primary winding. Similarly, a *step-down transformer,* as shown in Fig. 3-2, has fewer turns in its secondary winding than in its primary winding, so the secondary voltage will be lower than the primary voltage.

The letters identifying the input and output terminals in Fig. 3-2 follow the industry standard marking code. High-voltage winding terminals are marked H1, H2, etc., and low-voltage winding terminals are marked X1, X2, etc. Thus, the high-voltage winding is commonly called the *H winding,* the low-voltage winding is commonly called the *X winding,* and the numbers of turns of each winding are designated as Th and Tx.

POWER TRANSFORMER RATING

Power transformer capacity is rated in *kilovolt-amperes* (kVA). The output rating for a transformer is determined by the maximum current that the transformer can withstand without exceeding its stated temperature limits. Power in an AC circuit depends on the power factor of the load and the current, so if any AC electrical equipment is rated in kilowatts, a power factor must be included to make its power rating meaningful. To avoid this, transformers and most AC machines are rated in kVA, a unit that is independent of power factor.

In addition to its kVA rating, the nameplates of transformers typically include the manufacturer's type and serial number, the voltage ratings of both high- and low-voltage windings, the rated frequency, and the impedance drop expressed as a percentage of rated voltage. Some nameplates also include an electrical connection diagram.

Power transformers are generally defined as those used to transform higher power levels than distribution transformers (usually over 500 kVA or more than 67 kV). The kVA terminal voltages and currents of power transformers, defined in ANSI C57.12.80, are all based on the rated winding voltages at no-load conditions. However, the actual primary voltage in service must be higher than the rated value by the amount of *regulation* if the transformer is to deliver the rated voltage to the load on the secondary.

TRANSFORMER CONSTRUCTION

The two most common types of transformer construction are the core or form type and the shell type. The *core-type transformer* shown in Fig. 3-2 has an open rectangular laminated steel core with the primary winding wound on the left "leg" of the core and the secondary winding wound on the right "leg."

A transformer could be wound as shown in Fig. 3-2, but the separation distance between the primary and secondary windings would mean that much of the primary winding flux would not cut the secondary winding, resulting in transformer loss called *leakage flux.* To minimize leakage flux in commercial core-type transformers, the windings are divided, with half of each winding being placed on each leg of the core. The low-voltage winding is wound around the core and the high-voltage winding is wound over the low-voltage winding.

In the alternate *shell-type transformer* shown in Fig. 3-3, both the primary and secondary coils are wound on the central "leg" of the core. In shell-type transformers the magnetic circuit is short and the length of the windings is long. Typically the shell-type transformer has a larger core area and a smaller number of winding turns than a core-type transformer with the same output and performance. Also, the shell type typically has a greater ratio by weight of steel to copper. The laminated steel cores are made from stacks of E- and I-shaped stampings assembled around toroidal bobbins.

Stacked power transformers cores are made from a wide range of core steels to minimize core loss. High-voltage primaries are wound with wire, typically either aluminum or insulated copper magnet wire, and secondary windings are wound from sheet metal strips, typically aluminum. Windings are typically insulated

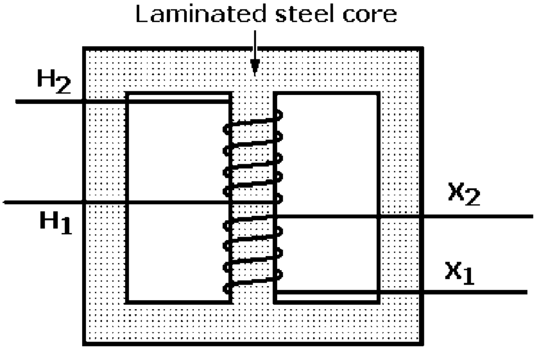


Figure 3-3 Shell-type transformer core construction.

between layers with adhesive-coated, thermally upgraded paper. The cores are made of single-turn laminations cut and formed so that each lamination completes a magnetic circuit. The laminations are assembled through and around the coil in a staggered joint pattern to keep core loss and exciting current to a minimum.

Most single- and three-phase power transformers are custom-made by transformer manufacturers to meet customer requirements. These can usually be met with either core- or shell-type construction. The purchase decision is usually based on the manufacturer's recommendations for the end-use application, cost, and the firm's manufacturing facilities. Customers can, however, state preferences based on field experience or other technical considerations. Both core- and shell-type transformers can be made with ratings up to about 300 kVA, but there could be a significant difference in price. They can be dry or oil-immersion units, for which additional insulation and cooling are required.

The *wound-core transformer* is yet another type of construction. It has a core that is formed by winding a strip of silicon steel into a tight spiral around the insulated windings. However, its maximum kVA ratings are lower than can be obtained from the other two types of construction.

TRANSFORMER LOSSES AND EFFICIENCY

The efficiency of all power transformers is high, but efficiency is highest for large transformers operating at 50 to 100 percent of full load. However, some losses are present in all transformers. They are classified as *copper* or *I^2R losses* and *core losses.*

Copper losses, also called *load losses,* are proportional to the load being supplied by the transformer. These losses can be calculated for a given load if the resistances of both windings are known. As in generators and motors, the core loss is due to *eddy-current induction loss* and *hysteresis* (molecular friction) *loss,* caused by the changing polarity of the applied AC. If the cores are laminated from low-loss silicon steel, both eddy-current and hysteresis losses will be reduced. Nevertheless, well-designed transformers in all frequency and power ranges typically have efficiencies of 90 percent or more.

TRANSFORMER COOLING

When a large transformer is operating under load, heat is generated in both the windings and the core, due to copper and core losses. The methods used for cooling transformers depend on their size, rating, application, and location. Power transmission and distribution transformers can be cooled by forced air, circulating water, electrical-grade mineral oil, or other suitable dielectric coolants.

The cooling liquid provides additional insulation between the windings, and it conducts heat from the windings to the conductive sidewalls and surface of the tank, where it can be dissipated in the surrounding air. The liquid circulates through the tank by natural convection because of temperature differences in the liquid. Some liquid-cooled transformer tanks are made with cooling fins so that the coolant has contact with a larger radiating surface. Where conditions require it, the oil can be circulated by pumps or the oil cooling can be supplemented by water cooling, forced air, or both.

Air-cooled dry transformers are specified where oil-cooled transformers located indoors in industrial facilities would present a fire hazard. The windings are wound so that the natural circulation of air will dissipate the heat from the windings and core. These transformers can be enclosed in perforated metal cases to allow maximum circulation of the air through the windings. Where conditions require it, natural transformer cooling can be supplemented by forced-air circulation.

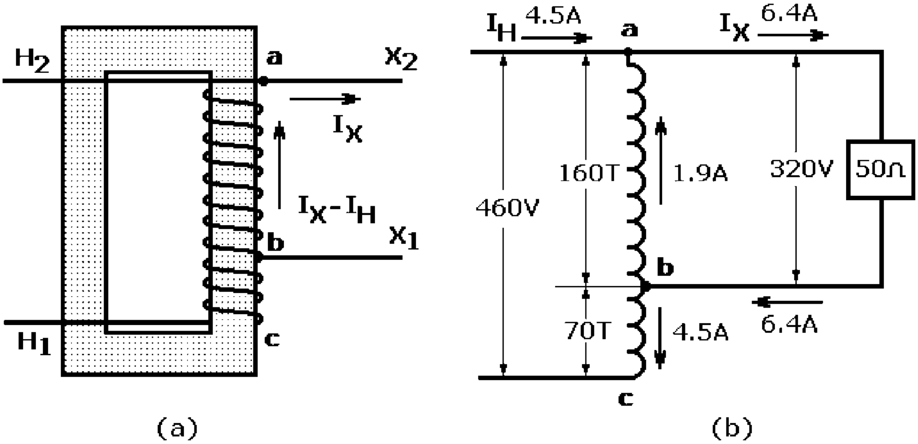
AUTOTRANSFORMERS

An *autotransformer* is a special transformer consisting of a single continuous winding that is used for both input and output voltages. Because the primary and secondary windings are the same, they are connected electrically as well as magnetically. Autotransformers have features that can make them superior to two-winding transformers for many applications because of their lower cost, greater efficiency, smaller size and weight, and better regulation.

Figure 3-4*a* is a schematic for a step-down autotransformer. The entire winding *ac* forms the primary winding, and section *ab* forms the secondary winding. It can be seen that section *ab* is common to both the primary and secondary windings. As in the standard two-winding transformer, the ratio of voltage transformation is equal to the ratio of primary to secondary turns, if the losses are neglected. The following relationships apply:

$$\frac{\mathrm{Eh}}{\mathrm{Ex}} = \frac{\mathrm{Th}}{\mathrm{Tx}} = \frac{\mathrm{Ix}}{\mathrm{Ih}}$$

The autotransformer winding shown in Fig. 3-4*b* has a total of 230 turns with sections *ab* and *bc,* which have 160 and 70 turns, respectively. If a voltage of 460 V is applied



(a) (b)

Figure 3-4 **Autotransformers: (*a*) schematic of a step-down autotransformer; (*b*) wiring diagram of an autotransformer supplying a load.**

to the winding *ac,* the voltage across each turn will be 2.0 V, and the voltage from *a* to *b* will then be 160 × 2.0 or 320 V.

If a noninductive load of 50 Ω is connected to winding *ab,* a current Ix of 320/50, or 6.4 A, flows, and the power output of the transformer is 320 × 6.4, or 2048 W. Neglecting the transformer losses, the power input must be 2048 W and the primary current must be 2048/460, or 4.5 A.

Thus the section of the winding that is common to both the primary and secondary circuits carries only the difference between the primary and secondary currents. For this reason, an autotransformer uses less copper wire in its windings and is more efficient than a comparably rated conventional two-winding transformer.

If a multivoltage supply is required for an application, an autotransformer with multiple taps can provide the required output voltages. The connections from the various taps are brought out to terminals or a switching matrix so that any of a number of voltages can be selected.

Autotransformers are most effective for voltage transformations near unity. For example, an autotransformer can *boost* a distribution voltage by a small increment to compensate for line drop. Autotransformers can also start AC motors because they permit a reduced voltage to be applied to the motor during the start-up period.

Autotransformers are not recommended for supplying a low voltage from a high-voltage supply, because if the winding common to both primary and secondary should open accidentally, the full primary voltage will appear across the secondary terminals. This could damage connected equipment or circuitry and pose a shock hazard for personnel.

TAP CHANGING

High-voltage windings of substation and distribution transformers are equipped with tap-changing devices to compensate for drops in line voltage and to make small adjustments in the transformer ratio. The winding is tapped in several places, and connections are made from these places to a tap-changing switch or a terminal block inside the transformer tank. By operating the switch or changing the connections to the terminal block, changes can be made in the number of active turns in the winding.

Taps are typically either two 2.5 percent above and below or four 2.5 percent below rated voltage. These changes are usually made with the transformer offline, but some transformers have external tap-changer switches that can be operated outside the tank for safe operation under load.

SINGLE-PHASE DISTRIBUTION TRANSFORMERS

Single-phase distribution transformers are usually made with the secondary or low-voltage windings in two sections, as shown in Fig. 3-5. The two sections can be connected in series as shown in Fig. 3-5*a* to supply a three-wire, 120/240-V load. This connection is widely used by power companies to provide both 120 and 240 V to residential and commercial customers. Alternatively, the two sections can be connected in parallel as shown in Fig. 3-5*b* to supply a two-wire 120-V load. Power companies use this connection where the load is comparatively small and the secondary circuit length is short. Examples are providing 120-V power for rural pump houses and roadside stands.

There are three general types of distribution transformers: *pole-type* or *overhead, pad-mounted,* and *submersible.* They are typically built to customer order and must comply with the latest industry standards.

Overhead single-phase distribution transformers Figure 3-6 is an electrical schematic for a single-phase distribution transformer that steps down a single-phase primary voltage (7.62 kV) to the more manageable 120/240 V AC. Single-phase overhead-type transformers are manufactured as conventional, protected, step-down, and high basic impulse level (BIL), and as autotransformers. A cutaway view of a single-phase overhead or pole-mounted distribution transformer is shown in Fig. 3-7. These transformers are made with a wide variety of ratings and meet or exceed the requirements of applicable ANSI and NEMA standards. Some are designed to meet the Rural Utilities Service (RUS) standards.

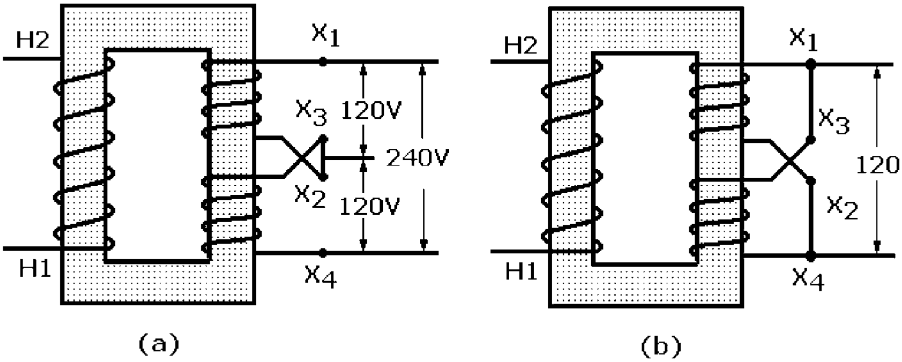


Figure 3-5 Single-phase transformers: (*a*) connected in series to supply a three-wire, 120/240-V AC system; (*b*) connected in parallel to supply a two-wire, 120-V AC system.

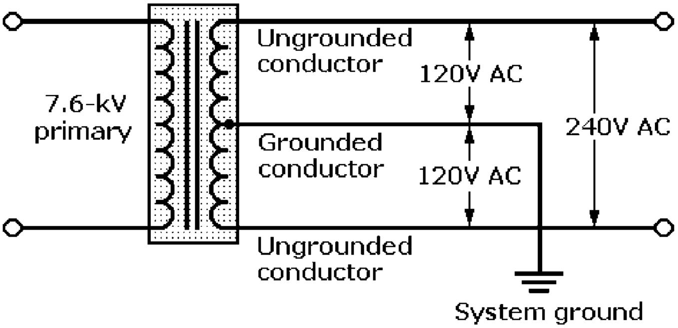


Figure 3-6 Schematic of a single-phase transformer for stepping down high distribution voltage to 120/240 V AC for electric service.

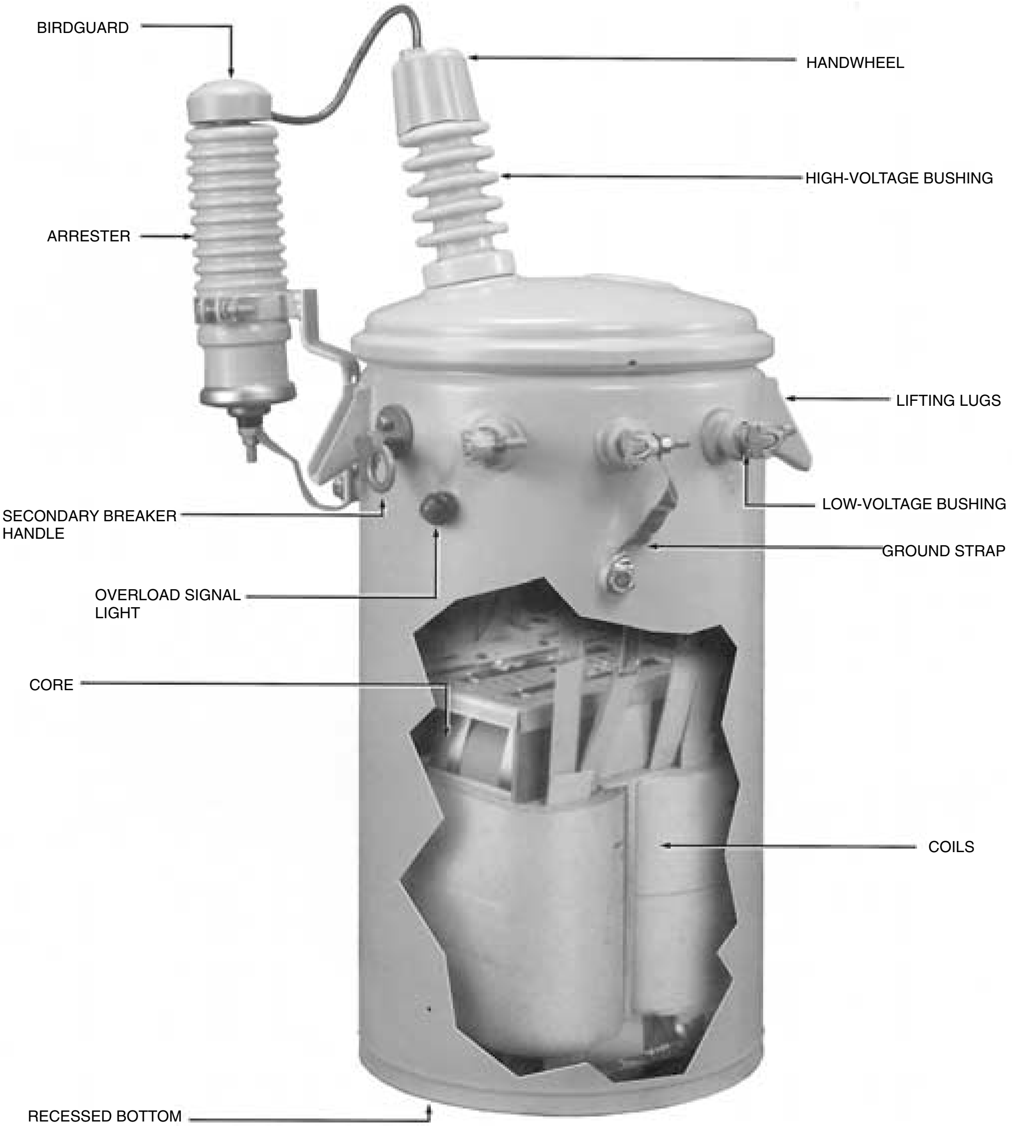


Figure 3-7 **Single-phase overhead distribution transformer.** *Courtesy Cooper Power Systems*

Conventional overhead transformers are manufactured in ratings of 5 to 500 kVA. Completely self-protected (CSP) overhead transformers are manufactured in ratings of 5 to 167 kVA. CSP transformers have direct-connected primary arresters, internal secondary breakers, and internal primary fuses. This eliminates the need for separately mounted protective devices, which otherwise must be installed at extra cost.

Single-phase step-down and autotransformers reduce single-phase distribution voltages to new distribution voltages. Step-down transformers are manufactured with ratings of 25 to 500 kVA with dual primary or secondary voltages through 250 kV BIL.

Autotransformers are manufactured in ratings of 167 to 5000 kVA depending on the ratio between the primary and secondary voltages. They are available in a variety of tap arrangements. Single-phase overhead high BIL transformers are manufactured with ratings of 5 to 500 kV and they have high BIL ratings from 200 to 250 kV.

The connections for single-phase pole-mounted or overhead distribution transformers are made inside their mineral oil-filled cylindrical cases. Only three secondary terminals are brought to the outside of the transformer case.

Pad-mounted single-phase distribution transformers Single-phase pad-mounted distribution transformers are used in underground distribution systems where it is preferable to have underground rather than overhead distribution. An example of a single-phase, pad-mounted distribution transformer with its cover raised is shown in Fig. 3-8. The electrical schematic for these transformers is the same as that for the overhead transformer in Fig. 3-6.

Single-phase, pad-mounted transformers are manufactured with ratings from 10 to 167 kVA. All of these distribution transformers are oil-insulated, self-cooled, and made with loop or radial feed. They can meet or exceed ANSI and NEMA standards.

Pad-mounted distribution transformers are enclosed in steel tamper-resistant protective cases designed with low profiles. They are usually painted green to blend in

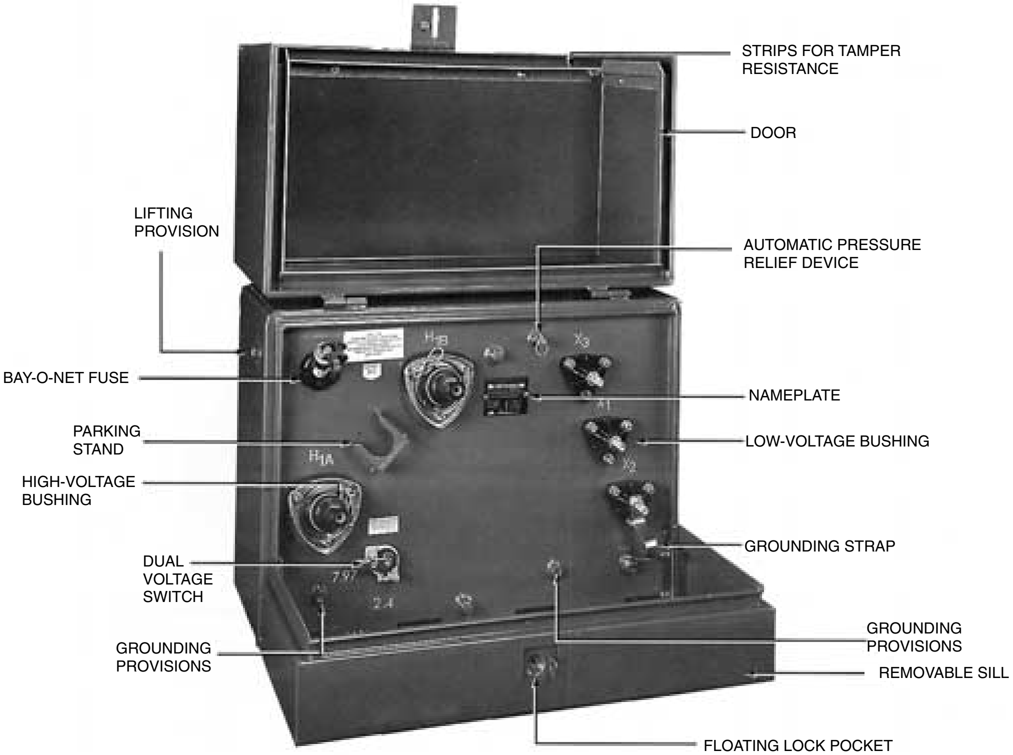


Figure 3-8 **Single-phase pad-mounted distribution transformer.** *Courtesy Cooper Power Systems*

with the shrubs and low hedges of residential landscaping. Smaller RUS-approved versions with ratings of 10 to 50 kVA for rural electrification power irrigation pumps and oil field equipment, and are also installed in sparsely populated residential areas.

Submersible single-phase distribution transformers Single-phase submersible underground transformers are enclosed in round vertical stainless steel tanks that are hermetically sealed for protection against repeated flooding and/or immersion. The terminals, ground pads, and nameplates are mounted on the covers for easy access from ground level. These transformers are made in ratings of 25 to 167 kVA. Their electrical schematics are the same as in Fig. 3-6.

Where submersible transformers are to be installed in a trench that is not subject to repeated flooding or immersion, they are enclosed in stainless steel tanks. Their terminals, ground pads, and nameplates are mounted on their covers.

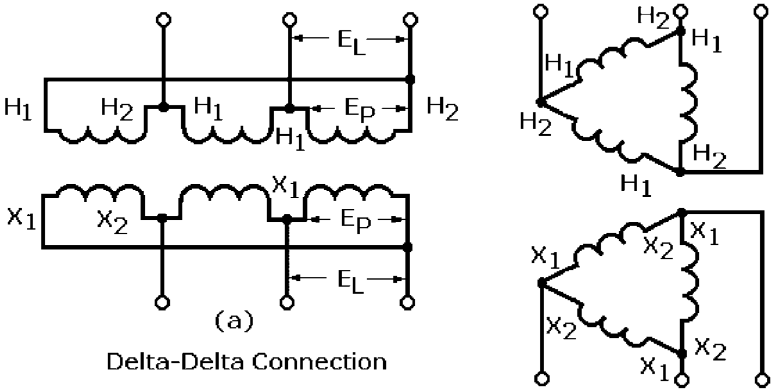
THREE-PHASE CONNECTIONS OF SINGLE-PHASE TRANSFORMERS

Single-phase transformers can be connected to form three-phase transformer banks for stepping voltages up or down in three-phase systems. Four common configurations for connecting transformers in three-phase systems are delta–delta, wye–wye, wye–delta, and delta–wye. The first three are shown in Fig. 3-9. The delta–wye is not shown because it is simply the reverse of the wye–delta connection.

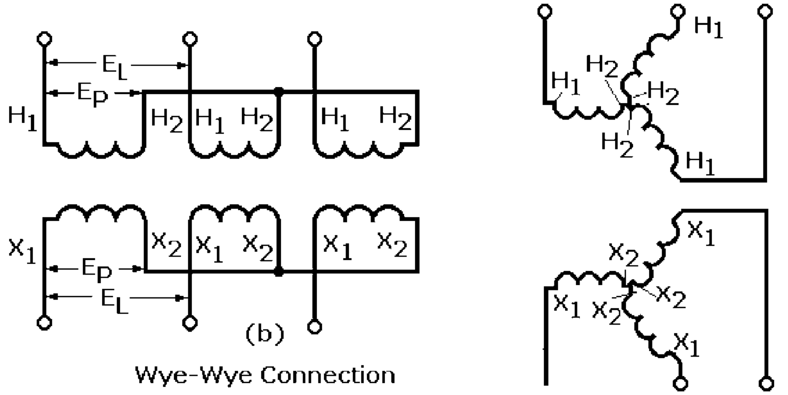
Delta–delta connection The delta–delta connection, shown in Fig. 3-9*a,* is widely used for moderate voltages. This connection has the advantage of remaining operational in what is known as the *open delta* or *V connection* if one transformer is damaged or taken out of service, leaving the remaining two functional. If it is operated this way, the bank still delivers three-phase currents and voltages in their correct phase relationships. However, the capacity of the bank is reduced to 57.7 percent of the value obtained with all three transformers in service.

Wye–wye connection In the wye–wye connection, shown in Fig. 3-9*b,* only 57.7 percent (or 1/1.73) of the line voltage is applied to each winding, but full line current flows in each transformer winding. The drawback to this connection is that power circuits supplied from a wye–wye bank generate serious electromagnetic interference, which could interrupt nearby communications circuits. Because of this and other disadvantages, the wye–wye connection is seldom used. However, the wye–wye connection can be used to interconnect two delta systems and provide suitable neutrals for grounding both of them.

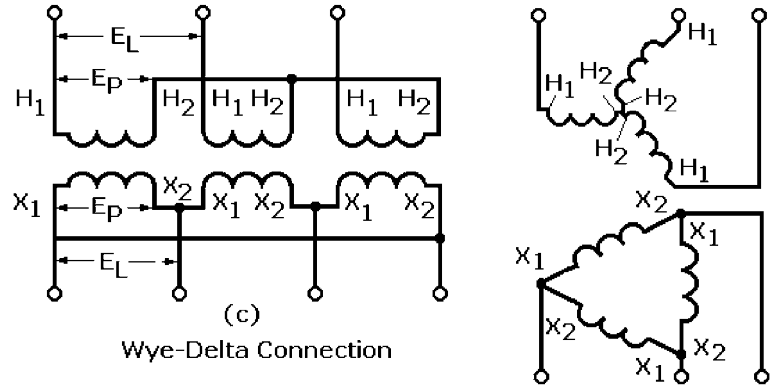
Delta–wye and wye–delta connections The delta–wye connection (not shown) is suitable for stepping up voltages because the voltage is increased by the transformer ratio multiplied by a factor of 1.73. Similarly, the wye–delta connection, shown in Fig. 3-9*c,* is used for stepping down voltages. The high-voltage windings of most transformers operating at more than 100 kV are wye-connected.



(a)
Delta-Delta Connection



(b)
Wye-Wye Connection



(c)
Wye-Delta Connection

Figure 3-9 Three-phase transformer connections.

To match the polarities correctly in a wye connection, the H and X markings must be connected symmetrically. In other words, if an H1 or X1 terminal is connected to the neutral, then all of the H1 or X1 terminals must be connected to the neutral and the remaining H2 or X2 terminals must be brought out as the line connections, as shown in Fig. 3-9*b*. By contrast, in a delta connection, H1 must always be connected to H2 and X1 to X2, and the line connections must be made at these junctions, as shown in Fig. 3-9*a*.

When a large number of single-phase loads are to be served from a three-phase transformer bank, the wye-connected low-voltage winding is recommended because the single-phase loads can be balanced evenly on all phases.

FOUR-WIRE DELTA SYSTEM

Power circuits for the operation of three-phase motors or other equipment are often supplied from 240-V delta-connected transformer secondaries, as shown in Figs 3-9*a* and 3-9*c*. To provide 120 V for lighting circuits, the midpoint of one of the transformers is brought out to form a *four-wire delta system.* This connection is shown in Fig. 3-10*a*; a three-wire, single-phase lighting circuit is formed by conductors A and B to N (neutral) with 120 V available across A to N and B to N. In this system a three-wire, three-phase power circuit is formed by conductors A, B, and C, with 240 V available across any two of the phase conductors A, B, or C.

To support this load adequately, the center-tapped transformer must have a larger kVA rating than the transformers on each side of it. The shortcoming of this system is that the phases will be unbalanced because the single-phase lighting load diminishes the available three-phase capacity.

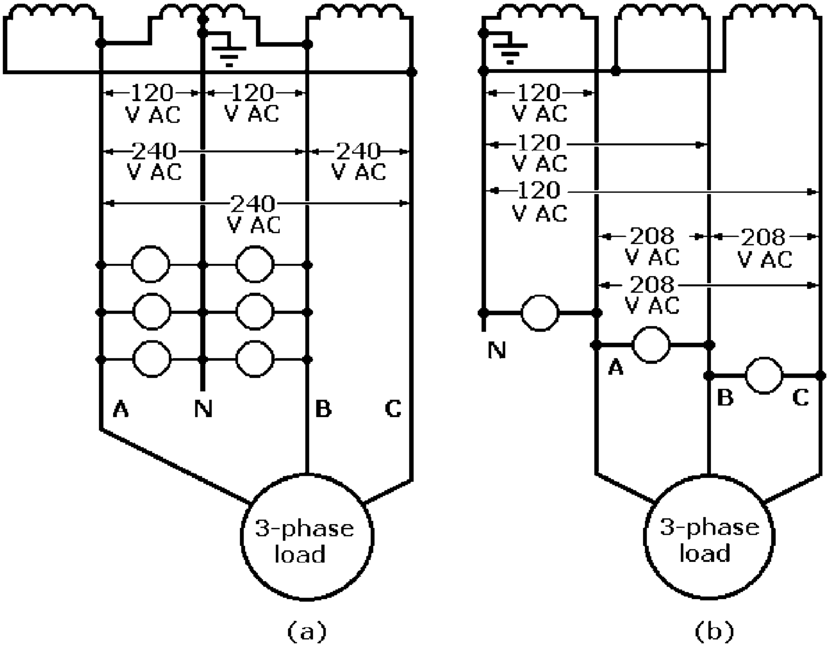


Figure 3-10 Three-phase transformer secondaries: (*a*) four-wire delta-connected; (*b*) four-wire wye-connected.

FOUR-WIRE WYE SYSTEM

When it is necessary to power many single-phase loads from a three-phase transformer bank, the *four-wire wye system* is preferred. The wye-connected, low-voltage winding permits single-phase loads to be balanced evenly on all three phases. Figure 3-10*b* shows the method for connecting both three-phase and single-phase loads to a four-wire wye-connected bank. The single-phase 120-V loads are connected between the three conductors A, B, and C to N, the neutral or grounded wire. In this system, the three-phase 208-V loads are connected across the phase conductors A, B, and C. This connection, with phase and line voltages of 120 and 208 V, is used in urban underground networks.

SCOTT OR T TRANSFORMER CONNECTION

The Scott or T connection is a method of transforming three-phase loads to two-phase loads, or vice versa, with two transformers, the *main transformer* and the *teaser transformer*. The connection was originally developed to transform two-phase power from a hydroelectric plant to three-phase power.

In the T connection shown in Fig. 3-11, the main transformer primary winding AB is connected from line to line of a three-phase delta input system, and the teaser transformer primary winding CD is connected from the midpoint of the main primary winding C to the third line of the three-phase system. The secondary windings of both main and teaser transformers, *a, b,* and *c,* are connected to a two-phase, three-wire output system.

The teaser transformer can be a duplicate of the main transformer so as to be interchangeable with it. The main transformer operates at a power factor of 0.866 so that if the two transformers are to be identical, the teaser transformer must be provided with an 86.6 percent tap. In this example their total rated capacity will be 15.5

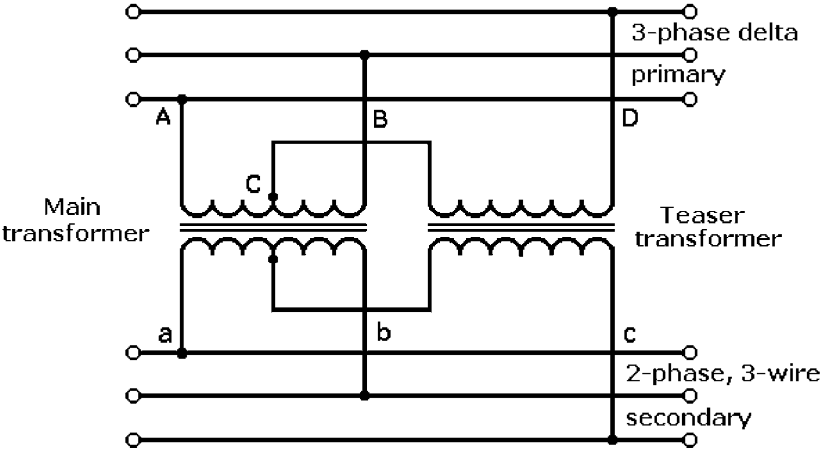


Figure 3-11 T-connected transformers.

percent greater than the capacity of the load in kVA. When connecting transformers in T, the relative phase sequence of the windings must be the same or the impedance of the main transformer could be excessively high and cause an unbalance.

THREE-PHASE TRANSFORMERS

Three-phase voltages can be transformed by three-phase transformers as well as banks of single-phase transformers. A primary and secondary winding of one phase is placed on each leg. Three-phase transformer cores can be made with only three legs because the fluxes set up by the three windings are 120° apart in time phase, as shown in Fig. 2-2.

The core of a three-phase transformer is made with three legs similar to the one shown in Fig. 3-3. Two core legs act as the return for the flux in the third leg. At any time the flux is at a maximum value in one leg, it is half that value and in the opposite direction through the other two legs. A core and coil assembly of a three-phase transformer is shown in Fig. 3-12. This transformer is rated 37.5 kVA, 60 Hz, 2400/4160Y to 240/416Y V.

The prime advantage that a three-phase transformer has over three single-phase transformers with the same kVA rating is that space and weight are saved by placing

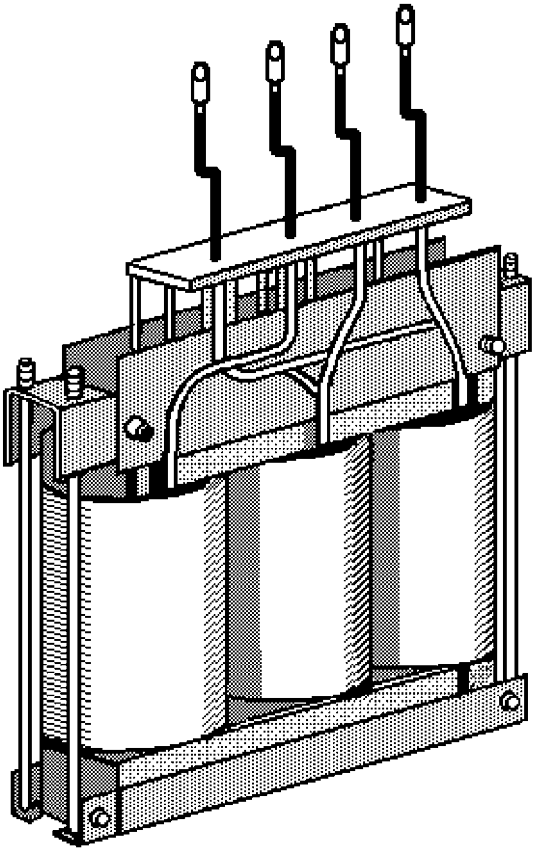


Figure 3-12 Three-phase core and coil distribution transformer rated for 37.5 kVA, 60 Hz, 2400/4160Y to 240/416Y V.

three windings on one core. Another advantage of the three-phase transformer is that it is slightly more efficient than a single-phase transformer, and in the larger ratings it is less expensive.

A disadvantage of the three-phase transformer is that if one of its phases fails, the whole transformer is disabled and must be removed from service. By contrast, if one of three single-phase transformers in a bank fails, that one unit can be replaced, leaving the other two in service.

Three-phase transformers can also be connected according to the four connection schemes previously discussed for single-phase transformers and illustrated in Fig. 3-9. These connections are made inside the tank. To make delta–delta connections, only three high-voltage and three low-voltage conductors need to be brought outside the tank. For wye-connected windings, however, four connections are brought outside the tank.

THREE-PHASE DISTRIBUTION TRANSFORMERS

A three-phase overhead distribution transformer is shown in Fig. 3-13. Where pole-mounted overhead distribution is used to supply three-phase power, three-phase transformers occupy less space than a bank of transformers, and they weigh less. Moreover, the cost of installation and maintenance is lower for a three-phase overhead transformer than for a bank of three single-phase units.

Three-phase overhead transformers are made with ratings from 30 to 300 kVA. Primary voltages range from 4.16 to 34.5 kV, and secondary voltages range from 120 to 480 V. The basic impulse level (BIL) ratings are 45 to 150 kV. They are available with wye, delta, or T–T connections. These transformers have four output connections, X0, X1, X2, and X3, and their cases are filled with electrical-grade mineral oil.

A three-phase, pad-mounted compartmental-type distribution transformer is shown in Fig. 3-14. These transformers are manufactured in ratings from 45 to 7500 kVA with high-voltage ratings from 2.4 to 46 kV. The standard connections are delta–wye, grounded wye–wye, delta–delta, wye–wye, and wye–delta. The transformers are housed in steel cabinets with front-opening, three-point latching steel doors. As in the overhead transformers, the cases of pad-mounted transformers are filled with electrical-grade mineral oil.

TRANSFORMERS CONNECTED IN PARALLEL

For the successful operation of two single-phase transformers connected in parallel, the instantaneous polarities of the transformers must be known. Two transformers with their primaries connected to the same power supply are shown in Fig. 3-15. The primary windings of both transformers no. 1 and no. 2 are wound counterclockwise around the core. However, the secondary winding of transformer no. 1 is wound counterclockwise, while the secondary winding of transformer no. 2 is wound clockwise. At the instant line A is positive, the direction of current flow will be from line A to line B through both primary windings.

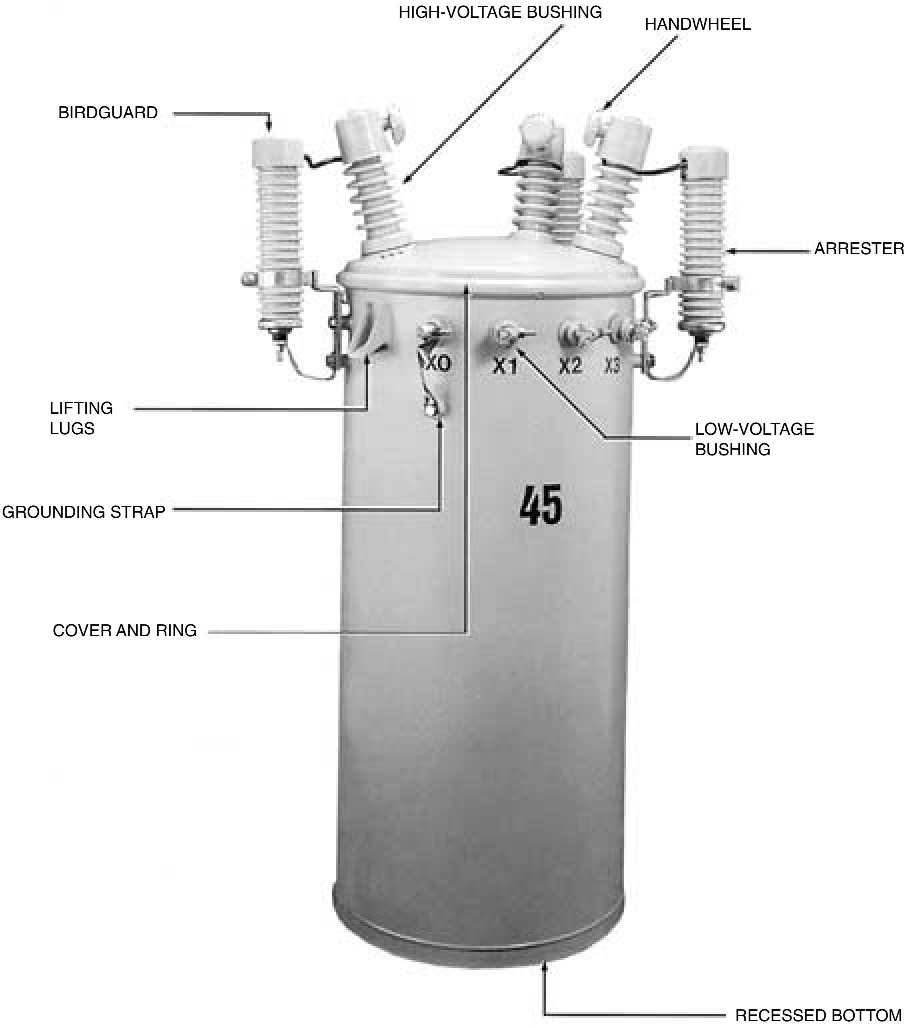


Figure 3-13 **Three-phase overhead distribution transformer.** *Courtesy Cooper Power Systems*

When primary current flows from H1 to H2, voltages are induced in the secondary windings, which oppose the applied primary voltages. Because the secondaries are wound in opposite directions, terminal X2 of transformer no. 1 is negative at any instant, while terminal X1 of transformer no. 2 is positive.

If the secondary windings are to be connected in parallel, both positive terminals must be connected to one line, such as C, and both negative terminals must be connected to the other line, such as D. The instantaneous voltages induced in the two secondary windings will then be in phase. Caution: *If terminals of unlike polarity are connected to the same line, the two secondaries will be short-circuited, resulting in excessive current flow.*

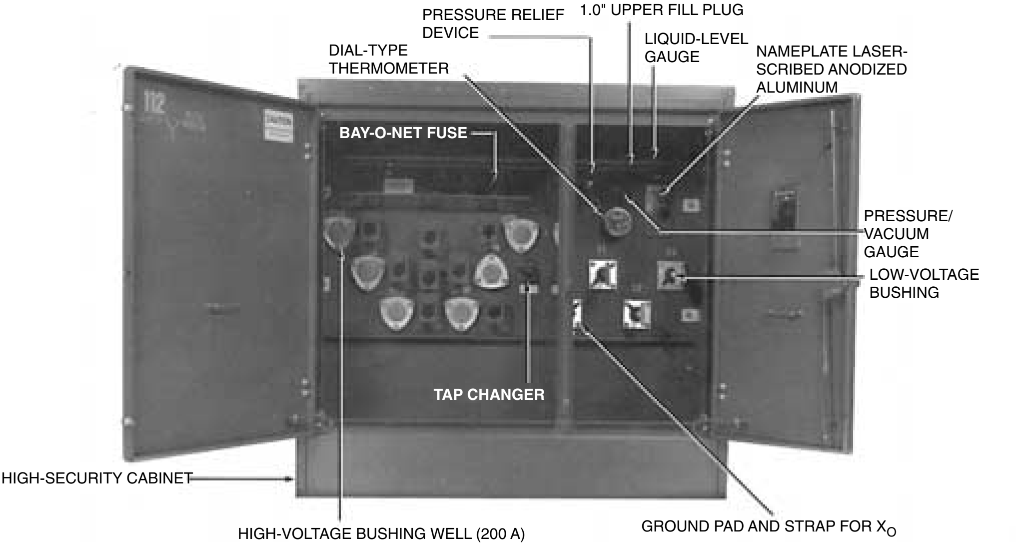


Figure 3-14 **Three-phase pad-mounted compartmental-type transformer.** *Courtesy Cooper Power Systems*

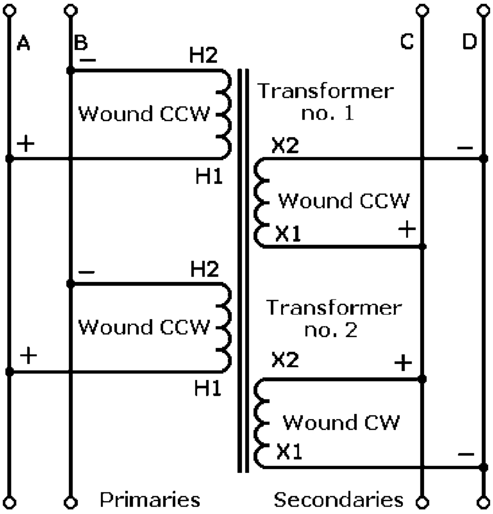


Figure 3-15 **Two transformers connected for parallel operation.**

Two three-phase transformers can also be connected in parallel if they are wound the same way, are connected with the same polarity, and have the same phase relationships. Furthermore, if the two transformers have the same voltage ratings, the same turns ratios, the same impedances, and the same ratios of reactance to resistance, load current will be divided in proportion to the transformers' kVA ratings, and there will be no phase differences between their currents. However, if there are differences in any of these characteristics, load current can be divided unequally and phase differences can occur between the currents in the transformers.

AUTO ZIGZAG GROUNDING TRANSFORMERS

Three single-phase transformers can be connected in an autotransformer arrangement to obtain a neutral from a three-phase, three-wire supply (phase shifting). Figure 3-16*a* is the schematic diagram for this arrangement, and Fig. 3-16*b* is the wiring diagram.

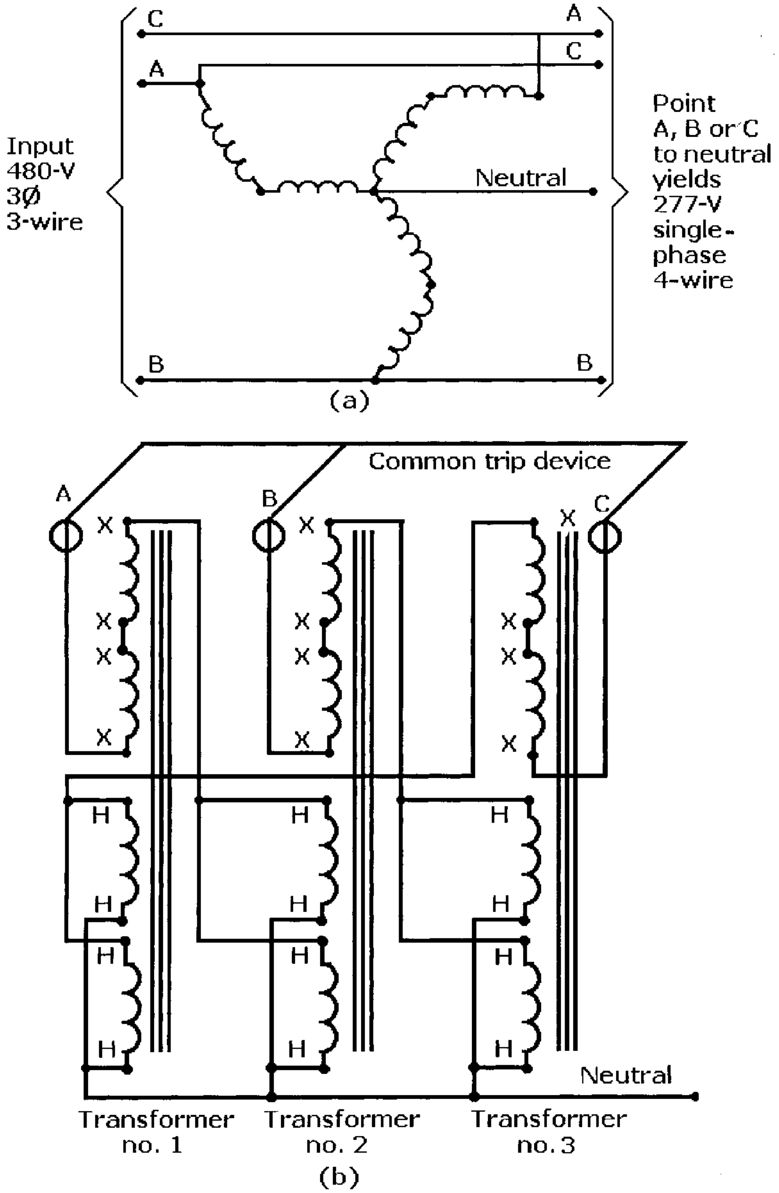


Figure 3-16 **Auto zigzag grounding transformer: (*a*) for deriving a neutral; (*b*) wiring diagram.**

Section 4 of NEC 2002, Article 450, covers autotransformers, and Section 5 covers grounding autotransformers, specifically zigzag or T-connected transformers connected to three-phase, three-wire ungrounded systems. These connections are made for creating three-phase, four-wire distribution systems or providing a neutral reference for grounding purposes.

BUCK-BOOST AUTOTRANSFORMERS

The buck-boost transformer is a simple and economical means for raising a voltage that is too low or decreasing a voltage that is too high. This transformer can raise or lower voltage being supplied to the load more than ±5 percent, to improve the efficiency of the device or system. Buck-boost transformers are small single-phase transformers designed to reduce (buck) or raise (boost) line voltage from 5 to 20 percent. A common application is boosting 208 V to 230 or 240 V AC. For example, there might be a requirement to power the motor in an air conditioner with a 230- or 240-V AC motor from the 208-V AC supply line. This can be done with a buck-boost transformer.

Buck-boost transformers are standard distribution transformers with ratings ranging from 50 VA to 10 kVA. Commercial units are made with primary voltages of 120, 240, or 480 V AC. They can also power low-voltage circuits for control or lighting applications requiring 12, 16, 24, 32, or 48 V AC. Schematics of buck-boost transformers that can transform 120 and 240 V AC to 12 and 24 V AC are shown in Fig. 3-17.

When the primary and secondary lead wires of buck-boost transformers are connected together electrically in a recommended bucking or boosting connection, they

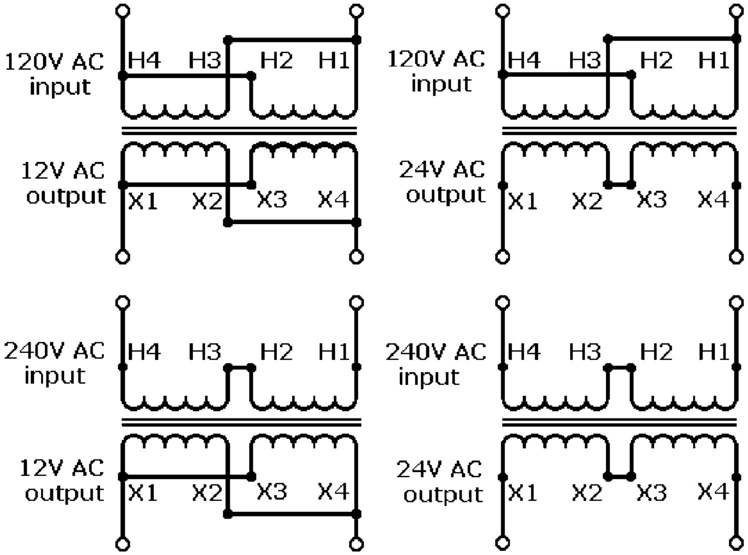


Figure 3-17 Wiring diagrams for low-voltage, single-phase, buck-boost transformers.

become autotransformers. Some typical connection diagrams for these transformers in autotransformer arrangements for single-phase systems are shown in Fig. 3-18.

Buck-boost transformers have four windings for versatility. Their two primary and two secondary windings can be connected eight different ways to provide many different voltage and kVA outputs. Because their output voltage is a function of input voltage, they cannot be used as voltage stabilizers. Output voltage will vary by the same percentage as the input voltage. These transformers can also function in three-phase systems. Two or three units can be used to buck or boost three-phase voltage. The number of units needed in a three-phase installation depends on the number of wires in the supply line.

INSTRUMENT TRANSFORMERS

Instrument transformers are used in power stations and substations to reduce high voltages and currents to safe and usable values for making electrical measurements with voltmeters, ammeters, and wattmeters, or to operate control apparatus. These transformers perform two functions: they act as ratio devices, making it possible to use standard low-voltage and

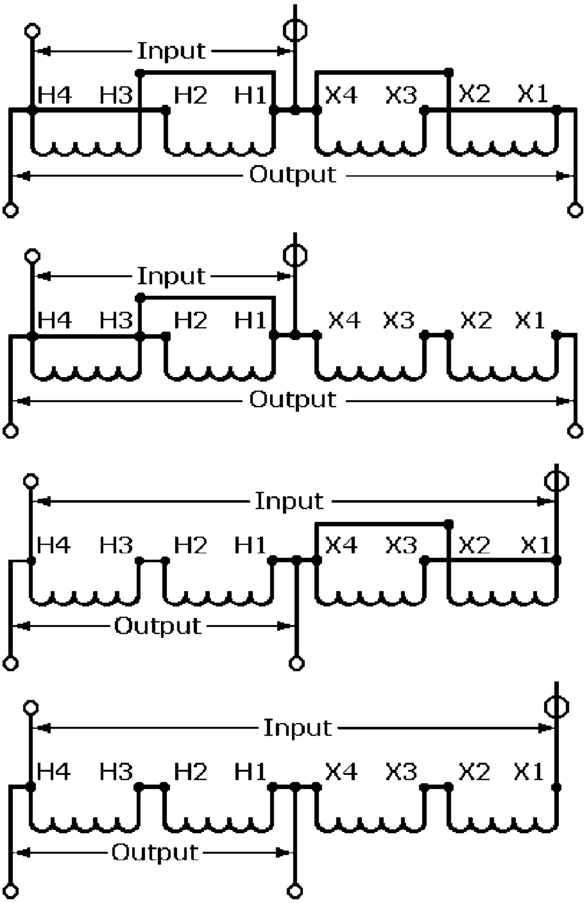


Figure 3-18 Connection diagrams for buck-boost transformers in autotransformer arrangements for single-phase systems.

low-current instruments and controls; and they act as isolators to protect the instruments, controls, and personnel from high voltages. The two kinds of instrument transformers are voltage transformers (also called potential transformers) and current transformers. These transformers operate on the same principles as power transformers.

Voltage transformers Voltage or potential transformers (VTs) are single-phase transformers that supply voltage to measurement instruments such as voltmeters, frequency meters, power factor meters, and watthour meters, as well as controls. The voltage applied to sensitive meters and controls is a fixed fraction of the higher line voltage being measured, low enough to be used by the instruments and controls without damaging or destroying them. The primary winding of a VT is always connected across the main power lines, as shown in Fig. 3-19.

These transformers are made to regulate the secondary voltage so that it will remain constant or nearly constant under all conditions. When the primary winding is connected across the line, the current flowing in the winding sets up a field in the core. This field linking the secondary winding induces a voltage that is proportional to the ratio of primary to secondary turns.

Most voltage transformers are designed for 120-V AC operation at the secondary terminals when the high voltage is applied at the primary winding. Because the load supplied by the VT is small, VA ratings are small, of the order of 50 to 200 VA. Voltage transformers are typically rated for 120 to 460 V AC, 50 VA. If VTs are to make measurements on three-phase systems, sets of two or three transformers are installed. There are, however, higher-rated, oil-filled VTs, rated up to 500 kV, for use outdoors in substation switching yards.

Current transformers Current transformers (CTs) step down line current to values that can be used to operate standard low-current measuring instruments and control devices without damaging them. These instruments and control devices are completely

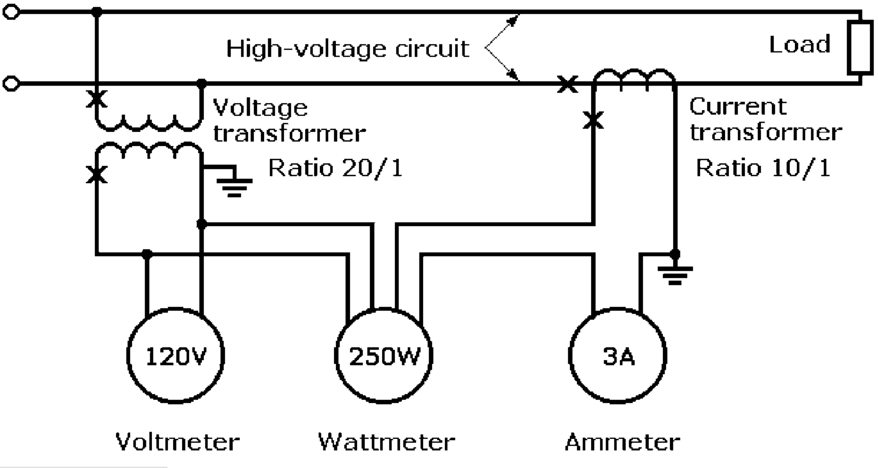


Figure 3-19 Instrument transformer connections: voltmeter, wattmeter, and ammeter.

insulated and isolated from the high-current circuits, assuring the safety of personnel monitoring them. The connection of a CT to a high-voltage line is shown in Fig. 3-19.

Current transformers supply current to current-measuring instruments, so their primary windings are designed to be connected in series with the line. Therefore, the impedance of the primary windings must be made as low as possible. This is done by using a few turns of low-resistance wire capable of carrying the higher line current.

Because CTs are ordinarily used to step current down, the secondary winding contains more turns than the primary winding. Thus, the ratio of primary current to secondary current is inversely proportional to the ratio of the primary to the secondary turns. These transformers are usually designed so that when the rated current flows in the primary, 5 A will flow in the secondary.

Dry-type, open-construction auxiliary CTs for summation and ratio-correction applications are made in current ratings of 0.1 to 50 A. There are also 600-V slip-over CTs that are built for use outdoors for relaying protection and control circuits. They are placed on high-voltage insulators (bushings) to allow a 600-V CT to be used on high-voltage systems. These CTs are encapsulated in cast resin material. Outdoor CTs for use in substation switch yards have ratings from 5 to 34.5 kV.

The secondaries of the current transformer are usually connected to current-measuring instruments such as ammeters, wattmeters, watthour meters, and power factor meters. They can also be connected to certain kinds of relays and the trip coils of some circuit breakers. One current transformer can operate several instruments connected in series so that each carries the same secondary current.

If the secondary circuit is opened while the primary winding is energized, the flux density can be high enough to induce a dangerously high voltage in the open secondary winding. To prevent damage to connected instruments or electrical shock to operating personnel, the secondary terminals of a current transformer must be short-circuited before removing or connecting an instrument in the secondary circuit while the primary winding is energized.

Although modern current transformers include automatic devices for short-circuiting the secondary winding when changes are to be made in the secondary circuit, personnel working with these circuits should make certain that the winding is actually short-circuited before making any changes in the circuit.

Wattmeters for making power measurements require output from both the voltage transformer secondary and the current transformer. The connections required to operate a wattmeter are shown in Fig. 3-19. Note that the secondary circuits are grounded. This is general practice when the transformers are connected in circuits that have a potential above ground of 300 V or more.

OVERCURRENT PROTECTION FOR TRANSFORMERS

Section 3 of NEC 2002, Article 450, covers overcurrent protection for transformers. Protection must be provided for high-voltage transformers rated over 600 V nominal and 600 V nominal or less in accordance with NEC Tables 450.3(A) and (B).

Table 450.3(A) applies in situations where qualified persons either do or do not monitor and service the transformer installation. Two alternatives are given: either primary-only protection or primary and secondary protection. The transformers rated over 600 V, dry or fluid-filled, can have any impedance. The ratings of fuses, circuit breakers, and secondary protective devices are covered as they apply to monitored and unmonitored locations. Where the indicated percentage of primary current does not correspond to a standard fuse rating or circuit breaker (CB) setting, the next higher standard size is permitted.

Table 450.3(B) covers all transformers rated 600 V or less. It states that the basic overcurrent protection may be provided just on the primary side or may be a combination of protection on both the primary and secondary sides. For the primary-side protection of transformers with primary current over 9 A, the maximum rating or setting of the circuit breaker or fuses is 125 percent of transformer primary full-load current (TPFLC). The conductors must also be rated 125 percent TPFLC. Here again, where the indicated percentage of primary current does not correspond to a standard fuse rating or CB setting (overcurrent device), the next higher standard rating is permitted.

Some of the other provisions of Table 450.3(B) include the following.

- A transformer with a rated primary current of less than 2 A may be protected by a primary overcurrent device rated or set at not more than 300 percent of rated primary current.
- A transformer with a rated primary current of less than 9 A may be protected by a primary overcurrent device rated or set at not more than 167 percent of rated primary current.
- When using the 167 or 300 percent factors, if the resultant current value is not exactly equal to a standard rating of fuse or CB, the next *lower* standard rated overcurrent device must be used.
- Protection of the secondary circuit must be independent of the primary-side transformer protection.
- If the transformer secondary has a protective device rated or set not more than 125 percent of the rated secondary current, the primary feeder protective device may be rated or set at not more than 250 percent of the primary current.
- Secondary protection by overcurrent protective devices, their use in protecting secondary feeder conductors and lighting panels, and their locations are specified.

If a transformer is equipped with coordinated thermal overload protection capable of interrupting the primary current, the primary feeder overcurrent device may be rated or set at not more than 6 times the rated primary current for transformers with not more than 6 percent impedance or not more than 4 times the rated primary current for transformers with more than 6 percent but less than 10 percent impedance.

Other NEC requirements related to transformer protection are given in Section 240.21.

Glossary of Transformer Terms

The following technical terms apply to transformers.

BIL: An abbreviation for *basic impulse level,* a dielectric strength test. Transformer BIL is determined by applying a high-frequency square-wave voltage with a steep leading edge between the windings and between the windings and ground. The BIL rating provides the maximum input kV rating that a transformer can withstand without causing insulation breakdown. The transformer must also be protected against natural or man-made electrical surges. The NEMA standard BIL rating is 10 kV.

Exciting current: In transformers, the current in amperes required for excitation. This current consists of two components: (1) real in the form of losses (no load watts) and (2) reactive power in kvar. Exciting current varies inversely with kVA rating from approximately 10 percent at 1 kVA to as low as 0.5 percent at 750 kVA.

Eddy-current losses: Contiguous energy losses caused when a varying magnetic flux sets up undesired eddy currents circulating in a ferromagnetic transformer core.

Hysteresis losses: Continuous energy losses in a ferromagnetic transformer core when it is taken through the complete magnetization cycle at the input frequency.

Insulating transformer: A term synonymous with *isolating transformer,* to describe the insulation or isolation between the primary and secondary windings. The only transformers that are not insulating or isolating are autotransformers.

Insulation system temperature: The maximum temperature in degrees Celsius at the hottest point in the winding.

Isolating transformer: See *insulating transformer.*

Shielded-winding transformer: A transformer with a conductive metal shield between the primary and secondary windings to attenuate transient noise.

Taps: Connections made to transformer windings other than at its terminals. They are provided on the input side of some high-voltage transformers to correct for high or low voltages so that the secondary terminals can deliver their full rated output voltages.

Temperature rise: The incremental temperature rise of the windings and insulation above the ambient temperature.

Transformer impedance: The current-limiting characteristic of a transformer expressed as a percentage. It is used in determining the interrupting capacity of a circuit breaker or fuse that will protect the transformer primary.

Transformer voltage regulation: The difference between the no-load and full-load voltages expressed as a percentage. A transformer that delivers 200 V at no load and 190 V at full load has a regulation of 5 percent.

High-Voltage Circuit Breakers

This section covers high-voltage circuit breakers rated for 1000 V to 72.5 kV intended for use in electrical power systems. The logic behind calling 1000 V to 72.5 kV a medium-voltage range is not obvious unless it is compared with the maximum North American grid voltages of 800 kV and more common transmission system voltages of 60 to 500 kV. Nevertheless, medium-voltage circuit breakers can protect AC generators, some transmission and subtransmission lines, and distribution substations.

The industry classifies circuit breakers in the following way:

- Medium-voltage power (1000 V to 72.5 kV)
- Low-voltage power (1000 V and below)
- Industrial molded case (600 V and below)
- Miniature or branch circuit (240 V and below)

All circuit breakers are electromechanical devices that make and break currents under normal conditions and make, carry for a specified time, and break currents under abnormal conditions such as short circuits. Circuit breakers, like transformers and batteries, are made in a wide range of ratings. Miniature or branch circuit breakers rated for 240 V or less are discussed in Chap. 5.

Because the higher-voltage circuit breaker contacts can be damaged or destroyed by the burning action of electric arcs when the contacts of a high-voltage circuit are opened, various methods have been developed to provide an appropriate quenching medium around the contacts that will assist in extinguishing any arcs formed as rapidly as possible.

The names of mediums used for extinguishing the arc are included in the descriptions of the circuit breaker. For example, there are oil circuit breakers, air-blast circuit breakers, and magnetic-air circuit breakers. The selection of the appropriate method for quenching the arcs depends on the cost-effectiveness and availability of sources of and means for providing air blasts, insulating gas, insulating oil, magnetic fields, or vacuums.

The two basic designs for high-voltage circuit breakers are oil and oil-less. The oil-type circuit breaker had been the most popular for outdoor service up to 362 kV, but the air-blast and gas-type versions have been gaining in popularity. At 550 and 800 kV, oil-less breakers predominate. For new indoor applications magnetic-air and vacuum circuit breakers predominate, along with some gas-type. Indoor magnetic-air, air-blast, and vacuum breakers have been adapted for outdoor use in the 2.5- to 34.5-kV range by protecting them with metal covers.

It is essential that the correct circuit breakers, fuses, and switches be selected for each power control application because of their importance in the design and function of the overall electrical system. Immediately upon sensing a short circuit or break in the supply line, fuses and circuit breakers must isolate the sections of the electrical network where the fault occurred, to prevent further damage while permitting the remainder of the network to remain operational.

POWER SYSTEM CIRCUIT BREAKERS

The five general types of high-voltage circuit breakers are as follows.

1. *Oil circuit breakers* use standard transformer oil, an effective medium for quenching the arc and providing an open break after current has dropped to zero. There are

two general types of oil circuit breakers: *dead-tank* for the higher voltage ranges and *live-tank* for lower voltages. Oil circuit breakers have been improved by adding such features as oil-tight joints, vents, and separate chambers to prevent the escape of oil. Also, improved operating mechanisms prevent gas pressure from reclosing the contacts, making them reliable for system voltages up to 362 kV. However, above 230 kV, oil-less breakers are more economical.

2. *Air-blast circuit breakers* were developed as alternatives to oil circuit breakers as voltages increased. They depend on the good insulating and arc-quenching properties of dry and clean compressed air injected into the contact region.
3. *Magnetic-air circuit breakers* use a combination of strong magnetic field with a special arc chute to lengthen the arc until the system voltage is unable to maintain the arc any longer. They are used principally in power distribution systems.
4. *Gas circuit breakers* take advantage of the excellent arc-quenching and insulating properties of sulfur hexafluoride (SF_6) gas. These outdoor breakers can interrupt system voltages up to 800 kV. These circuit breakers are typically included in gas-insulated substations (GISs) that offer space-saving and environmental advantages over conventional outdoor substations. Gas (SF_6) circuit breakers are made with ratings up to 800 kV and continuous current up to 4000 A. They are alternatives to oil and vacuum breakers for metal-clad and metal-enclosed switchgear up to 38 kV.
5. *Vacuum circuit breakers,* more accurately termed vacuum-bottle interrupters, are generally used for voltages up to 38 kV and continuous current ratings to 3000 A. They are used for higher system voltage, current, and interrupting ratings, and are typically specified for metal-clad and metal-enclosed switchgear in distribution systems.

HIGH-VOLTAGE CIRCUIT BREAKER CONSTRUCTION

All high-voltage circuit breakers have

- Contacts that operate at system voltage
- Insulation between main contacts and ground potential (porcelain, oil, or gas)
- Operating and supervisory devices
- Insulated links between the operating devices and the main contacts

Most power circuit breakers are opened and closed automatically by remote control. Various kinds of operating mechanisms are used. Among them are AC or DC solenoids, compressed air, high-pressure oil, springs, or electric motors.

HIGH-VOLTAGE CIRCUIT BREAKER RATINGS

High-voltage circuit breakers are rated by maximum voltage, insulation, maximum continuous and momentary current-carrying capacity, maximum interrupting capacity, transient recovery voltage, interrupting time, and trip delay.

Circuit interruption occurs when a plasma arc with temperatures exceeding 20,000 K appears for a short time interval between the main contacts. This occurs when the current passes zero, and it is determined by the time relationship between the buildup of dielectric strength of the gap between the open contacts and the rise of transient *recovery voltage.*

The *interrupting capacity* of a circuit breaker, measured in kilovolt-amperes (kVA), is the product of the phase-to-ground voltage in kilovolts (kV) of the circuit and the interrupting ability, in amperes (A), at stated intervals and for a specific number of operations. The current is the root-mean-square (rms) value existing during the first half-cycle of arc between contacts during the opening stroke.

Circuit Switchers

Circuit switchers are mechanical devices that combine the features of a disconnect switch and circuit breaker. They typically combine sulfur hexafluoride (SF_6) as an arc-interrupting medium and a trip device connected to a relay to open the circuit switcher automatically, with an air-break disconnect switch, under certain abnormal conditions. Blade-type circuit switchers with fault-interrupting ratings up to 15,000 A are being manufactured, and they are capable of interrupting voltages of 38 to 230 kV.

The disconnect provides visual isolation, meaning that when the circuit has been interrupted it can be seen that the disconnect blade, part of the switching mechanism, has sprung open, leaving a large air gap between the blade end and its closed position.

Circuit switchers are used primarily for transformer protection. They can also provide load-switching capability, line and loop switching, capacitor or reactor switching, and load management, usually with protection features. They combine the functions of a circuit breaker (without its high-speed reclosing capability) and a disconnecting switch, filling a role between high-power fuses and circuit breakers.

Circuit switchers must be able to make, carry, and break normal load currents within a defined temperature range to prevent damage to key system components such as contacts, linkage, terminals, and isolators. They must also be able to make and carry load currents for predetermined lengths of under certain abnormal conditions not seen as endangering the integrity of the system, and they must be able to break currents under overcurrent or fault conditions.

The variables that define circuit switchers are maximum operating voltage, basic insulation level (BIL), rated load current, and interrupting current, whether or not they include isolators or trip devices or are manually or automatically operated.

CIRCUIT SWITCHER OPERATION

A single pole of a blade-type circuit switcher with the interrupter and blade connected in series is shown in Fig. 3-20. To switch three-phase AC, three poles are mounted in parallel on a structural steel frame mounted on a pedestal high above the ground. The three-phase lines are connected to the input ends of the interrupters, and under normal conditions, three conduction paths are completed through the interrupters, drivers, and hinged disconnect blades to line continuations atop the second

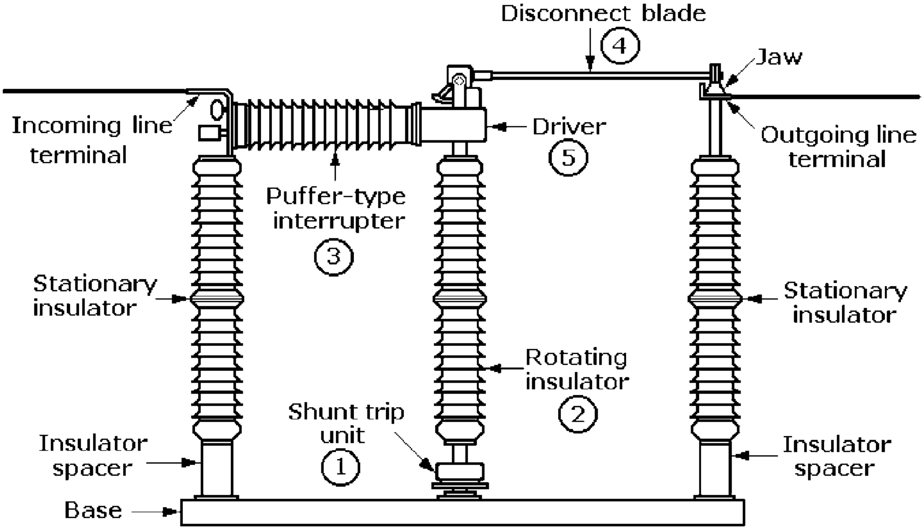


Figure 3-20 Single pole of a blade-type circuit switcher.

stationary insulators. The circuit is interrupted when the disconnect blades spring out of their normal positions.

A key component in each pole of the circuit switcher is the live-tank SF_6 gas "puffer"-type interrupter. This is a spring-loaded piston assembly contained inside a horizontally mounted section of cylindrical insulator. The interrupter mechanically generates a "puff" of SF_6 to cool and deionize the arc that is established before the circuit is interrupted. The gas is prepressurized to be ready for ejection when the circuit switcher is tripped. After the trip signal initiates the process and the blade opens, a destructive electric arc is formed. It is the task of the puffer to extinguish that arc as rapidly and harmlessly as possible. The arc actually forms as separate bursts rather than a continuous stream in response to the current waveform, resulting in two current zeros every cycle.

At the first current zero the pressurized SF_6 gas ejected from two tubes is dense enough to provide the necessary dielectric strength to stop the arc from reestablishing itself so it is extinguished. However, if the arc is sufficiently "hot" or conductive as it passes through the SF_6 gas, and the gas is not dense enough to extinguish it, the destructive arc could reestablish itself. In modern circuit switchers the entire process from trip-signal initiation to current interruption takes about 130 ms. The process of opening and closing one pole of a blade-type circuit switcher is described as follows.

The shunt trip unit (1) receives a trip signal when the relay system detects a fault within the system or when an operator wants to open the circuit rapidly. The operating spring is then released and the shunt trip unit rotates the insulator mounted on it at high speed, thus tripping and opening the driver's (5) mechanism spring. This actuates the interrupter (3) to open the circuit and extinguish the arc with SF_6 gas jets.

The motor of the drive train rotates the insulator until the disconnect blade (4) springs open to provide sufficient air isolation to break the circuit. The rotation of the insulator continues after the disconnect blade is open to “toggle” the drive-train control and lock the blade in its open position.

To close the switcher, the rotation of the insulator is reversed until it releases the drive-train toggle. This allows the disconnect blade to begin closing. (The shunt trip unit has recharged during the opening operation.) As the disconnect blade closes, the closing springs are reset by the driver (5). The last few degrees of closing rotation lock the disconnect blade in its closed position and release the closing spring in the driver, thus closing the switcher. The opening springs are reset as the closing springs relax. If the fault has been cleared, the circuit will close into a condition that will permit it to accept another trip signal to actuate the shunt trip unit. This will allow the opening process to begin again immediately because all of the springs have been set, the SF_6 puffer interrupter is repressurized, and all of the controls are ready.

Reclosers

Reclosers are automatic, high-voltage electric switches used throughout power distribution systems, from substations to residential utility poles. They range from small units used on single-phase distribution lines to large three-phase reclosers used in substations and on high-voltage power lines up to 38 kV. Reclosers act like 120/240-V thermal circuit breakers that shut off electric power when overvoltages and short circuits occur.

A residential circuit breaker remains shut off until it is reset manually. By contrast, a power distribution recloser first automatically tests the electrical line to determine if the fault has been cleared. If it finds that it has been cleared, it then automatically resets itself to restore electric power. Statistics indicate that 80 to 90 percent of faults on high-voltage lines are temporary. They are caused by such factors as lightning, wind-blown tree branches that brush against power lines, or short circuits caused by birds or rodents. These outages will be quickly removed from the electric line if the power is shut off before permanent damage to the line occurs. The recloser senses when trouble occurs and automatically shuts off the power. An instant later (the length of time might be noticeable as the flickering of a light bulb), the recloser turns the power back on. However, if the fault is still present, the recloser shuts off the power again.

The recloser is programmed to permit three attempts at reclosing before it determines that the problem is permanent and it remains off. A power company crew must then repair the line fault and manually reset the recloser to restore power. Examples of permanent outages include power lines or other equipment damaged by lightning strikes, fallen tree limbs that break the wires, or vehicle collisions that knock down power poles.

Reclosers save electric power utilities time and expense because they permit power to be restored automatically, after only a flicker or two. In addition, if the outage requires a utility crew to make repairs, reclosers minimize the outage area and help the crews to locate the problem quickly so that power can be restored. In addition, electric power customers are saved the inconvenience and possible expenses due to losses that would be incurred by frequent power outages.

The introduction of the first commercially successful recloser—the Kyle type H—revolutionized the protection of high-voltage (2.4- to 38-kV) electric lines, making it possible for electric utilities to provide more dependable electric power service.

Interrupter Switches

The increasing electrical loads on distribution lines caused by increasing demand, particularly in the suburbs, have caused utilities to raise their operating voltages. Voltages are now being distributed at 13.8, 23, and 34.5 kV and higher. This higher voltage has led to the formation of smaller service regions or more sectionalizing to minimize the impact of an electrical outage in parts of each region.

Ironically, the probability of fault occurrence has increased as operating voltages have increased because of the combination of higher voltages and longer distribution lines. These have made the lines more susceptible to outages on lower-voltage, shorter lines because of the higher probability of transformer bushing flashovers, falling tree limbs, lightning strikes, and other causes.

Early in the last century conventional disconnect switches met the requirements for sectionalizing, but this is no longer true. The switching capability of a disconnect, while marginal at 2.4 to 4.8 kV, is completely inadequate at 13.8 kV and higher. To isolate a section of distribution line by opening a disconnect, the entire feeder must first be dropped, and this adds to the extent of the outage. Moreover, during emergency conditions the probability of the occurrence of a disconnect caused by operator error increases proportionally.

Many different kinds of switches are now available to meet a wide variety of applications economically. The *single-pole switch* and *side-break switch* are intended for pole-top installation on distribution feeders, while the *vertical-break switch* was designed for distribution substations or feeders. These switches perform all of their switching duties without causing external arcing, and they also provide the reliable isolation of a visible air gap. A few examples of their versatility and use are the following.

- During emergency situations requiring fast response, a modern interrupter switch can drop the load without complicated circuit breaker and switch sequencing.
- There is no need to drop individual loads because the switch can drop the entire load.
- Lines can be extended and additional load accommodated (within the rating of the switch) without affecting switching ability.
- A loaded circuit can be dropped inadvertently (through an error or misunderstanding) with no hazard to the operator or to the system.
- Interlocking is not required between the primary switch and the secondary breaker in transformer operation.

Because of the no-external-arc feature of most modern interrupter switches, phase conductor spacing can be much less than that established for the older *horn-gap switch.* On the secondary side of the substation there are more feeders and more heavily loaded and longer transmission lines.

Voltage Regulators

All of the components in an electrical system are designed to operate at their rated voltages for optimum efficiency and long service. An ideal electrical system would provide constant voltage to all customers under all conditions of load. Unfortunately, because of the unpredictable dynamics of a practical system, none is ideal. Thus, it is necessary to include voltage regulators in the system to correct its performance and keep its voltage reasonably close to an ideal constant.

There are now at least four different methods for maintaining close to ideal voltage on electric power transmission and distribution systems. These include the use of step-voltage regulators, transformer load-tap changers, fixed and switched capacitors, and static var (volt-amperes reactive) systems (SVS). However, single-phase step-voltage regulators are most frequently used to regulate voltage in electric power distribution systems.

There are many reasons, both technical and economic, why system voltage should be held close to its intended standard. Among them is the fact that overvoltage shortens the life of heating elements in resistive appliances, components in electronic products, and filaments in both incandescent and fluorescent lamps. Moreover, overvoltage can damage motor-driven appliances and tools.

On the other hand, undervoltage increases the time taken for the resistive elements of appliances to heat up while also causing motors to overheat and lose efficiency. It will also reduce the performance of electronic products such as computers, radios, and TVs, and dim the illumination from luminaires.

STEP-VOLTAGE REGULATORS

Step-type voltage regulators are actually tapped autotransformers that have one winding common to both the primary and secondary circuits. The primary (exciter) winding is both magnetically and electrically connected to the secondary (series) winding. The series winding is connected in series with the load current. Both single-phase and three-phase step-voltage regulators are being manufactured. They are built in both pole-mounted and pad-mounted styles.

A single-phase pad-mounted step-voltage regulator is shown in Fig. 3-21. It performs the same function as the traditional overhead-mounted tank-type and substation-mounted regulators, with the convenience of pad mounting. The unit shown provides regulation in 32 voltage steps of approximately $^5/_8$ percent each for a maximum of 10 percent regulation when used singly or in wye-connected banks.

These voltage regulators are made in ratings of 7620/7200 and 14.4 kV for 60-Hz systems. Their current ratings are from 50 to 548 A. Voltage regulation is

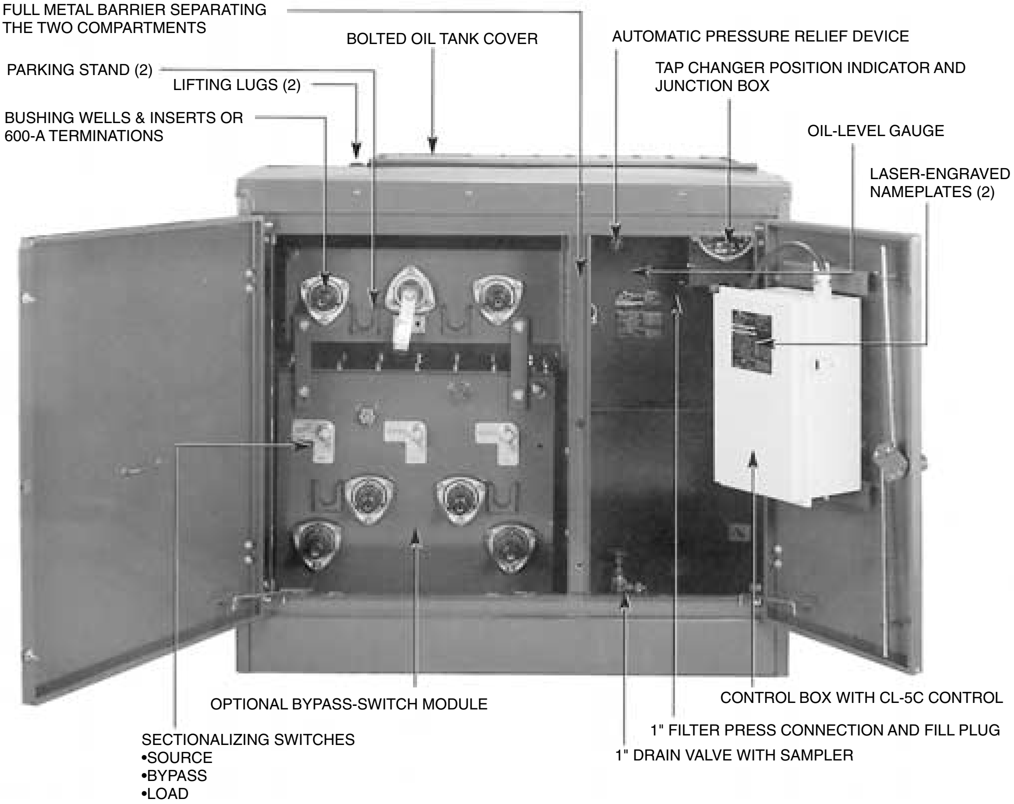


Figure 3-21 **Single-phase pad-mounted voltage regulator.** *Courtesy Cooper Power Systems*

microprocessor-controlled, and the autotransformer core and coil assembly is immersed in insulating oil. Pad-mounted voltage regulators are housed in steel enclosures with front access doors that are painted green to blend in with residential surroundings.

Figure 3-22 is a simplified wiring diagram for a single-phase step-voltage regulator. The regulator includes a series winding and a shunt winding that make up the main transformer and a bridging reactor or preventive transformer. The series winding is typically rated for 10 percent of the voltage of the shunt winding. There are usually eight taps attached to the series winding, and these are wired to segments of a dial switch assembly as individual contacts. The voltage difference between these segments is $1^1/_4$ percent voltage.

Contacts on the center-tapped preventive autotransformer are designed to bridge the gap between the dial switch segments to avoid momentary loss of the load. Although arcing occurs as the bridge slides, the load is not lost because one contact remains on the segment. As a result of this sliding action, load voltage become the average voltage of the taps bridged.

A reversing switch permits the polarity of the series winding to be reversed with respect to the shunt winding, permitting both plus and minus regulation. Both a voltage

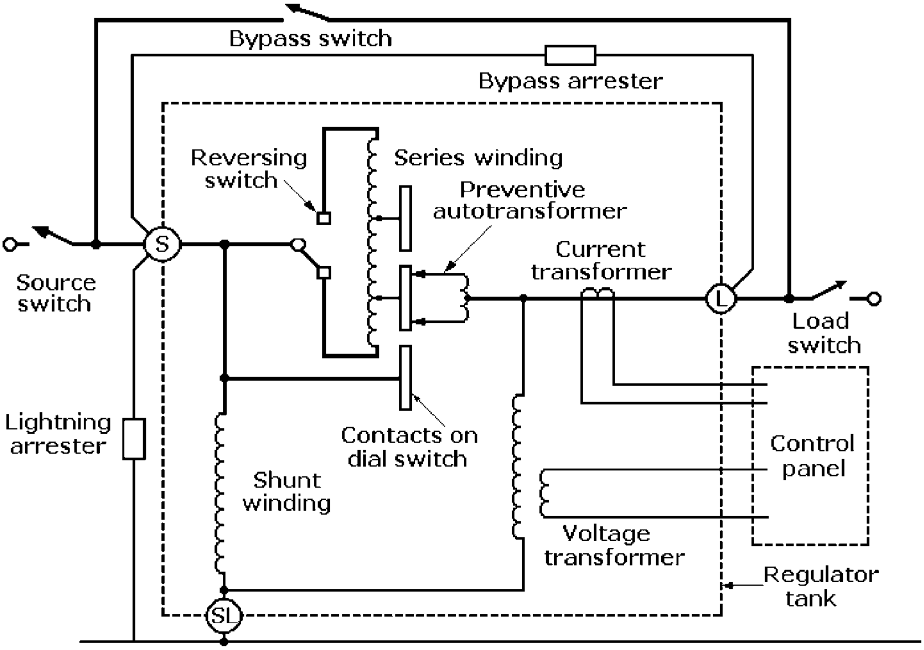


Figure 3-22 **Wiring diagram for a typical distribution step-voltage regulator showing both internal and external connections.**

transformer and a current transformer provide the control signal for the regulator. Any surges propagated on the line will be shunted past the regulator by the bypass arrester. The lightning arrester also protects the regulator from overvoltage surges.

Source (S), load (L), and source-to-load (SL) or common bushings (indicated as lettered circles) permit the wiring to pass into and out of the oil-filled regulator tank. Tap-changer position indicators and control-panel enclosures are mounted outside both pole- and pad-mount regulators.

Modern regulators are controlled electronically. They include a *voltage sensor* that monitors regulator output and signals the control circuit and a *switching section* that delays and/or transmits the signal. They also include a *tap-changing motor drive circuit* for driving a motor, which changes the taps as necessary to correct the voltage.

Digital controls are available that display voltage, current, power factor, kW, kvar, and various other quantities. Many control systems can send this information to a remote terminal unit (RTU). Thus the regulator control becomes a sending station for a SCADA (supervisory control and data acquisition) system.

Power Factor

If AC current and voltage were always in phase, the average power over a complete cycle would be equal to the product of the current and voltage and power could be measured in watts. However, this is a theoretical situation because there is always some reactance present in an AC circuit that keeps the current and voltage out of phase. Where phase difference is minimal, a reasonable approximation of actual power can be determined as the product of current (I) and voltage (E), which yields watts (W). This is the formula for determining actual power in a DC circuit.

However, when voltage and current are out of phase, current can be negative and voltage positive and vice versa at various times during each cycle. As a result, the value of power is less than the product of $E \times I$. The terms *volt-amperes* (VA) or *kilovolt-amperes* (kVA) express the product of the effective values of voltage and current in an AC circuit. To determine useful or *actual* power, the volt-ampere product must be multiplied by a value called the *power factor* (PF).

Power in a single-phase AC circuit is found from

$$P \text{ (watts)} = EI \times \text{PF}$$

or

$$P \text{ (kilowatts)} = \frac{EI}{1000} \times \text{PF}$$

By transposing the second equation,

$$\text{Power factor} = \frac{P}{EI} \qquad \text{or} \qquad \frac{\text{kW}}{\text{kVA}}$$

Thus, power factor is defined as the ratio of the actual power in watts to the volt-amperes of an AC circuit. When the current and voltage are in phase, power is equal to $E \times I$ and the power factor is unity. When current and voltage are out of phase by 90° (as in a purely capacitive or inductive circuit), the power factor is zero. In this situation no actual power is produced. However, in circuits that contain both resistance and reactance, the value of PF lies between 1 and 0, and it depends on the relative values of resistance and reactance in the circuit.

According to the convention used in discussing power factor, voltage in an inductive circuit leads current, and in a capacitive circuit voltage lags current. Power factor can be expressed as either a decimal or a percentage. Some typical average power factors encountered in the operation of electrical equipment are expressed as percentages:

- Incandescent lamps—95 to 100 percent
- Large induction motors carrying rated load—85 to 90 percent
- Fractional-horsepower induction motors—60 to 75 percent

Current lags voltage both in lamps and motors, which are inductive loads. Current in an AC circuit is considered to consist of a component in phase and a component out of phase with the voltage, as illustrated in the vector diagram Fig. 3-23*a*.

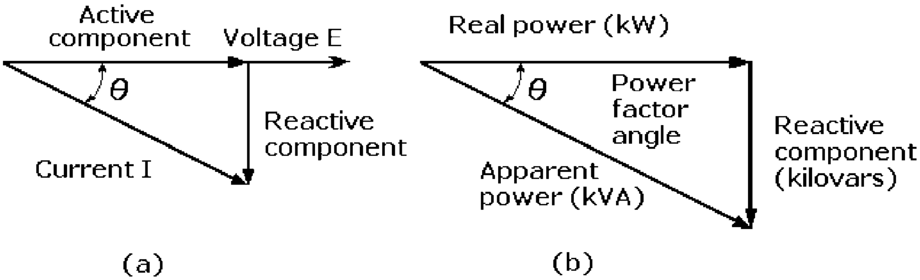


Figure 3-23 **Vector diagrams of active and reactive components in an AC circuit: (*a*) voltage and current; (*b*) real and apparent power.**

The in-phase component is called *active* or *real* because, when multiplied by voltage, it gives the useful or real power in watts or kilowatts. The out-of-phase component is called *reactive* because it contributes nothing to the real power of the circuit. The product of the reactive component of the current and voltage is called *reactive power* or *reactive volt-amperes,* and it is measured in *vars* (volt-amperes reactive) or *kilovars.* If there were no capacitive component to cancel part of the inductive component, voltage and current would be out of phase by 90 electrical degrees.

In Fig. 3-23*a* the greater the phase angle θ, the greater is the value of the reactive component. The cosine of the phase angle θ is the ratio of the active current to the total current. Because the actual power is the voltage multiplied by the active component of current,

$$P = E \times I \cos \theta$$

where P = power, E = voltage, and I = current.

Thus the power factor of an AC circuit is equal to the cosine of the phase angle. The cosine of 0° is 1 and the cosine of 90° is 0, so as the phase angle is reduced, the power factor approaches 1.

Figure 3-23*b* shows the relation between real power in kilowatts (kW), apparent power in kilovolt-amperes (kVA), and the reactive component in kilovars (kvar), units appropriate for practical electrical power measurement.

POWER FACTOR CORRECTION

The efficiency of power generation, transmission, and distribution systems is improved when they are operating near-unity power factor. The most cost-effective way to obtain near-unity power factor is with the use of high-voltage power factor capacitors. Capacitors provide leading reactive current that can reduce the lagging inductive current in the system. An advantage of this method for power factor correction is that capacitors can be installed near the load. Another unit of equipment, called a *synchronous condenser,* can provide continuous power factor correction without the use of capacitors.

A synchronous condenser is a synchronous motor operated without a mechanical load for improving power factor. By overexciting its field, a synchronous condenser will operate at a very low leading power factor. The only input power required is that necessary to supply its losses. When used at the end of a long transmission line, the synchronous condenser neutralizes the effects of lagging power factor loads, thus improving the regulation of the transmission line.

Primary and Secondary Power Capacitors

Capacitors for power factor correction are usually connected in shunt across the power lines. They can be energized continuously or switched on and off depending on load changes. Two kinds of capacitors perform power factor correction: *secondary* (low voltage) and *primary* (high voltage). These capacitors are rated in kilovars.

Low-voltage capacitors with metallized polypropylene dielectrics are available with voltage ratings from 240 to 600 V over the range of 2.5 to 100 kvar, three-phase. These capacitors are usually connected close to the lagging reactive loads on secondary lines. Low-voltage capacitors can either reduce the kVA requirements on nearby lines and transformers or allow a larger kilowatt load without requiring higher-rated lines or transformers.

High-voltage capacitors for primary high-voltage lines have all-film dielectrics and are available with 2.4- to 25-kV ratings over the range of 50 to 400 kvar. By connecting these capacitors in series and parallel arrangements, higher kvar ratings can be achieved. Because modern high-voltage capacitors consume lower watts per kvar than low-voltage capacitors, they can be operated more efficiently.

High-voltage capacitors for overhead distribution systems can be mounted on poles in banks of 300 to 3600 kvar at nearly any primary voltage up to 34.5 kV, phase-to-phase. Pad-mounted capacitors for raising the power factor in underground distribution systems are available in the same range of sizes and voltage ratings.

The increasing use of motor-driven appliances and building service equipment has increased overall power loads as well as the inductive kvar on most power systems. It is desirable to cancel them because

- Substation and transformer load capacity can be taxed to full thermal limits.
- High inductive kilovar demands can cause excessive voltage drops.
- Local utilities charge power factor penalties.

The size of the power factor correction (number of kvar) that must be injected into the electric power system determines the method to be used. If the load is less than 500 kvar, capacitors can provide the capacitive reactance to cancel the inductive reactance, but if the load exceeds 500 kvar, a *synchronous condenser* is commonly installed. Also, if there are large, rapid, and random swings in kvar demand during the day, a synchronous condenser is preferred. However, if the changes in kvar demand are small and can be corrected with capacitors, incremental capacitor banks provide a more practical solution.

As a result of this kind of correction, circuit current can be brought more nearly in phase with the applied voltage and the power factor can approach 100 percent. Capacitors can reduce the kilovar demand from the point of demand back to the generators. The installation of capacitors can increase generator and substation capability for additional load at least 30 percent, and can increase individual circuit capability in terms of voltage regulation from 30 to 100 percent.

In actual power systems, full correction to achieve 100 percent power factor is usually not attempted. If a system had a constant 24-hr load at an established power factor, this correction would be possible and even reasonable, but changing load conditions typically rule that out that possibility.

The addition of a preset number of capacitors to cancel out the inductive (lagging) kvar would lead to changes between a surplus of leading capacitive kvar at certain periods during the day to excess inductive kvar at other times of the day. Rather than maintain a fixed number of capacitors in the system, a fixed number of capacitors is kept in the system, and they are supplemented by capacitors that are switched incrementally into and out of the system either by automated or manual means as required to correct inductive reactance and improve power factor.

Kilovarmeters

A recording instrument called a kilovarmeter can plot the graph of power factor versus time and load conditions as was discussed earlier. Figure 3-24, a plot of kilovars versus a 24-hr period of time, shows the results of adding switched capacitors to fixed capacitors to cancel inductive reactance. This graph can represent either the kilovar curve of power demand for a town or an individual feeder on a large distribution system.

It can be seen that the lowest kilovar requirement occurs at 4:00 a.m., when the load is lowest. The bank of permanently installed 400-kvar capacitors can correct the power factor at that time. However, additional capacitors from a bank of 1000-kvar switchable capacitors can be switched into the system as needed to eliminate leading power factor in the shaded area from midnight to 4:00 a.m. and from 4:00 a.m. to the next midnight. It can be seen that maximum load and correction occurs at about 8:00 p.m.

If a severe voltage drop occurs in the system, the capacitors will be removed. However, if the voltage problems that occur on a distribution system are not serious in the town or feeder represented in this figure, and the prime purpose for installing capacitors is to correct power factor on the generators, the capacitors would be probably be installed at the generating station.

Synchronous Condensers

A synchronous condenser can provide continuous power factor correction without the use of capacitors. Precision control of the motor fields of the latest synchronous condensers

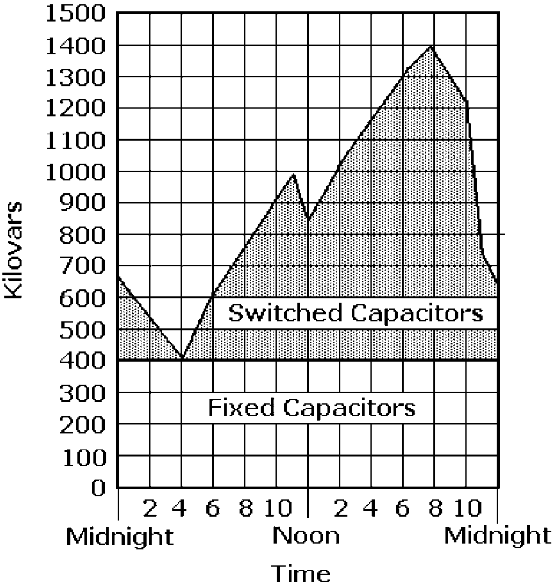


Figure 3-24 **Plot of kilovars versus time, showing the effects of using fixed and switched capacitors.**

produces the exact amount of vars needed to correct any power factor without annoying switching transients. These units are not affected by the harmonic currents produced by solid-state motor drives. Features of a standard synchronous condenser are

- Three-phase synchronous brushless motor
- Solid-state voltage and power factor regulators
- Electrically operated main circuit breaker
- Switchboard-grade varmeter and power factor meter
- Start and control logic with internal fault monitors

Phase Converters

Single-phase power can be obtained from any three-phase electrical system by connecting any two phase leads. However, it is not possible to obtain three-phase power from a single-phase power source without recourse to either a rotary or static phase converter.

A *rotary phase converter* is a machine that can convert single-phase power to three-phase power. More accurately termed a *phase generator* than a converter, it generates a voltage that, when paralleled with two voltages obtained from single-phase line power, produces three-phase power. Rotary converters can provide three-phase current that can power three-phase as well as inductive loads.

Figure 3-25 is a schematic diagram for a rotary converter. The electromechanical machine is connected to a single-phase source, and it generates a third phase output for powering three-phase loads and motors. Single-phase lines L1 and L2 are connected to a three-phase fused disconnect switch or magnetic starter. The outputs of the switch or starter are designated TI and T2. Parallel branches are fed to the rotary converter terminals, also designated TI and T2. The converter produces an output T3, which, after passing through the switch or starter, is combined with T1 and T2 to form the three-phase output (T1, T2, and T3) for driving motors or other three-phase loads.

When the rotary converter is running alone without a load, line T3 provides the highest voltage with respect to ground. This line should not be used to power any single-phase loads. The manufacturers of these machines caution that all electrical equipment should be grounded as required by the NEC, and that the rotary converter should always be started before energizing motor loads. All wire sizes, lengths, and voltage drops should be in accordance with the manufacturer's recommendations.

Rotary converters can power metalworking and woodworking machines, farm equipment, pumps, compressors, elevators, lasers, battery chargers, plasma cutters, electrodischarge machining (EDM) systems, heating elements, and variable-frequency drives. However, they are not suitable for powering heavy starting loads or instantly reversing or momentarily overloaded motors such as those that power laundry extractors, paper cutters, air conditioners, hoists, or high-speed lathes.

Because of the high current required to start a motor (which can be from 5 to 10 times the normal running current), the horsepower of the largest motor or combination of motors started at exactly the same time should not exceed the manufacturer's maximum rating for the rotary converter. However, once the motor or combination of motors has been started, it is acceptable to start additional smaller motors up to but not exceeding the total horsepower rating of the converter. For example, a 3-hp rotary converter could run motors whose combined rating is up to 9 hp if they are running lightly loaded.

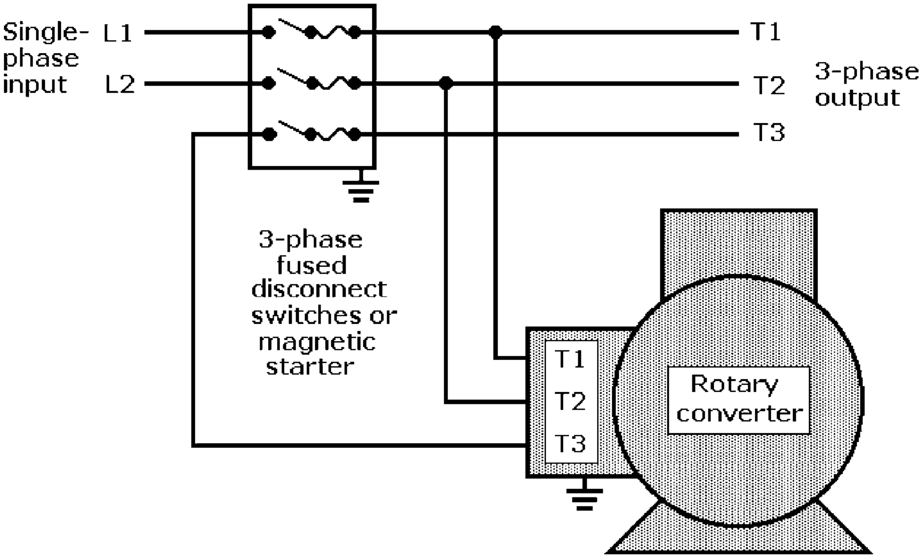


Figure 3-25 Rotary converter generates a third phase to power three-phase loads from a single-phase supply.

Magnetic controls or single-phase loads must always be energized by lines T1 and T2. Phase converter manufacturers warn against connecting a ground or neutral to the T3 line, the artificially produced phase which can easily be identified as the line with the highest voltage to ground when the converter is running.

The manufacturers agree that the user must pay close attention to recommended wiring size and length to prevent slow starting caused by a voltage drop. They add that when starting a motor whose horsepower rating equals the rating of the rotary converter, lower starting torque can occur. This is most likely to happen when the motor is driving a heavy load, because of the higher starting current. However, full running torque usually can be obtained.

Rotary phase converters should be located in a clean, dry room with sufficient air circulation to provide adequate air cooling. Moreover, the converter should not be operated near flammable liquids, gasses, or dust, because these could ignite fires in the insulation of the converter and damage or destroy it.

Rotary phase converters that operate from 220 and 460 V, single-phase power are available. Almost all machine loads require that the converter be sized at least 50 percent higher than the largest horsepower rating of any motor that is to be driven. Where large horsepower loads are to be powered, additional rotary phase converters can be paralleled to drive those loads safely.

A *static phase converter* is another option for converting single-phase to three-phase power. These converters are suited only for operating motor loads. For all other applications, rotary converters must be used. The static phase converter includes capacitors to start the motor as is done in single-phase capacitor-start motors (see Chap. 10).

Static phase converters do not actually generate three-phase power continuously the way rotary phase converters do. Just as in capacitor-start motors, the capacitors are disconnected once the motor has started, and the motor continues to run on single-phase power. However, because only two of the three windings are powered while the motor is running, the power output of the motor is reduced to 66 percent of its rated value. For example, a 10-hp motor will start with a 10-hp output but will run only as a 6.6-hp motor.

Motor loads that have high starting torque but will run with reduced power are important characteristics in the selection of an appropriate static phase converter. These phase converters can be used with air compressors, for example, because of their high starting torque characteristics. However, in many applications the pulley diameter of the motor must be reduced to compensate for the loss of horsepower once the compressor is running.

Static phase converters are not recommended for driving motor loads that operate close to their maximum rated horsepower ratings. For example, a static phase converter might be acceptable for driving a three-phase motor in a lathe only if it will function satisfactorily at slow speeds. When higher speed is required, the converter can start the lathe turning, but the higher speed settings cannot be achieved because of diminished horsepower output. Rotary phase converters are better suited to these applications.

Another factor to take into account when considering the purchase of a static converter is duty cycle. (This is defined as the percentage of time a motor runs fully or nearly fully loaded with respect to its overall operating time.) Three-phase motors that operate at or close to full load most of the time are more likely to overheat when driven from a static rather than a rotary phase converter.

Most three-phase motors are either wye- or delta-wired. Those that are delta-wired typically cannot be operated from a static phase converter, but they will operate with a rotary phase converter. However, most U.S.-made motors with ratings up to 15 hp are wye-wired, so they can be run on a static phase converter. While many U.S.-made motors rated over 15 hp are also wye-connected, delta windings are increasingly common, especially among motors made in Asia. Static phase converters that operate from 220- and 440-V line power are being made commercially.

Power Semiconductor Devices

SOLID-STATE CIRCUITRY

Over the past 30 years solid-state electronic circuitry has become an increasingly important factor in electric power and lighting. Discrete power semiconductor devices such as diodes, transistors, silicon controlled rectifiers (SCRs), and triacs were the first devices to impact the power industry because they could perform such essential functions as power switching, rectification, amplification, and lighting and motor control more reliably and economically than vacuum tubes or electromechanical devices.

With the introduction of small-signal and power integrated circuits, circuit boards and modules that could perform these functions could be made small enough to be embedded in the products they controlled.

Later the factory-programmed or field-programmable microcontroller and the software-controlled microprocessor with associated peripheral devices replaced analog functions, gaining an even stronger foothold in monitoring, supervisory control, and communications equipment.

Finally, programmable controllers and computers made it possible to monitor transformers, circuit breakers, and other power equipment, leading to more efficient operation of power systems and faster and more economical recovery from outages.

Solid-state circuitry found its way into many consumer, commercial, and industrial products. These include motor starters and controls, GFCI circuit breakers and receptacles, and infrared, acoustic, and radiofrequency (RF) motion or occupancy sensors. In addition, this circuitry became integral parts of smoke and carbon monoxide detectors, surge-protection devices (SPDs), dimmer switches, and standby and emergency lighting.

Electronic ballasts improved the efficiency of familiar fluorescent luminaires and made compact fluorescent lamps (CFLs) practical replacements for incandescent lamps. Solid-state relays are faster than the electromechanical relays they replaced, and they are more reliable. These sealed relays can operate reliably in damp or wet environments, and because they have no moving contacts that could cause an electric arc, they eliminate the threat of causing fires or explosions in the presence flammable or explosive vapors, airborne particulates, or solids.

POWER RECTIFIER DIODES

A power rectifier diode is a power semiconductor device capable of converting AC into DC. Its basic structure and schematic diagram are shown in Fig. 3-26. With the same structure as their small-signal counterparts, power rectifier diodes can conduct 1 A or more of current or dissipate 1 W or more of power. Most are now made from silicon, having replaced earlier germanium devices. The dies for power diodes have large PN junctions, which permit them to dissipate the internal heat they generate safely.

Typically packaged as discrete devices, these rectifiers can be paralleled to increase their ability to function without being damaged or destroyed in high-voltage and high-current circuits. They have replaced earlier vacuum- and gas-tube circuitry. Rectifiers rated from about 12 to 75 A are usually packaged in metal cases. Some have threaded base studs for fastening their cases directly to heatsinks or other heat-dissipating surfaces.

Some important electrical ratings for rectifier diodes are

- Repetitive peak reverse voltage, V_{RRM}
- Average forward current, $I_{F(AV)}$
- Repetitive peak forward current, I_{FRM}

Standard PN junction rectifiers are specified for linear power supplies operating at input frequencies up to 300 Hz. They are, however, inefficient in power supplies switching at frequencies of 10 kHz or higher because of their slow recovery time. *Recovery time* is the finite time required for the minority and majority carriers—electrons and holes—to recombine after the polarity of the input signal has changed. The minority carriers must be dispersed before full blocking voltage can be obtained.

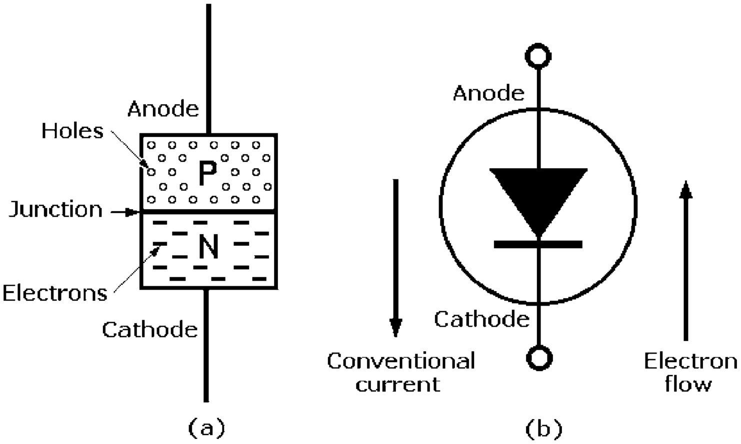


Figure 3-26 Power rectifier silicon PN junction diode rated for 1 W or more: (*a*) functional diagram; (*b*) schematic symbol.

Although standard PN junction rectifiers have slow recovery times, they still have advantages over higher-frequency rectifiers: they offer lower reverse currents, the ability to operate at higher junction temperatures, and the ability to withstand higher inverse voltages.

The three kinds of fast silicon rectifiers that perform more efficiently than standard PN junctions at the higher-frequency switching rates are

- Fast-recovery rectifiers
- Schottky rectifiers
- Ultrafast (superfast)-recovery rectifiers

POWER RECTIFIER BRIDGES

Power rectifier bridge circuits rectify or convert AC (usually from the AC line) to DC. The three most widely used circuit configurations for single-phase rectification in power supplies are

- Half-wave rectifiers
- Full-wave center-tapped rectifiers
- Full-wave bridge rectifiers

The single-phase, full-wave bridge rectifier circuit shown in Fig. 3-27 contains a bridge consisting of four silicon rectifier diodes (D1, D2, D3, and D4), a transformer T1, and an output resistor R1. This circuit is capable of providing virtually ripple-free DC for powering electronic equipment. It is able to provide a smoother DC output than either the half-wave or the full-wave center-tapped rectifier. Consequently, it is widely used in DC power supplies for electronic products ranging from test instruments to computers.

As factory-made packaged components, bridge rectifiers save the time and cost of wiring together discrete rectifiers. These assemblies conserve circuit board space, and their integral heatsinks improve heat dissipation from the rectifiers. Standard bridge rectifiers are rated from 1 to 40 A. Power bridges rated 20 A or higher have

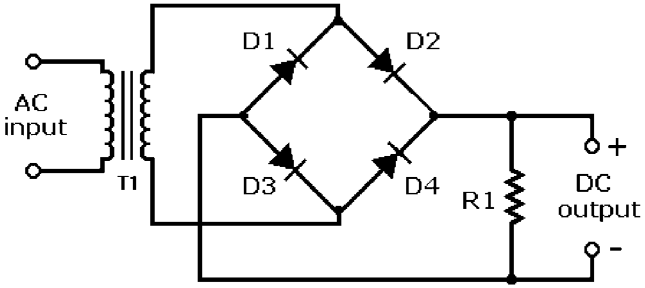


Figure 3-27 Full-wave rectifier circuit contains a bridge of four silicon diodes, a transformer, and an output resistor.

fast-connect, solder, or wire-wrap terminals for external connections. The user furnishes the transformer and the output resistor.

POWER TRANSISTORS

A power transistor is a transistor capable of dissipating 1 W of power or more or drawing 1 A of current or more during normal operation without being damaged. Power transistors are important components in amplifiers, oscillators, switching power supplies, motor controls, and frequency converters. The three small-signal transistor geometries that have been scaled up to perform as power transistors are the bipolar junction transistor (BJT), the Darlington pair, and the MOSFET.

Power bipolar junction transistors Power bipolar junction transistors (BJTs) have geometries that are similar to those of discrete small-signal transistors. Most power BJTs have vertical geometries, with their bases and emitters grown on top of the substrate, which also functions as the collector. There are both NPN and PNP power transistors.

In the absence of a universal versatile power BJT, many different variations have been developed to provide a wide range of electrical and thermal characteristics to optimize them for various applications. Each version has its own set of technical performance advantages and disadvantages or trade-offs.

These structural variations can be classed by the number of diffused layers, the use of an epitaxial base, or combinations of these. BJTs can be made with mesa or planar structures. Some common power bipolar structures are

- Single-diffused (hometaxial)
- Double-diffused (mesa, planar, epitaxial mesa, planar mesa, and multiple epitaxial mesa)
- Triple-diffused (mesa and planar)
- Epitaxial-base (mesa)
- Multiple-epitaxial base (mesa)

A *mesa* is a raised section of the die with the emitter and base geometry in relief above the level of the silicon collector substrate. It is formed by selectively chemically etching away all but the corners of a completed double-diffused die. *Planar* transistor construction is similar to mesa construction, but the collector–base junction terminates under a protective oxide layer at the surface.

Power transistors with these topologies have different voltage ratings, switching speeds, saturation resistances, and leakage currents. The most advanced switching BJTs have multiple-epitaxial, double-diffused structures.

The following parameters determine the applications for BJTs.

- Voltage rating, collector-to-emitter
- Current rating of the collector
- Power rating

- Switching speed
- DC current gain
- Gain–bandwidth product
- Rise and fall times
- Safe operating area (SOA)
- Thermal properties

The popularity of switching-regulated or switchmode power supplies has created a demand for power bipolar transistors capable of switching at frequencies in excess of 10 kHz. A power transistor suitable for this application must be able to withstand at least twice its input voltage. It must also have collector current ratings and safe operating areas (SOAs) that are high enough for the intended application.

A bipolar transistor operated at high power densities is subject to *second-breakdown failure.* This occurs when a thermal hot spot forms within the transistor chip and the emitter-collector voltage drops 10 to 25 V. Unless power is quickly removed, current concentrates in the small region causing the temperature to rise in that region until the transistor is damaged or destroyed.

Safe operating area (SOA) is a parameter that quantifies the ability of a power transistor to sustain simultaneous high currents and voltages. It can be shown graphically with enclosed areas plotted on the collector current versus collector-to-emitter voltage axes. This plot defines, for both steady-state and pulsed operation, the voltage–current boundaries that result from the combined limitations imposed by voltage and current ratings, the maximum allowable dissipation, and transistor second-breakdown limitations.

Power Darlington pairs A power Darlington pair consists of two power bipolar transistors that are formed and internally coupled as DC emitter followers on the same silicon die. This power device, considered to be discrete, is packaged in a single case with three external leads. A power Darlington pair can provide higher input resistance and more current gain than a single power BJT.

Power MOSFETs A power MOSFET is a high-input-impedance, voltage-controlled transistor with an electrically isolated *gate.* Figure 3-28*a* is a cross-sectional view of an N-channel, enhancement-mode power MOSFET made by the DMOS process. As a majority-carrier device that stores no charge, it can switch more quickly than a bipolar transistor can.

Most power MOSFETs, unlike small-signal MOSFETs, have multiple sources and gates and a single drain. They are fabricated in a vertical geometry with the substrate functioning as the drain and the sources and gates formed on top of the device.

With no voltage applied between the gate and source terminals, the impedance between them is very high. But when voltage is applied between the gates and source terminals, electric fields are set up within the MOSFET that lower the drain-to-source resistance. Conventional current then flows from the drain to the source, but electron flow is opposite, moving from the source to the drain, as shown.

Figure 3-28*b* is the electronic schematic symbol for an N-channel enhancement-mode power MOSFET. It includes the diode symbol in parallel with the MOSFET

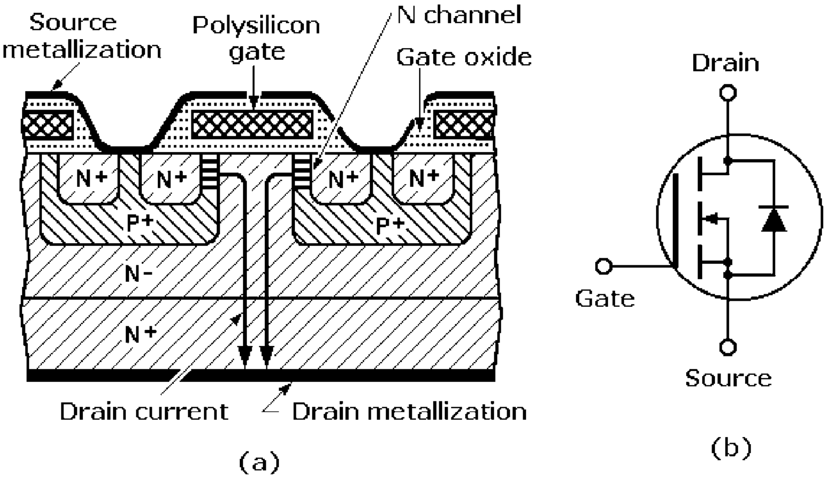


Figure 3-28 N-channel enhancement-mode power MOSFET: (*a*) section view; (*b*) schematic symbol.

structure to indicate the apparent PN junction in this MOSFET geometry. A P-channel enhancement-mode power MOSFET is similar in construction to this N-channel MOSFET except that the polarities and doped regions are reversed.

Power MOSFETs are widely used in high-frequency switching power supplies, chopper and inverter systems for DC and AC motor-speed control, high-frequency generators for induction heating, ultrasonic generators, audio amplifiers, and AM transmitters. Power MOSFETs have the following advantages over bipolar transistors:

- Faster switching speeds and low switching losses
- Absence of second breakdown
- Wider safe operating area
- Higher input impedance
- High if not higher gain
- Faster rise and fall times
- Simple drive circuitry

THYRISTORS

A thyristor is a four-layer semiconductor switching device whose conduction can be controlled by applying a voltage to a *gate electrode.* The most important thyristors are the silicon controlled rectifier, the triac, and the silicon controlled switch.

Silicon controlled rectifiers A silicon controlled rectifier (SCR) is a four-layer PNPN thyristor. The functional diagram of an SCR, Fig. 3-29*a* shows its three junctions and three terminals: *anode, cathode,* and *gate.* The SCR is essentially a rectifier diode with a control element, the gate, but because it is a diode, it can only control DC or half-wave AC. Figure 3-29*b* is the electronic schematic symbol for an SCR. The anode voltage of the SCR must be positive for conventional forward-biased operation, but it is nonconducting without positive triggering.

The SCR can be switched ON with a brief positive gate current pulse. Once turned ON, the gate has no further control, and the SCR remains ON until the anode–cathode voltage is reduced to near zero. The application of positive gate current can be delayed up to 90° of the positive cycle, reducing the anode-to-cathode current and power to the load. This characteristic permits the SCR to dim lamps and control motor speed. The SCR switches OFF when the anode-to-cathode current is reduced to a value less than holding current, but this usually occurs when the half-cycle crosses the zero level.

SCRs also function as controlled rectifiers in power bridges. High-power SCRs can conduct hundreds of amperes or function at voltages up to 1500 V with triggering current of less than a few milliamperes. However, most SCRs are rated for 40 A or less.

Triacs A triac (TRIode AC) is a bidirectional gate-controlled thyristor that can control DC or full-wave AC power. Figure 3-30*a* is a functional diagram of a triac showing its four junctions and three terminals: *terminal 1, terminal 2,* and *gate.* It functions like two SCRs in parallel, with the anode of one connected to the cathode of the other, as shown in its schematic symbol, Fig. 3-30*b.* When the triac anode is positive, a positive gate pulse will trigger the device into conduction, and when the anode is negative, a negative gate pulse will trigger the device into reverse conduction.

By delaying the application of gate pulses to the triac, conduction is delayed and the front ends of both the positive and negative half-cycles of the sine wave applied

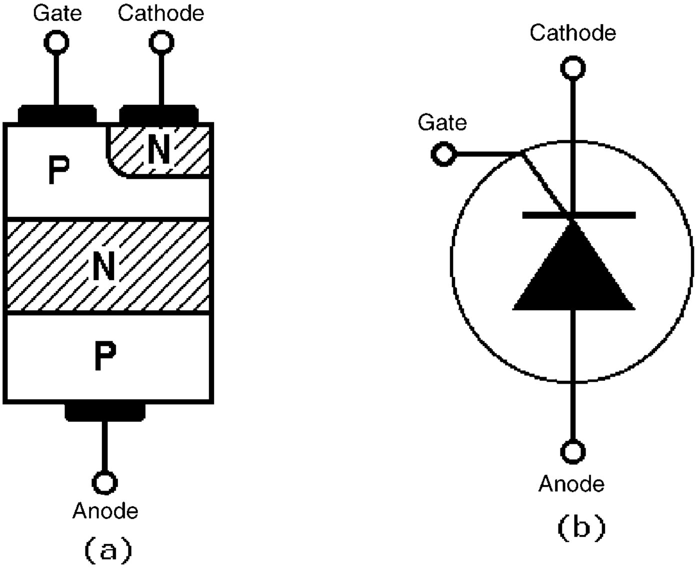


Figure 3-29 Silicon-controlled rectifier (SCR): (*a*) functional diagram; (*b*) schematic symbol.

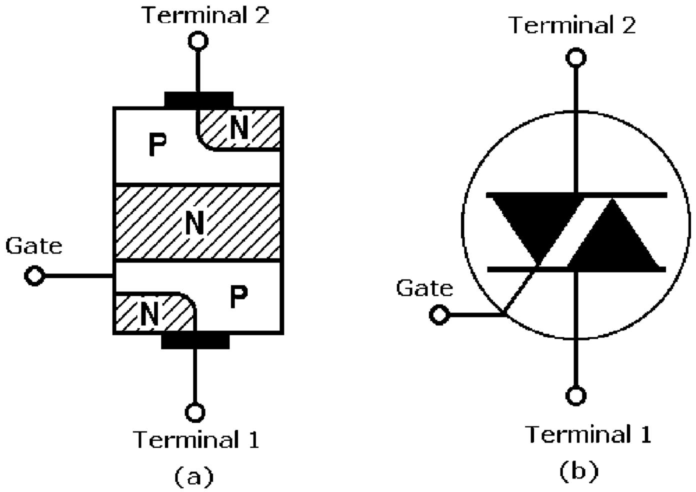


Figure 3-30 Triac: (*a*) functional diagram; (*b*) schematic symbol.

to the triac are “chopped” or removed. This results in a narrower series of positive and negative half-cycle waveforms, which reduce both anode-to-cathode current and power to the load. This is the characteristic that permits triacs to dim incandescent lamps and control AC and DC motor and fan speed. Gate pulse delay can reduce load current from 95 to 5 percent of its full value.

Silicon controlled switches A silicon controlled switch (SCS) is a low-current SCR with two gate terminals: *anode* and *cathode.* A negative pulse on the anode gate turns the SCS ON, and a positive pulse on that gate turns it OFF. However, a positive pulse on the cathode gate can also switch the SCS ON, but a negative pulse on that gate is required to turn it OFF.

4

SUBSTATIONS AND ELECTRICAL DISTRIBUTION

CONTENTS AT A GLANCE

Overview
Distribution Substations
Primary Distribution Systems
Secondary Distribution Systems
Monitoring Distribution Systems
Local Distribution
Connection Systems
Underground Distribution Systems
Underground Distribution Cables
Overhead Distribution Connections

Overview

A block diagram of an independent power generation, transmission, and distribution system is shown in Fig. 4-1. Completely self-contained public power systems no longer exist. They are now connected to power grids that cover most of the United States and extend into parts of Canada and Mexico. They permit the interchange of electrical energy from many different power sources. Following electric power deregulation, electrical energy is now becoming more of a commodity that can be bought and sold on the open market. Moreover, the ownership of many power generation plants in North America is now being consolidated in corporations that specialize in that activity.

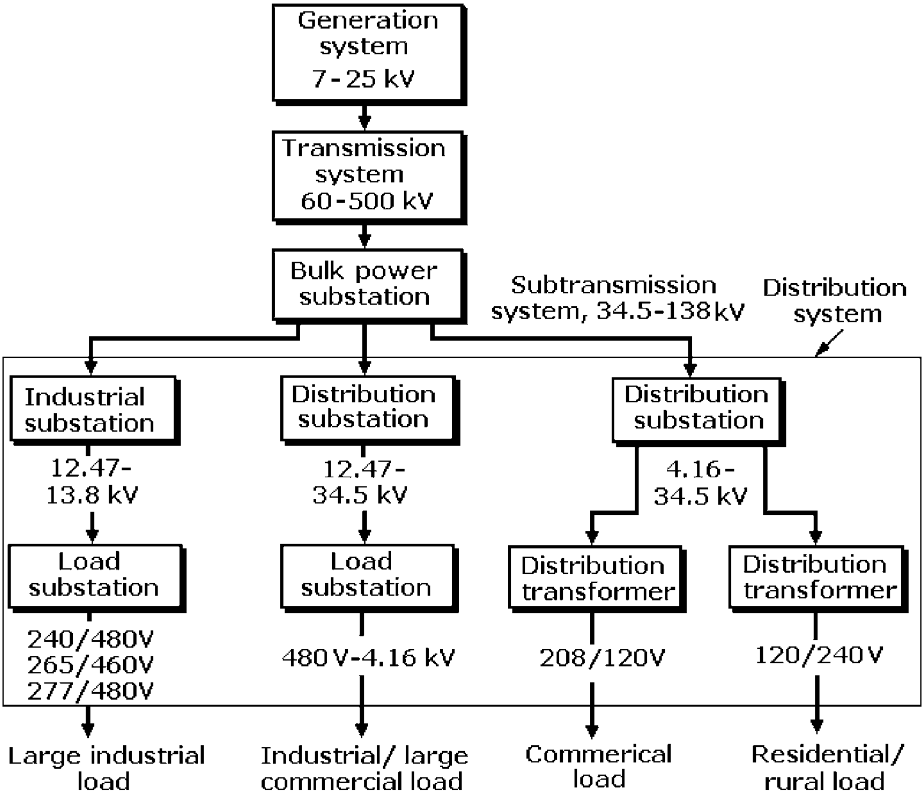


Figure 4-1 Simplified diagram of a power system from generation to distibution.

As a result, most public electric power utilities are predominately power distribution companies. However, public utilities still own their own generation plants, which are capable of meeting routine customer demand when supplemented by purchased power, particularly in periods of heavy demand. Public utilities are free to purchase electrical power when and where it is needed to add to any existing capacity. Local power utilities typically purchase power from bulk sources if it is cheaper than the cost of generating it themselves. Power from the grid can make up for losses in local generation capability during power station maintenance or as a result of disruptions caused by storms, fires, or floods.

In the past, electric utilities invested 30 to 50 percent of their equipment budgets in distribution equipment. With more power generation facilities being consolidated in the hands of national power generation corporations or brokers, shareholder-owned public utilities have been increasing the shares of their budgets for distribution equipment, operation, and maintenance. They now put more emphasis on meeting specific customer voltage requirements and improving the reliability of their service.

The blocks in Fig. 4-1 representing the generation and transmission systems and the bulk power substation were discussed in Chap. 2. This chapter focuses on the distribution system, also called the *subtransmission system.* In this system high-voltage electrical energy from the bulk power substation is stepped down by distribution substations for local transmission at lower voltages to serve the local customer base.

Distribution Substations

Distribution substations serve a wide range of private and public customers in distributing electric power. They can be shareholder, cooperatively, privately, and government owned. All substations contain power transformers and the voltage-regulating apparatus required for converting the high incoming subtransmission voltages to lower *primary system voltages* and maintaining them within specified voltage tolerances. Those voltages, typically 11 to 15 kV, are then sent to distribution transformers and load substations for serving regional and local customers.

Substations serve many purposes, including connecting generators, transmission or distribution lines, and loads to each other and generally stepping higher voltages down to lower voltages to meet specific customer requirements. They can also interconnect and switch alternative sources of power and control system voltage and power flow. Power factor can be corrected and overvoltage can be regulated by substations. In addition, instruments in substations measure power, detect faults, and monitor and record system operational information.

The basic equipment in substations includes transformers, circuit breakers, disconnect switches, bus bars, shunt reactors, power factor correction capacitors, lightning arresters, instrumentation, control devices, and other protective apparatus related to the specific functions in the power station.

Circuit breakers and other switching equipment in a substation can be organized to separate a bus, part of a transformer, or a control device from other equipment. The common system switching arrangements are shown in the one-line diagrams in Fig. 4-2. In these diagrams connections are indicated by arrowheads, switches by offset lines, and circuit breakers by boxes.

The single-bus switching system in Fig. 4-2*a* is bus protected by the circuit breakers on the incoming and outgoing lines. The double-bus system in Fig. 4-2*b* has two main buses, but only one is normally in operation; the other is a reserve bus. The ring bus in Fig. 4-2*e* has the bus arranged in a loop with breakers placed so that the opening of one breaker does not interrupt the power through the substation.

A typical distribution system consists of

- *Subtransmission circuits,* which carry voltages ranging from 12.47 to 245 kV (of these, 69, 115, and 138 kV are most common) for delivering electrical energy to the various distribution substations.
- *Three-phase primary circuits* or *feeders,* which typically operate in the range of 4.16 to 34.5 kV (11 to 15 kV being most common) for supplying the load in designated areas.

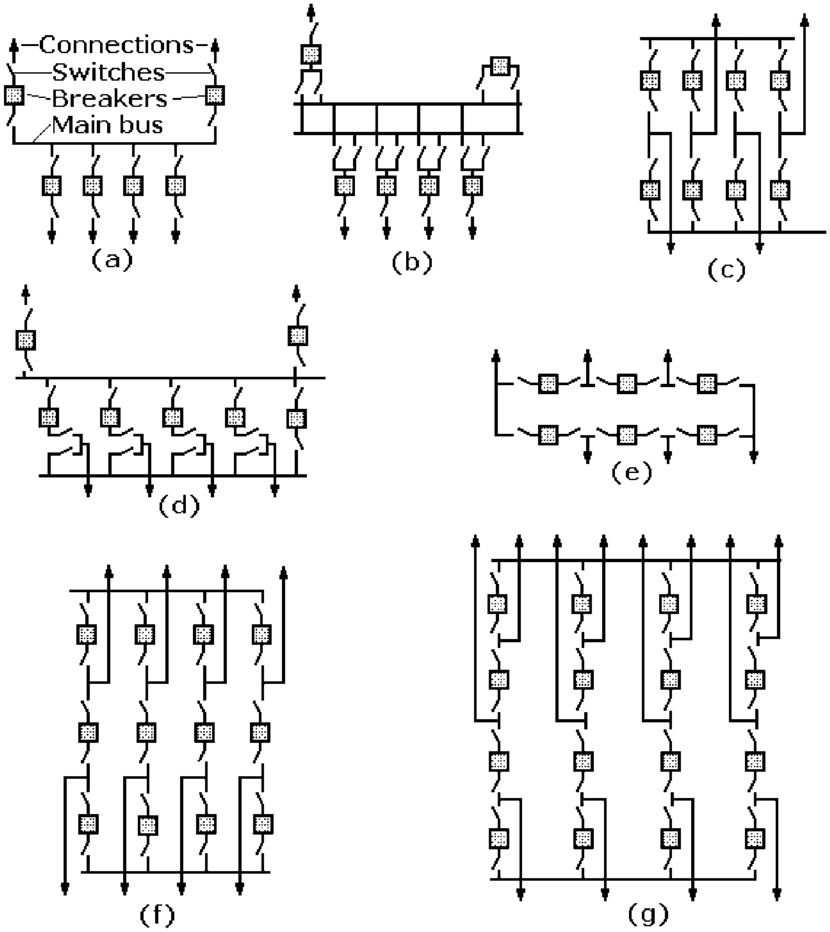


Figure 4-2 **One-line diagrams of substation switching arrangements: (*a*) single bus; (*b*) double bus, single breaker; (*c*) double bus, double breaker; (*d*) main and transfer bus; (*e*) ring bus; (*f*) breaker-and-a-half; (*g*) breaker-and-a-third.**

- *Distribution transformers* rated from 10 to 2500 kVA, installed on poles, on aboveground pads, or in underground vaults near customers. These transformers convert primary voltage to useful voltages for practical applications.
- *Secondary circuits* at useful voltage levels, which carry the energy from the distribution transformers along highways, streets, or rights-of-way. These can be either single- or three-phase lines.
- *Service drops* and *service laterals,* which deliver energy from the secondary circuits to the user's service entrance equipment.

Power is switched from the substation transformers as shown in Fig. 4-1 to separate distribution buses. In some systems the buses distribute power to two separate sets of distribution lines at two different voltages. Smaller transformers connected to the bus step the power down to a standard single-phase line voltage of about 7.2 kV for residential and rural loads, while power from larger transformers can leave in another direction at the higher three-phase voltages to serve large industrial and commercial loads.

SUBSTATION EQUIPMENT

Substation transformers have laminated steel cores and are built with isolated primary and secondary windings to permit the transfer of power from the primary side to the secondary side at different voltages. These transformers typically range in size from small units rated for 1 MVA to large units rated for 2000 MVA.

Most of these transformers are insulated and cooled with oil, making them vulnerable to fire. Adequate precautions must be taken to minimize the possibility of fire and to extinguish any fires that occur as rapidly as possible. In addition to the installation of fire extinguishers, they are located at safe distances from other equipment and positioned in pits to contain any oil leakage. Additionally, fire walls might be built between them.

Substation circuit breakers capable of interrupting the highest fault currents are installed in substations. They are typically rated for 20 to 50 times the normal current and are built to withstand high voltage surges that occur after interruption. Switches rated only for normal load interruption are called *load-break switches.*

Disconnect switches have isolation and connection capability but lack current interruption capability.

Bus bars make connections between substation equipment. Flexible conductor buses connect insulators, but rigid buses, typically hollow aluminum alloy tubes, are installed on insulators in air or in gas-enclosed cylindrical pipes.

Shunt reactors compensate for line capacitance in long lines, and *shunt capacitors* compensate for the inductive components of the load current.

Current and *potential transformers* are used to measure currents and voltages, and they provide low-level currents and voltages at ground potential for control and protection.

Control and protective devices include protective relays that can detect faults rapidly in substation equipment and lines, identify their locations, and provide appropriate signals for opening circuit breakers. They also include equipment for controlling voltage and current and selecting optimum system configurations for the load conditions. Included in this category are fault-logging and metering instruments, internal and external communications equipment, and auxiliary power supplies.

Solid-state digital instruments containing microprocessors have replaced many of the earlier-generation analog moving-coil instruments. Most substations are fully automated yet have provision for manual override. Essential status information is transmitted via communications channels to the central office dispatcher and can be displayed on video terminals.

POWER DISTRIBUTION

Power can leave a typical substation in sets of three wires, each headed down the distribution network in a different direction. Three wires at the top of the poles are required for three-phase power, and a fourth or neutral/ground wire is usually positioned lower down on the utility pole.

Homes and small businesses (offices and stores) usually need only one of the three phases, so those requirements are met by tapping single-phase power from the three-phase transmission lines for distribution on individual conductors, at about 7.2 kV. The second wire, positioned lower on the utility pole, is the neutral/ground wire. In some locations two single-phase conductors and a neutral/ground wire are carried on the same pole. One of those phases serves nearby homes and offices, while the second phase continues on as an individual conductor to serve more distant loads.

In most newer residential subdivisions the single-phase power line is brought down from a pole near the entrance to the subdivision to pad-mounted transformers for underground distribution to homes. However, underground service has been provided for cities for many years in an effort to eliminate the jumble of poles and wires.

Voltage regulators are located along the routes of both overhead and underground power lines to regulate the voltage on the line, preventing undervoltage or overvoltage conditions. These regulators contain switches that allow them to be disconnected for maintenance. Regulator voltage is also typically about 7.2 kV.

Substation voltage is controlled with tap changers on the distribution substation transformers, but some require separate voltage-regulating transformers, individual feeder-voltage regulators, or induction voltage regulators. Most distribution substations perform metering, relaying, and power control automatically. The main units of equipment to be controlled are the feeder circuit breakers if the substation includes them. Metering is required to provide consumption data for billing customers if the power provider does not own the distribution system.

The American National Standards Institute (ANSI) has defined the voltage range for single-phase residential users as 114/228 V to 126/252 V at the user's service entrance and 110/220 V to 126/252 V where it is being used. The difference in these values recognizes that there will be a voltage drop in the consumer's system. Nominal voltage in the United States and Canada is 120/240 V, 60 Hz.

Dips in voltage large enough to cause incandescent lamps to flicker are expected to be limited to 4 to 6 percent if they occur infrequently and 3 to 4 percent if they occur several times an hour. Frequent dips caused by the start-up of large electrical machines such as motors or elevators should be limited to 1.5 or 2 percent.

Primary Distribution Systems

The primary distribution system is that part of the electric distribution system between the distribution substation and distribution transformers. It is made up of circuits called *primary feeders* or *distribution feeders.* These feeders include the *primary feeder main* or *main feeder,* usually a three-phase, four-wire circuit, and *branches* or *laterals,* which can be either three-phase or single-phase circuits. These are tapped from the primary feeder main, as shown in the simplified distribution

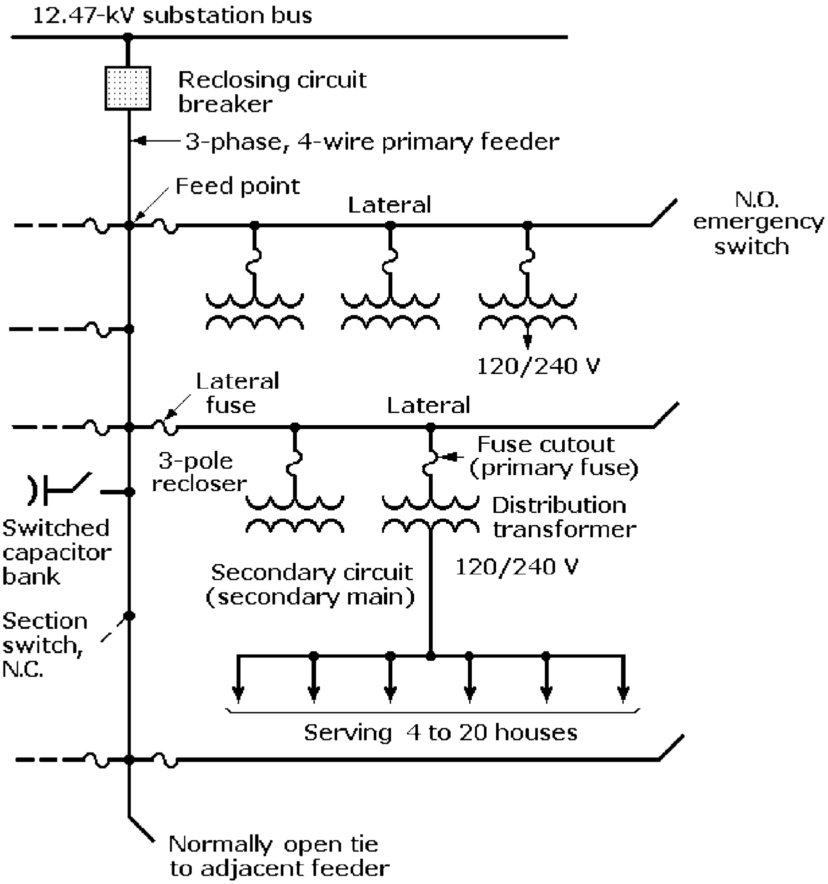


Figure 4-3 Simplified diagram of a power distribution feeder.

feeder diagram of Fig. 4-3. A typical power distribution feeder provides power for both primary and secondary circuits.

In primary system circuits, three-phase, four-wire, multigrounded common-neutral systems, such as 12.47Y/7.2 kV, 24.9Y/14.4 kV, and 34.5Y/19.92 kV, are used almost exclusively. The fourth wire of these Y-connected systems is the neutral, grounded at many locations for both primary and secondary circuits. Single-phase loads are served by distribution transformers with primary windings that are connected between a phase conductor and the neutral. Three-phase loads can be supplied by three-phase distribution transformers or by single-phase transformers connected to form a three-phase bank. Primary systems typically operate in the 15-kV range, but higher voltages are gaining acceptance.

The primary feeder main is usually sectionalized by reclosing devices positioned at various locations along the feeder. This arrangement minimizes the extent of primary circuitry that is taken out of service if a fault occurs. Thus the reclosing of these devices confines the outage to the smallest number of customers possible. This can be achieved by coordinating all the fuses and reclosers on the primary feeder main.

In block diagram Fig. 4.3, distribution substation voltage is 12.47 kV line-to-line and 7.2 kV line-to-neutral (this is conventionally written as 12,470Y/7200 V). However, the trend is toward higher primary four-wire distribution voltages in the 25- to 35-kV range. Single-phase feeders such as those serving residential areas are connected line-to-neutral on the four-wire systems.

The use of underground primary feeders that are radial three-conductor cables is increasing. They are serving urban areas where load demand is heavy, particularly during the hot summer months, and newer suburban residential developments.

Both cost factors and the importance of reliability to the customers being served influence the design of primary systems. The simplest and least expensive (as well as least reliable) configuration is the *radial distribution system* shown in Fig. 4-4*a,* because it depends on a single power source. Despite their lower reliability, radial systems remain the most economical and widely used distribution systems for serving homes because an electrical power outage there is less likely to have serious economic or public safety consequences. As a hedge against outages, most utilities plan their distribution systems so that they will have backup if those events occur. The goal of

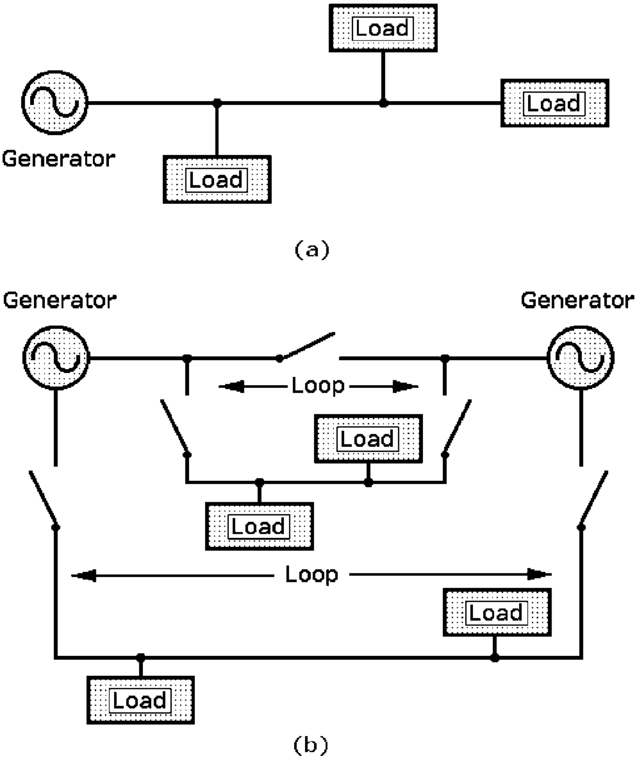


Figure 4-4 Simplified diagrams of the basic electrical distribution systems: (*a*) radial and (*b*) loop.

all electrical distribution systems is the economic and safe delivery of adequate electric power to serve the electrical loads.

The reliability of the primary feeder can be improved with the installation of a *loop distribution system,* as shown in Fig. 4-4*b.* In loop systems the feeder, which originates at one bulk power source, "loops" through the service area and several substations before terminating at the original substation or another bulk source. The strategic placement of switches at the substations permits the electric utility to supply customers in either direction. If one power source fails, switches are opened or closed to bring an alternative power source online.

Loop systems provide better service continuity than radial systems, with only short service interruptions during switching. However, they are more expensive than radial systems because of the additional switching equipment requirements. As a result, loop systems are usually built to serve commercial and light industrial buildings and shopping malls, where power outages are more likely to endanger human lives or result in property losses.

Reliability and service quality can be significantly improved at even higher cost with a *multiple parallel circuit pattern.* In these systems, two or more circuits are tapped at each substation. The circuits can be radial or they can terminate in a second bulk power source. These interconnections permit each circuit to be supplied by many different substations.

Secondary Distribution Systems

The secondary distribution system is that part of the electrical power system between the primary system and the customer's service entrance. This system includes distribution transformers, secondary circuits (secondary mains), customer services (consumer drops), and watthour meters to measure customer power consumption. Secondary voltages are provided by distribution transformers that are connected to the primary system and sized for the voltages required for specific parts of the service area.

Heavy industries or mines, which require the most power, are usually supplied with three-phase power by privately owned or corporate industrial substations. They are typically located on land owned by those companies and close to the equipment being served. These substations are capable of providing a wide range of voltages from the 12.47- to 13.8-kV transformers located there.

Factories, high-rise buildings, shopping centers, and other large power consumers are furnished with three-phase power from load substations in the 480-V to 4.16-kV range. Many commercial and light industrial customers are supplied by 208Y/120-V or 480Y/277-V three-phase, four-wire systems.

The most reliable service in densely populated urban business and commercial areas is provided by grid-type secondary systems at 208Y/120 V or by *spot networks,* usually at 480Y/277 V. Spot networks are usually located in urban areas near high-rise office buildings, factories, hospitals, and dense commercial properties such as shopping malls, which have high load densities. In these networks the transformers and their protective equipment are typically placed adjacent to or within the properties being served.

Secondary network systems are used in about 90 percent of all cities in the United States with populations of 100,000 or more and in one-third of all cities with populations between 25,000 and 100,000. Despite the generally high reliability of these systems, many facilities such as hospitals, computer centers, and chemical or pharmaceutical industries performing critical processes that cannot tolerate power outages have backup power sources. These include standby or emergency generators and/or storage batteries together with automatic switching so that service to critical loads can be maintained if the normal utility supply is interrupted. Some of these facilities have automatic switching that puts alternative utility power sources online without human intervention. This subject is covered in more detail in Chap. 11.

Monitoring Distribution Systems

The components of an electrical power distribution system are vulnerable to the vagaries of storms, fires, and accidents because of their exposed locations and wide dispersion throughout the distribution service area. Power lines can be brought down by ice storms, falling tree branches, or inadvertent severing by excavating machines. Poles can be knocked down by heavy winds or vehicular collisions, and lightning strikes can disable status-monitoring and communications links.

The public expects electric utilities to maintain service near the 100 percent level at all times, even as its dependence on electricity for safety, physical comfort, and preservation of perishables increases. This has put pressure on utilities to improve their methods for locating faults and restoring service rapidly following all outages, regardless of cause.

The response time of electric utilities to faults or outages depends on their ability to identify and locate the source of the problem, determine a solution, and, if necessary, dispatch service crews to make repairs, all in a timely manner.

Electric utilities use different techniques to monitor the status of control components, and new technologies are assisting them in their efforts. "Smart" digital relays are replacing the older-style relays with induction disks, where only their contact positions indicate when a fault occurs that trips a circuit breaker. The digital relays not only monitor the status of the system, they also perform self-diagnosis. With these capabilities, the relay can signal the dispatchers that an equipment defect needs attention. However, an ever-increasing number of relays or indicator lights is required to extend the coverage beyond simply monitoring the tripping of breakers.

New programmable monitoring controllers are being introduced that eliminate the need for large numbers of relays or lights. The controllers can perform comprehensive monitoring of the operational status of all critical control circuits on a continuous basis. The manual and visual checking of components in those critical circuits has long been labor-intensive. The programmable controllers monitor the presence of the proper operating voltages for circuit breakers, the continuity of circuits and device coils, the state of switch contacts, and condition of the sulfur hexafluoride (SF_6) gas supply for arc quenching and insulating circuit breakers.

Local Distribution

Power leaves the substation on three, three-phase "hot" power lines that are strung adjacent to highways or along local roads to points of use. All three phases share a single neutral line and have the same voltage, but they are 120 electrical degrees out of phase with each other, as explained in Chap. 2.

The local electrical utility usually decides where the three-phase and single-phase services are to be located in the area that it serves. Initially dispatched as three phases, the phase lines are separated to feed different localities. The three-phase service for industrial and large commercial customers is separated from the single-phase lines for serving residential, small business, and rural customers.

The nominal 120/240-V power is obtained from transformers strategically located on poles for overhead service and above ground on concrete pads or in underground protective vaults for underground service. Large electrical appliances such as ranges, water heaters, clothes dryers, and air conditioners typically require 240 V, while 120 V meets the needs for lighting, small appliances, TVs, personal computers, and convenience outlets. However, when residences are located in an area served by a 208Y/120-V distributed secondary network, large appliances are powered by 208 V, but lighting, small appliances, entertainment electronics, and outlets are supplied with 120 V.

COMMON POWER SERVICE

Secondary circuits provide electrical power in various forms to satisfy customer demand. These include

- Single-phase, three-wire, 120/240 V
- Three-phase, four-wire, 120/208-V wye-connected
- Three-phase, four-wire 120/240-V delta-connected

The most common distribution wiring configuration for homes, small businesses, and farms is 120/240-V, single-phase service. Figure 4-5 is a schematic diagram of a

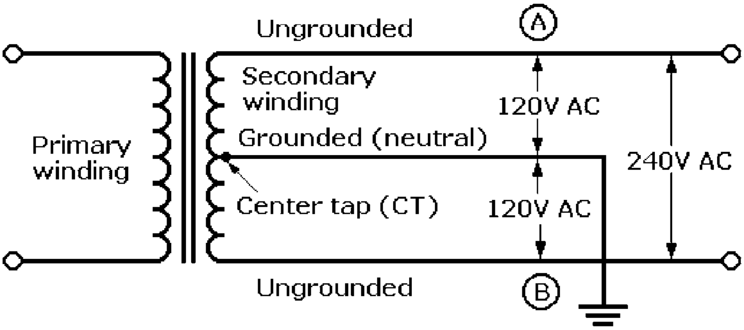


Figure 4-5 Secondary of a single-phase transformer provides 240 V across A and B and 120 V across either A or B and the neutral.

distribution transformer for 120/240-V single-phase service. The 240 V is obtained by making connections between the two ungrounded “hot” conductors, and the 120 V is obtained by making connections between either of the two “hot” ungrounded conductors and the neutral (grounded) conductor.

Connection Systems

WYE-CONNECTED SYSTEMS

Different voltages can be obtained with three-phase, four-wire, 120/208-V wye-connected service, as illustrated in Fig. 4-6. The terminal points of the three windings of a wye-connected transformer are designated A, B, and C. The voltage between any of the points A, B, and C and the neutral (grounded) conductor is 120 V, and the voltage between any two of the points A to B, B to C, or C to A is 208 V. This 208 V is the product of the voltage between any phase and neutral (120 V) and the square root of 3 or 1.732 (120 V × 1.732 = 207.84 V, rounded off to 208 V). Therefore, the following voltages can be obtained from the wye-connected system:

- 120-V, single-phase, two-wire (A to neutral, B to neutral, and C to neutral)
- 208-V, single-phase, two-wire (A to B, B to C, and C to A)
- 208-V, three-phase, three-wire
- 120/208-V, three-phase, four-wire

Another popular wye-connected three-phase, four-wire system is rated at 277/489 V. Feeder and branch circuits connected to this supply can provide

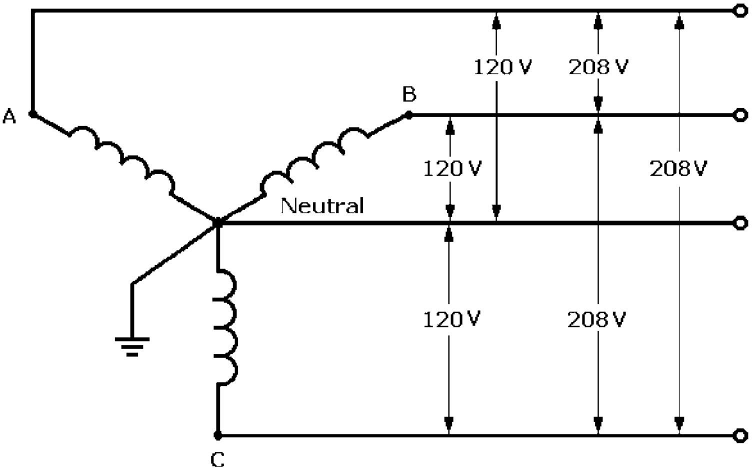


Figure 4-6 A wye-connected, three-phase, four-wire secondary transformer can provide 120- and 208-V AC electric service.

- 277-V, single phase, two-wire
- 480-V, single-phase, two-wire
- 480-V, three-phase, three-wire
- 277/480-V, three-phase, four-wire

DELTA-CONNECTED SYSTEMS

A different set of output voltages can be obtained with the three-phase, four-wire delta-connected transformer secondary as shown in the schematic Fig. 4-7. The three windings are connected in series to form an equilateral triangle or Greek letter Δ. Each of the vertices of the triangle is designated by a letter, A, B, or C, representing one of the three phases that feed the network. The midpoint of the winding between vertices B and C is grounded at neutral point N. The voltage between any two vertices A to B, B to C, and C to A is 240 V. However, the voltage between B and neutral and C and neutral is 120 V, while the voltage between A and neutral is 208 V.

This 208 V is obtained by multiplying the 120 V between either C or B and neutral by the square root of 3 or 1.732 (120 V × 1.732 = 207.84, rounded off to 208 V). Therefore, the following voltages can be obtained from the delta-connected system:

- 120-V, single-phase, two-wire (B to neutral and C to neutral)
- 240-V, single-phase, two-wire (A to B, B to C, and C to A)
- 240-V, three-phase, three-wire
- 120/208-V, three-phase, four-wire

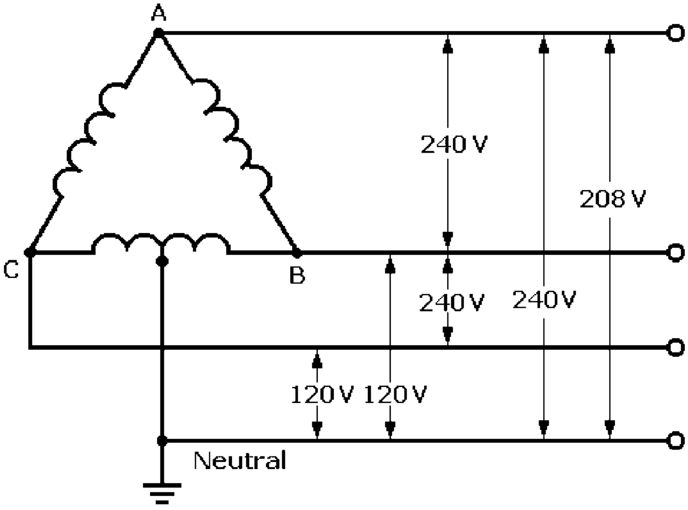


Figure 4-7 A delta-connected, three-phase, four-wire secondary transformer can provide three output voltages: 120, 208, and 240 V AC.

Caution is required when making connections to a three-phase, four-wire transformer secondary because of the potential damage that can be caused by accidentally connecting the "high-leg" A to neutral voltage where the lower voltage is desired.

NEC 2002, Section 215.8, "Means of Identifying Conductor with the Higher Voltage to Ground," states that "On a 4-wire, delta-connected secondary where the midpoint of one phase winding is grounded to supply lighting and similar loads, the phase conductor having the higher voltage to ground shall be identified by an outer (insulation) finish that is orange in color or by tagging (or taping) or other effective means."* The intent of this NEC precautionary requirement is prevent any connections from being made accidentally between A and ground and getting 208 V when the intent was to obtain 120 V from either B or C to ground. Thus the wire from A to ground would have orange insulation or be marked with orange tape or an orange tag.

Underground Distribution Systems

A well-designed distribution system must provide for anticipated load growth that can be accommodated economically. This means that provisions must be made to furnish electrical service to new as well as existing customers.

Both overhead and underground distribution systems have existed in large metropolitan areas for many years, but underground distribution was rarely used in suburban residential areas, small towns, or rural areas because of the high cost of these installations. Overhead distribution was almost universally used in those locations.

However, within the past 20 years low-cost solid dielectric cables suitable for direct burial have been introduced and pad-mounted distribution transformers and accessories have been mass-produced, reducing their cost. These developments, along with the introduction of trenching machines for the mechanizing the burial of cable, have made underground residential distribution (URD) more affordable.

Despite these reductions, the cost of a typical URD system for a new residential subdivision can be as much as 50 percent greater than that for an overhead system in locations where the soil conditions are unfavorable for cable burial. On the other hand, where the land is dry, relatively treeless, and with few or no underground rocks, the cost gap between the two technologies has narrowed. It is believed that this cost gap between URD and overhead service will shrink even further because of the falling prices of the equipment due to increasing demand.

Studies have shown that both builders and homeowners will accept a reasonable cost differential because of the recognized improvements made in residential landscaping as a result of eliminating overhead wires and poles. It has been estimated that 70 percent of new residences are being served by URDs. Moreover, some states have passed legislation making underground distribution mandatory for new residential subdivisions because of the improvements in the appearance of the new developments.

---

* Reprinted with permission from NFPA 70-2002, National Electrical Code®, copyright © 2001, National Fire Protection Association, Quincy, Mass. 02269. This and other reprinted material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Most of the widely used underground distribution systems in densely populated parts of North American cities are secondary systems with cables installed in conduit or ducts beneath the streets and sidewalks. The conductors for primary voltages of 5 to 35 kV are typically paper-insulated, lead-covered (PILC) cable. Single-conductor secondary cables for both primary and secondary circuits typically have rubber insulation and neoprene jackets for conducting up to 34 kV, but single-conductor, polyethylene-insulated cable is gaining in popularity.

While copper predominated as the conductor of choice in the past, aluminum as a conductor in cable is gaining in popularity for new installations. However, because of its larger diameter than cable with copper wires, cable with aluminum wires is not usually used if it is anticipated that it must share the limited internal space of a conduit with other cables in the future.

Underground Distribution Cables

In suburban areas, underground distribution systems serve shopping centers and commercial and industrial parks. The conductors for this service are typically direct-buried cables, but they are usually run in conduits or ducts when passing under streets, sidewalks, or other paved surfaces. If the cable must be removed later for replacement or repair, it would be costly and labor intensive, to say nothing of inconvenient, if it had to be dug out by breaking up concrete slabs or pavement. Aluminum conductors predominate in these newer installations. For primary cables, the insulation most widely used is solid dielectric cross-linked polyethylene and ethylene-propylene rubber (EPR), also known as ethylene-propylene monomer (EPM).

Concentric neutral wires have become common. Secondary cables in these applications are constructed of similar material, and aluminum conductors with cross-linked polyethylene insulation are most common. The neutral in this secondary cable is typically an insulated conductor, but bare copper neutrals are also being used.

In distribution systems for 5 kV or higher, the cables are usually shielded with conducting or semiconducting materials that cover the cable insulation to confine the electric field to the insulation. This shielding can be outside the cable insulation, directly over the main conductor, or both.

Outside shielding, typically done with wound metal tape, a metal sheath, or concentric wires, must be grounded. This shielding provides a return path for short-circuit current if the cable fails, while also protecting installers from shock. Underground cables can be separately insulated single- as well as two-, three-, and four-conductor, enclosed by a single sheath or jacket.

NEC UNDERGROUND INSTALLATION REQUIREMENTS

NEC 2002 Sections 300.5, "Underground Installations," and 310.7, "Direct Burial Conductors," cover the requirements for various aspects of underground installations. Section 300.5, for example, discusses minimum cover requirements, grounding, underground cables under buildings, and protection (of conductors) from damage. Section 310.7 gives the requirements for direct-burial conductors. It states that "Cables rated above 2000 V shall be shielded," but it also gives some exceptions. This section also states that "The metallic shield, sheath, or armor shall be grounded through an effective grounding path meeting the requirements of NEC 2002 250.4(A)(5) or 250.4(B)(4)."

DIRECT-BURIAL CONDUCTORS

Type USE cable (underground service entrance) is approved for direct burial in the earth because its moisture-resistant jacket does not require any additional protective cover. Single-conductor USE cable as well as parallel or cabled conductor assemblies can include bare copper conductors. These assemblies do not require outer overall jackets. USE cable can be used for underground services, feeders, subfeeders, and branch circuits.

Type UF cable (underground feeder and branch circuit) is also approved for direct burial in the earth. It includes copper conductors sized from No. 14 AWG through No. 4/0. The jackets of type UF cable are flame-retardant and moisture-, fungus-, and corrosion-resistant. This cable is approved for direct earth burial as feeders or branch circuits if it meets the rated ampacity overcurrent protection requirements of the NEC.

Type MC and *type MI cable* are approved for direct burial under certain conditions.

CABLE BURIAL INSTRUCTIONS

Where single-conductor cables are to be installed, all cables of the feeder circuit, subfeeder circuit, or branch circuit (including the neutral and equipment grounding conductors, if any) must be run together in the same trench or raceway.

Nonmetallic-armored cable can also be used in underground installations. Its interlocking armor consists of a single strip of interlocking tape that extends the length of the cable. The round surface of the cable allows it to resist inadvertent blows from trenching tools better than flat-bend armored cable. The cable must have an outer covering that will not corrode or rot. A covering of asphalt-jute can be used as cable covering if the cable is to be exposed to particularly corrosive chemicals such as gasoline.

Cables approved for direct burial range from single-conductor insulated wires for low-voltage applications to multiconductor cables for conducting electrical energy, communications, or alarm signals. In direct-burial methods, the conductors are buried in the ground by placing them at the bottom of an excavated trench, which is later backfilled. Where soil conditions and circuit configurations are favorable, the cable can be buried directly with a special machine called a *cable plow.* It breaks the earth ahead of the cables, guides them into the furrow, and immediately backfills the furrow over the cable.

DIGGING THE CABLE TRENCH

The methods for installing direct-burial cable vary according to the length and the size of the cable being installed and the soil conditions. For short runs such as those from a residential basement to a garage located about 20 ft away, the excavation can be made manually; but for longer runs, trenching machines or backhoes are usually hired to perform the work faster and more economically.

After digging the trench to a depth at least 3 to 4 in. beyond the minimum depth specified by NEC 2002 Table 300.5, "Minimum Cover Requirements, 0 to 600 Volts," all sharp rocks, roots, and extraneous solid objects should be removed from the trench to prevent them from damaging the direct-burial cable.

MINIMUM COVER REQUIREMENTS

According to NEC 2002, Article 300.5, all underground installations must be grounded and bonded in accordance with Article 250, and underground cable installed under a building must be in a raceway that extends beyond the outside walls of the building. The article further states that direct-buried conductor and cable shall be protected by enclosures or raceways (including conduit) under the following conditions:

- *Emerging from grade* from the minimum cover distance to a point at least 8 ft above finished grade. The protection required need not exceed 18 in. below finished grade.
- *Conductors entering buildings* must be protected to the point of entrance.
- *Underground service conductors* not encased in concrete that are buried at least 18 in. below grade must have their location identified by a warning ribbon that is placed in the trench at least 12 in. above the conductors.
- *Conductors and cables subject to damage* must be installed in approved metal or nonmetallic conduit.
- *Listing:* Cables and insulated conductors installed in enclosures or raceways in underground installations must be approved for wet locations.

Figure 4-8 is a cross-sectional view of a trench with two direct-burial cables installed. NEC 2002, Table 300.5, defines five different types of buried cable and wiring situations:

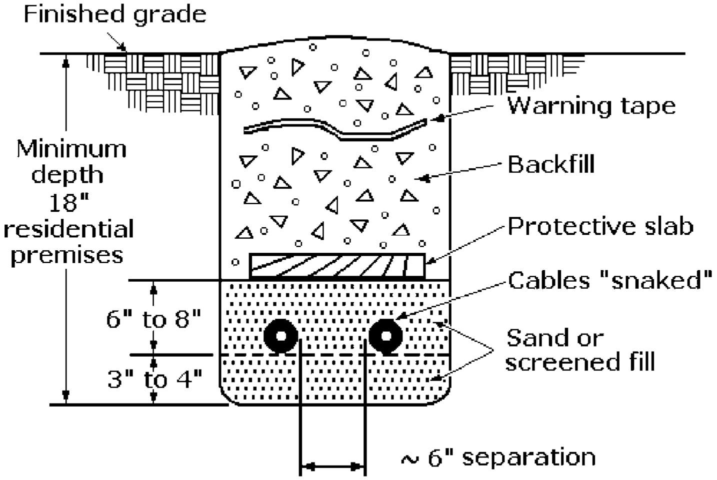


Figure 4-8 Section view of a trench containing direct-burial cables in nonresidential areas.

1. Direct-burial cables or conductors
2. Rigid or intermediate metal conduit
3. Nonmetallic raceways for direct burial without concrete encasement
4. Residential branch circuits rated 120 V or less with GFCI and overcurrent protection
5. Low-voltage circuits for irrigation or lighting

The table also gives seven different locations of wiring or circuits, of which five are

1. In a trench under a 2-in. concrete slab
2. Under a building
3. Under a concrete slab at least 4 in. thick
4. Under streets, highways, roads, alleys, driveways, and parking lots
5. Under residential driveways

In general, burial depths range from a 4 in. for all categories under 4-in.-thick concrete slabs to 24 in. for direct-burial cable in unspecified locations. For example, direct-burial cables and conductors must be buried at least 18 in. deep under residential driveways, but GFCI- and overcurrent-protected 120-V or less residential branch circuits must be buried at least 12 in.

After the trench is dug deeper than the minimum depth requirements, a 3- to 4-in. bed of sand should be placed at the bottom of the trench to protect the cable from sharp stones that might still be at the bottom of the trench. The cable or cables should then be placed in the trench without crossovers and slightly "snaked," to allow enough slack for earth settlement, movement, or heaving due to frost action. Single conductor cables should be kept uniformly apart by about 6 in. along the length of the trench.

After the cable is laid in the trench, another 3-in. layer of sand or sifted backfill should cover the cables. Then a treated wooden plank or concrete slab, wide enough to cover the cables, should be placed over them to protect the cables from any future excavations. The trench is then backfilled another 12 in. (if depth permits). A colored plastic ribbon should then be placed in the trench before completing the backfilling, to warn future excavators that electrical conductors are buried underneath.

MANHOLES

A cross-sectional view of a typical electrical manhole is shown in Fig. 4-9. The base ring or square is positioned at the bottom of the excavation, and the conical or pyramidal throat is placed on top of the base with its opening at ground or finished-grade level.

Manholes are sized to provide enough room for installers and maintenance personnel to splice cables or mount equipment as well as carry out routine inspections. There are rules for dimension of access openings and other features of electrical manholes.

- *Round access:* If the manhole is round and it contains only power cables, the diameter must not be less than 26 in.
- *Round access:* If the manhole is round and it contains a fixed ladder that does not obstruct the opening or it contains optical fiber cables, fire alarm circuits, or remote control or signaling circuits, the diameter must not be less than 24 in.

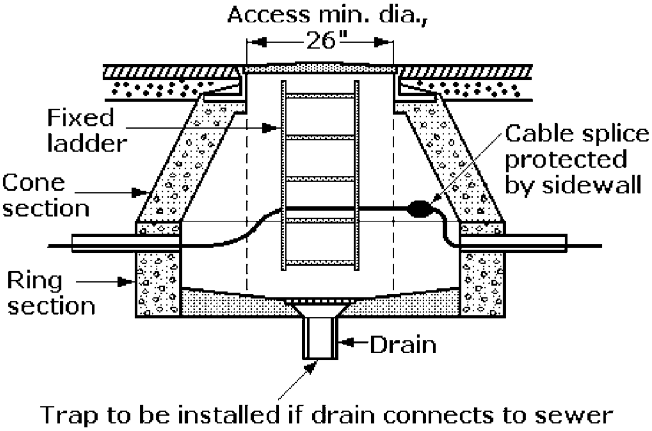


Figure 4-9 **Section view of a typical power cable manhole.**

- *Rectangular access:* If the opening in the manhole is rectangular, it must not be less than 26 × 22 in.
- *Slope:* The slope of the sidewalls must be sufficient to provide protection for cable splices or other installed equipment so they will not be directly under the opening.
- *Drain:* The drain must be located centrally under the opening.
- *Traps:* Where water drainage will go into sewers, suitable traps or other means must be provided to prevent the entry of sewer gas into the manhole.

Manholes for underground electrical distribution are separated by distances in an underground duct system that are short enough to permit pulling conductors or cables between them during initial construction. They also permit access to the conductors or cables for testing, cable replacement, and maintenance. Access to manholes is gained through openings or throats extending from the manhole cavity to the surface (ground level or finished grade). At ground level a heavy, durable manhole cover is used to close the manhole securely.

Underground cable runs normally terminate inside a manhole, where there is sufficient room for them to be spliced to another length of cable. Manholes can be constructed manually from bricks and mortar, but today most of them are prefabricated from reinforced concrete in two parts: a base ring or base square section and a conical or pyramidal throat.

There are three basic designs for electrical/communications manholes: two-way, three-way, and four-way.

- *Two-way manhole:* Ducts and cables enter this manhole from one side and leave from the other side, 180° away.
- *Three-way manhole:* Same as for a two-way manhole, except that a third duct for cables leaves the manhole 90° away the other two ducts.
- *Four-way manhole:* It has two entry ducts and two leaving ducts, all 90° apart.

A cross-sectional view of a typical underground duct system linking two two-way manholes is shown in Fig. 4-10. The ductwork should be arranged so that it slopes

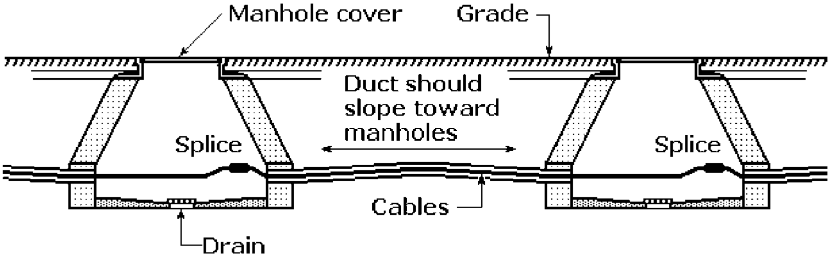


Figure 4-10 Section view of a typical underground duct system.

toward the manhole, so that water cannot accumulate in the ducts. Underground duct systems typically include manholes, handholes, transformer vaults, and risers.

DUCTS AND DUCT BANKS

In electrical construction work, a *duct* is a single enclosed raceway through which conductors or cables are pulled. One or more ducts in a single trench is usually called a *duct bank.* A duct system provides a protected passageway for power lines, fiberoptic cables, and telephone and other kinds of communications cables, or both. A duct bank can usually be placed in a trench and covered with earth or further enclosed in concrete.

Ducts for underground electrical systems can be made of fiber, vitrified tile, metal, plastic, or concrete. The cross sections of four electrical ducts banks with one, four, six, and nine electrical ducts are shown in Fig. 4-11. The drawings are based on NEC 2002, Figure 310.60, "Cable installation dimensions." There is uniform spacing or 7.5 in. horizontally and vertically between all of the ducts shown.

The inside diameter of ducts for specific applications is determined by the size of the cables that will be installed in them. Inside diameters of 2 to 6 in. are most common.

Fiber duct is made from wood pulp bonded with adhesives to make a lightweight, low-cost raceway that resists rotting. These ducts can be enclosed in a concrete envelope if at least a 3-in. thickness of concrete surrounds it on all sides. The smooth interior walls of fiber duct lengths makes it easy to pull cable through them.

Vitrified clay duct, also called *hollow brick,* is used principally in underground systems for low-voltage (under 600-V) conductors and communication cables. These ducts are recommended where runs must be routed around underground obstacles, because their lengths are shorter than ducts made from other materials so it is easier to make direction changes with them. Four-duct banks are most common, but clay banks with as many as 16 ducts are available. Square conduits are typically $3^1/_2$ in. square, but round conduit diameters vary from $3^1/_2$ to $4^1/_2$ in.

Metal conduit is more expensive to install than other underground ducts, but it provides better protection than many other ducts, especially against later trench digging.

Plastic conduit is made from polyvinyl chloride (PVC), polyethylene (PE), or styrene. Because it is made in lengths up to 30 ft, fewer couplings are needed than for most other duct systems.

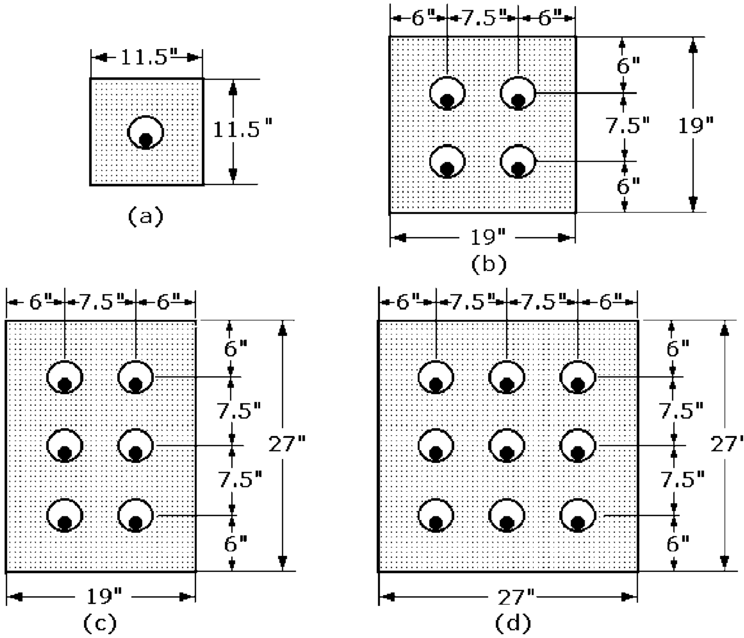


Figure 4-11 Electrical duct banks for (*a*) one duct, (*b*) four ducts, (*c*) six ducts, and (*d*) nine ducts. Duct bank *c* can also be positioned horizontally.

Monolithic concrete ducts are typically poured at the job site. Multiple ducts can be custom-formed by setting up straight or curved bonded plastic impregnated paper tube cores within the forms prior to pouring the concrete. The cores can be removed after the concrete has set. Either way, the ducts have smooth interiors. This duct is recommended where there are to be curves or bends in the duct system.

Cable-in-duct is a popular assembly that can be installed rapidly at low cost because it is not necessary to pull cable through the ducts. Both the duct and the cable inside it can be shipped on a reel for ease in installation. If the cable should become defective, it can be removed and replaced by new cable as in any other duct system.

DUCT INSTALLATION

Soil conditions and voltage levels dictate whether concrete encasement is required in any underground duct system. If the soil is not firm, unsupported vertical trench walls are likely to collapse. Therefore, the trench must be made wide enough to accommodate the ductwork at the specified depth, and concrete encasement is mandatory. Ductlines that are unable to withstand the pressure of earth backfill must be supported.

However, if the soil is firm enough to permit trenching vertical sidewalls to the depth required and concrete encasement is still desired or specified, the trench need only be wide enough for the ducts and their concrete envelope. The concrete is then poured between the conduit and the earth walls. Where the soil is only marginally firm or exhibits variations in firmness and concrete encasement is required, the trench should be dug 3 in. wider on each side of the duct bank, to provide space for the concrete forms.

Ducts can be classified in several different ways, but for power distribution, each duct should have at least one side exposed to earth or the outside of the concrete envelope. Therefore, in laying out underground power distribution ducts the banks should be restricted to either two conduit widths or two conduit depths. This permits heat generated by the transmitted power to radiate or be conducted into the surrounding earth.

Power ducts should not be surrounded by ducts for other kinds of wires or cables. For example, the inner duct of a nine-duct bank is called a *dead duct* because heat from any cables in this duct is not dissipated as fast as it would be from the eight surrounding ducts, making it unsuitable for any power cable. However, dead ducts can be used for street light wiring or control or communications cable, because the heat emitted by these cables is relatively low. Low-heat-emitting cables can be arranged in any bank configuration.

BENDING SPACE FOR CONDUCTORS

Section 314.54 of NEC 2002, “Bending Space for Conductors,” covers bending space for conductors operating at 600 V or below. Section 314.71(A), “For Straight Pulls,” covers the size of pull and junction boxes, stating that “The length of the box shall not be less than 48 times the outside diameter, over sheath, of the largest shielded or lead-covered cable entering the box.” It adds, “The length shall not be less than 32 times the outside diameter of the largest non-shielded conductor or cable.” Section 314.71(B), “For Angle or U Pulls,” states distance requirements between cable or conductor entry inside the box and the opposite wall of the box and the distance between a cable or conductor entry and its exit from the box.

Overhead Distribution Connections

Although overhead distribution is losing favor in residential areas, it is still widely used in many parts of the country, particularly in towns and rural areas. Nevertheless, overhead distribution still has many economic and technical advantages.

- Old or faulty transformers on existing poles can easily be replaced and new transformers can be added on existing poles with minimum service interruption.
- New poles can be added to extend existing service, and poles can be moved to accommodate the widening of old roads or the addition of new ones.
- Maintenance of overhead transformers and cables is easier and less costly than it is for pad-mounted transformers and underground cables.
- If local power requirements are to be upgraded, changes in cables and insulators are more easily accomplished. (By contrast, the entire underground cable system might have to be replaced to be upgraded.)

OVERHEAD DISTRIBUTION CABLE AND CLEARANCE

Service drops are cables from pole-mounted overhead distribution transformers to the customer's premises, and *service laterals* are the underground cables from pad-mounted distribution transformers to the customer's premises. These terminate the local power company's distribution network. The power company is, however, obligated to pull the cables to the designated service points or points of attachment on homes or buildings and make the splices either to the overhead or underground service entrance conductors.

The builder or electrical contractor must establish these entry points according to specifications issued by the power utility. These are available to the electrical contractor as written documents that conform to the NEC. However, the utility specifications and local building codes can be more restrictive than the NEC requirements.

The installation of an overhead service drop is more complex than the installation of a service lateral because the connection point must be high enough above the grade to allow the minimum clearance distances specified by the power utility. Figure 4-12*a* on p.132 illustrates minimum clearance distances of the service drop.

The location of the service point must be calculated so that it will be high enough to provide the minimum clearance distances between the estimated cable droop and the various ground or structural surfaces. The service point can be an anchor bolt driven into the outside wall of most two-story buildings, but single-story structures typically require the installation of a rigid steel pipe mast to meet the clearance requirements.

The power company will string the service drop from the pole to the service point and fasten it to the anchor bolt and insulator installed by the electrical contractor. This is described in detail in Chap. 5.

The following statements supplement the information given graphically in Fig. 4-12*a*.

- The service point shall not be less than 12 ft above grade or greater than 21 ft, unless approved in writing.
- All service connections must be reachable from a ladder placed on the ground, so their placement above roofs of garages or other building extensions is not allowed.
- There shall be 2-ft minimum clearances between power cables and lateral telephone lines and TV cables.
- A 3-ft clearance is required from the service drop connections to all windows, doors, and mountings on the building wall if a pipe mast is not used.
- Add 6 in. to all clearances for any open wire construction.

Figure 4-12*b* illustrates the specialized service drop clearances over swimming pools and fountains or spas (hot tubs). It also shows the minimum slant distances from the edge of the swimming pool to the service drop connection on the pole, and the high-voltage conductor on the top of the pole. Minimum cable clearance or droop must take into account the height of any diving boards or other pool-related structures such as viewing stands or pool heating and water-circulating machinery enclosures.

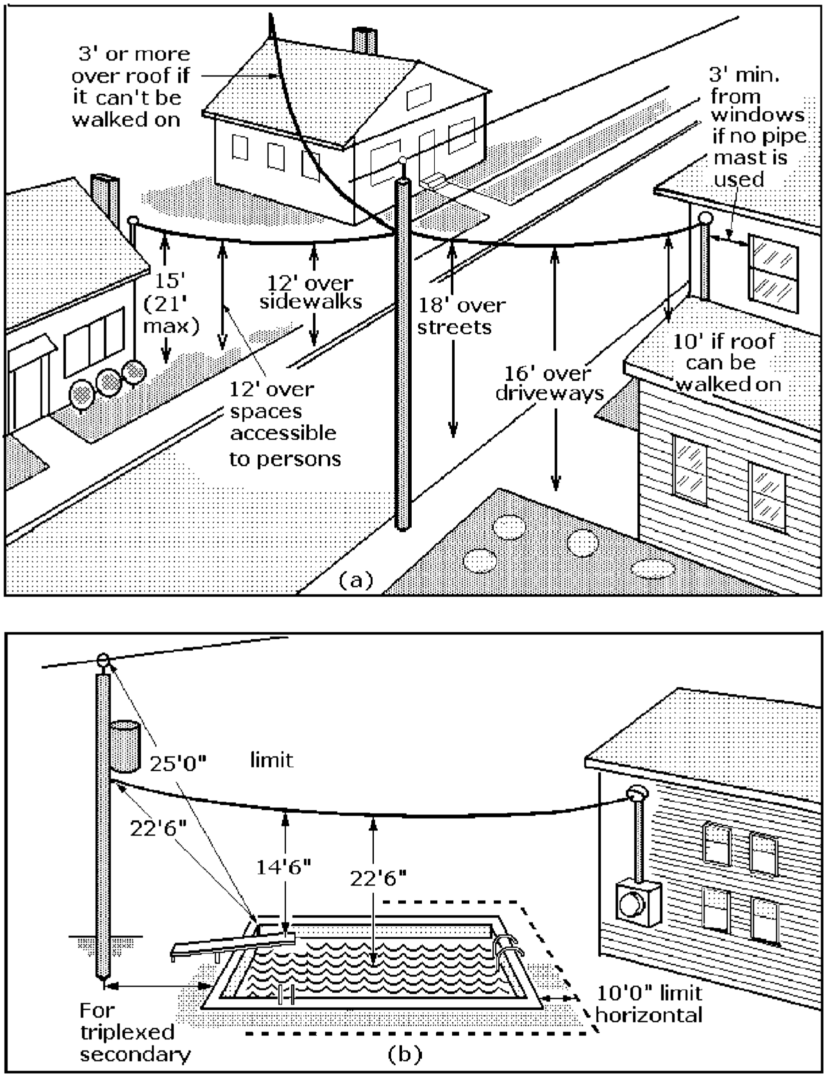


Figure 4-12 Clearance dimensions for service laterals: (*a*) typical residential situations; (*b*) over a swimming pool and accessories.

5

SERVICE ENTRANCE, LOADCENTERS, AND GROUNDING

CONTENTS AT A GLANCE

Overview
Overhead Electrical Service
Underground Electrical Service
Service Entrance Cable
Watthour Meter Bases
Loadcenters (Main Service Panels)
Miniature Circuit Breakers
GFCI Circuit Breakers
Fuses Rated for 60 A or Less
Grounding Electrical Service
Ground Testing
Temporary Electrical Service
Glossary of Electrical Service Terms

Overview

Electric service is defined as the conductors and equipment that deliver electrical power from the electric power utility's distribution system to the customers being served. The *service entrance* is the interface between the overhead or underground cable from the local transformer where the power utility's responsibility ends and the home or building owner's electrical system and responsibility begin. The utility splices the power cable to the owner's service entrance cable but retains ownership of the watthour meter.

This chapter also covers *main service panels* (a.k.a., *panelboards* or *loadcenters*) and the types of circuit breakers and fuses used to protect branch circuits in homes and offices. It explains the organization of a National Electrical Code (NEC)–approved grounding system, and discusses some of the test procedures required to assure that the ground system is performing effectively. Finally, the assemblies of cable, meter, disconnect, and fittings used for temporary service by builders and electrical contractors are illustrated and explained. At the end of the chapter is a glossary of electrical service terms for quick reference.

Overhead Electrical Service

In *overhead* or *aerial service,* illustrated in Fig. 5-1, the high voltage from an overhead (typically) single-phase secondary line attached to a utility pole is transformed to useful values by a pole-mounted overhead transformer near the building being served. The transformer steps the single-phase power, typically at 3 to 8 kV, to 120/240 V AC. The other elements of an overhead system are the *service drop* or *triplex,* the *service point* or *point of entry,* and the service equipment.

A common variation of the single-phase 120/240-V AC overhead system is the three-phase overhead system. This provides either 120/208 V AC or 120, 208, and 240 V AC. Three-phase power is typically used for commercial or light-industrial electrical service.

When it reaches a residential district, either underground or overhead, the typical "hot" secondary line is a single-phase high-voltage conductor. For example, on a typical outdoor wood utility pole, as shown in Fig. 5-1, the high-voltage "hot" wire is supported on an insulator mounted on top of the pole. A lower neutral ground or common wire is strung between poles below the hot wire, and a vertical grounding wire, spliced to the neutral wire, runs down the pole to a buried grounding rod. Secondary high voltages also power municipal street lights attached to the same poles as the transformer.

The pole-mounted or overhead step-down transformer within a cylindrical steel tank from 4 to 6 ft high is immersed in oil for cooling and insulation. (See Figs. 3-7 and 3-13 for more technical details on overhead transformers.)

Figure 5-2 is a simplified electrical schematic for a single-phase 120/240-V AC step-down transformer. The primary winding is connected between the high-voltage (7.6-kV "hot") conductor and the neutral or grounding conductor. It induces 240 V AC in the center-tapped secondary winding. The center tap (CT) is positioned equidistant from the "hot" terminals at each end, and is connected to the same grounding conductor as the primary winding.

The voltage across the two "hot" lines of the transformer secondary (A and B) is 240 V AC for heavy-duty appliances such as ranges and clothes dryers. The center tap

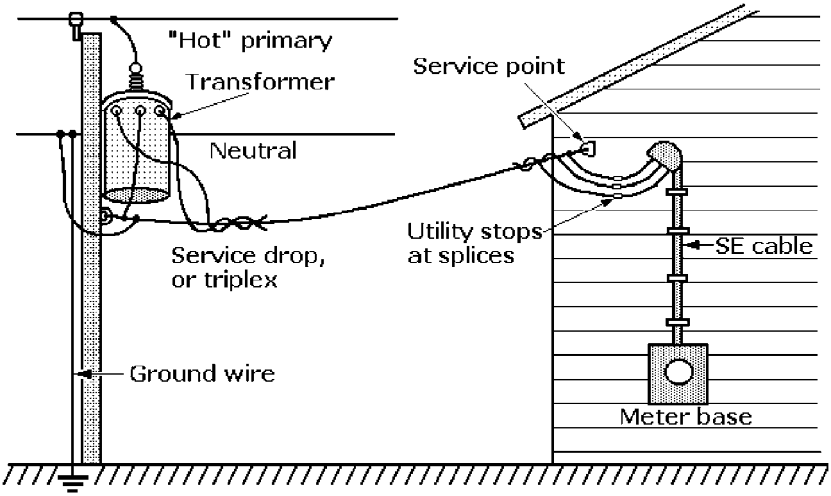


Figure 5-1 Overhead service provides electricity via a service drop from the utility pole transformer to the building service point.

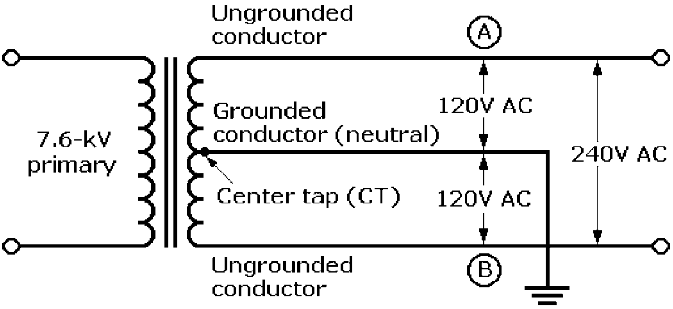


Figure 5-2 Single-phase distribution transformer steps 7.6 kV down to 240 V AC across the secondary winding; 120 V AC is obtained across both points A and B and the grounded conductor.

splits that 240 V to provide 120 V AC between either "hot" line (A or B) and the grounding conductor for lighting, light-duty appliances such as refrigerators, washing machines, and toasters, as well as TVs and computers.

The *service drop* or *triplex* contains the two "hot" insulated wires that conduct the 240-V power to the service entrance and the bare steel cable that is both the neutral/grounding and support cable for the two 240-V conductors. One end of the bare cable is fastened to the utility pole and the other end is fastened to an anchor bolt at the point of attachment to the home or building being served. Overhead pole-mounted step-down transformers are located on selected utility poles within the service area, so that one transformer can serve many homes.

OVERHEAD SERVICE CONNECTIONS

The details of how the service lateral or triplex cable provided by the electrical utility is fastened and spliced to the customer's service point are illustrated in Fig. 5-3. The bare neutral/grounding cable that supports the triplex is fastened at one end to the utility pole and the other end is fastened at the service point with a combination insulator and anchor bolt crimped onto the cable. This attachment method leaves the end of the neutral/grounding cable and the bare ends of the two insulated "hot" conductors available for splicing. Electrical utility employees splice these three ends to corresponding ends of the customer's service entrance (SE) cable, which is installed by the electrical contractor.

The three ends of the customer's SE cable are pulled through the bushings in a protective metal hood called the *weatherhead* or *service head* with enough slack to permit an adequate *drip loop* to be formed when the three conductors are spliced. The drip loop, which must be at least 36 in. long, prevents water from entering the weatherhead. Without a drip loop, water could drain down the conduit to the cable connections inside the meter base to the bus bars that power the watthour meter, corroding them and causing a short circuit.

The details of two different aerial feed service entrances are illustrated in Fig. 5-4. A 200-A service entrance made with three-wire service entrance (SE) cable is shown in Fig. 5-4*a.* The cable from the weatherhead is brought down to the meter base, where the busbar connections to the meter are made. Another length of SE cable goes from the meter bus bars to the loadcenter. A second version of a 200-A service entrance has the SE cable protected by metal or nonmetallic conduit between the weatherhead and the meter base, as shown in Fig. 5-4*b.* The service entrances for 175- and 100-A service are identical except that the SE cable has either a 175- or a 100-A rating. The limits of the meter height dimensions above grade level are approved by NEC 2002.

A 200-A service with the triplex cable terminating on a metal conduit mast is shown in Fig. 5-5. The mast projects high enough to comply with NEC 2002 for the minimum

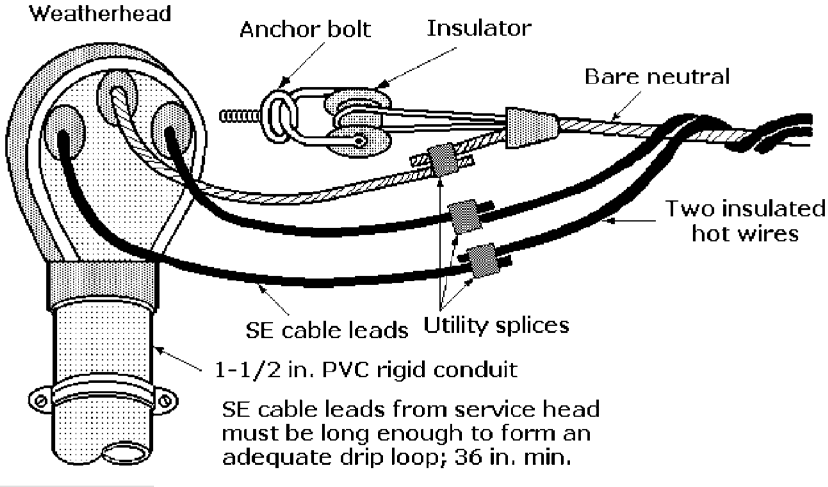


Figure 5-3 Splice details for an aerial drop to a service entrance cable at the service point.

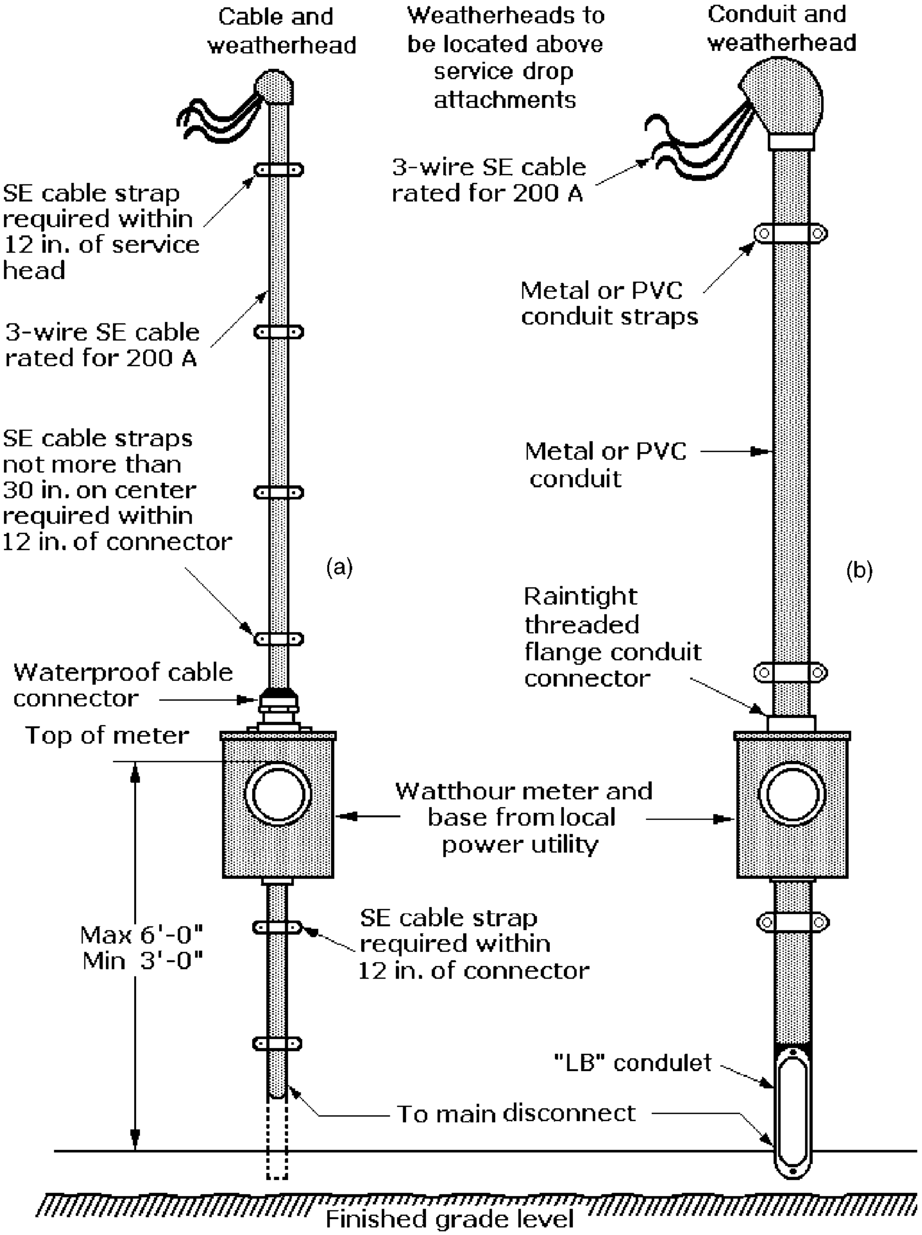


Figure 5-4 Examples of 200-A service entrances using type SE cable: (*a*) without protective conduit; (*b*) with conduit.

distances of the triplex termination above the ground. The hollow pipe functions as both a mast and a conduit for SE cable from the weatherhead to the meter base. As in Fig. 5-4, the service entrances for 100- to 175-A service are identical except for the lower SE cable ratings. All of the dimensional limits shown are those approved by NEC 2002.

GROUNDING OVERHEAD SERVICE

A household electrical system is grounded through a grounding rod driven into the earth, as shown in Fig. 5-6, a diagram applicable to all overhead service. This figure supple-

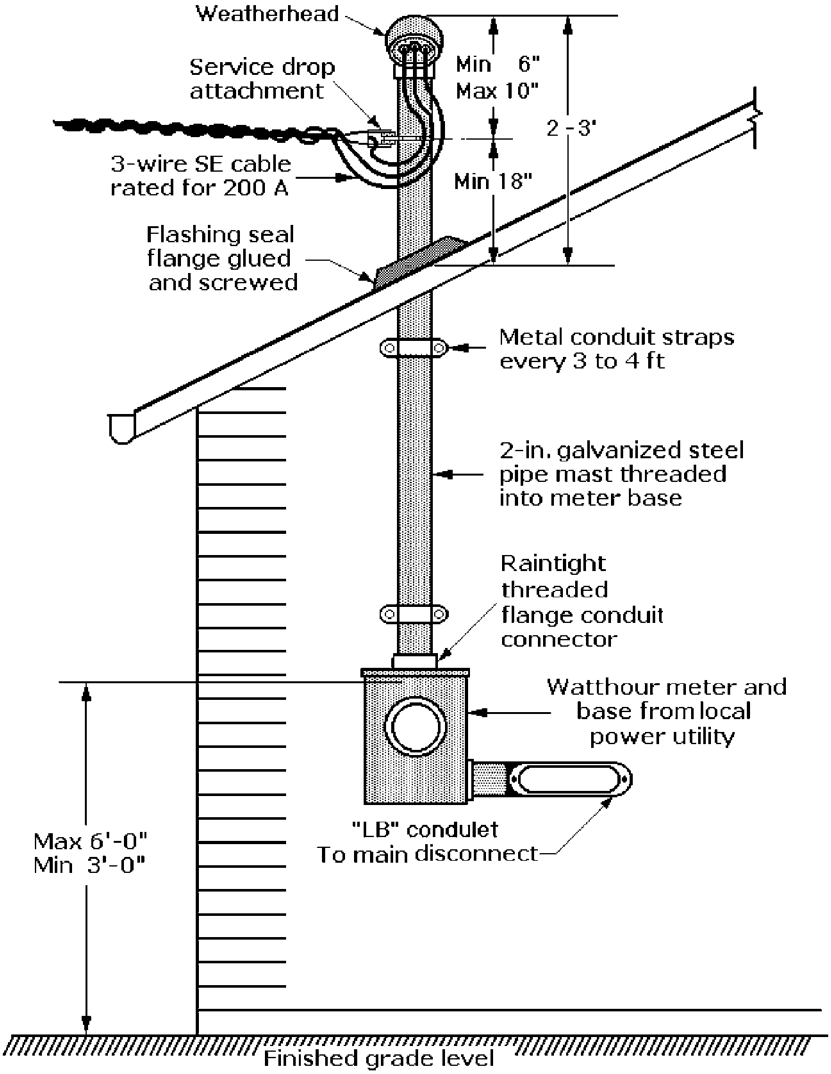


Figure 5-5 A 200-A through-roof service entrance. Layouts for 100 and 175 A are similar except that the SE cables have lower ratings.

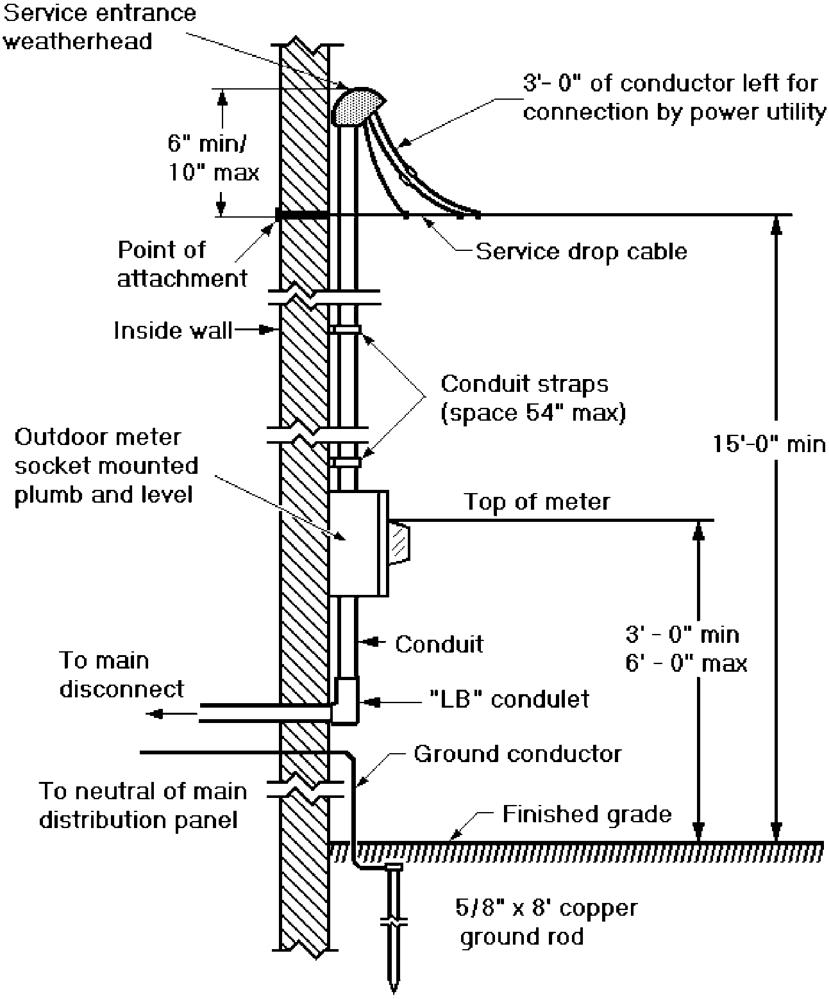


Figure 5-6 **Riser layout for a typical overhead service entrance, giving dimensions and grounding details.**

ments the information given in Figs. 5-3, 5-4, and 5-5, and all the dimensional limits are those approved by NEC 2002. The options available for installing an approved ground in accordance with NEC 2002 are discussed in detail later in this chapter.

Underground Electrical Service

A general overview of underground or buried electrical service is shown in Fig. 5-7. This service is becoming more popular in new housing developments and industrial parks, although it has been in use for more than a half-century in large cities. The typical “hot”

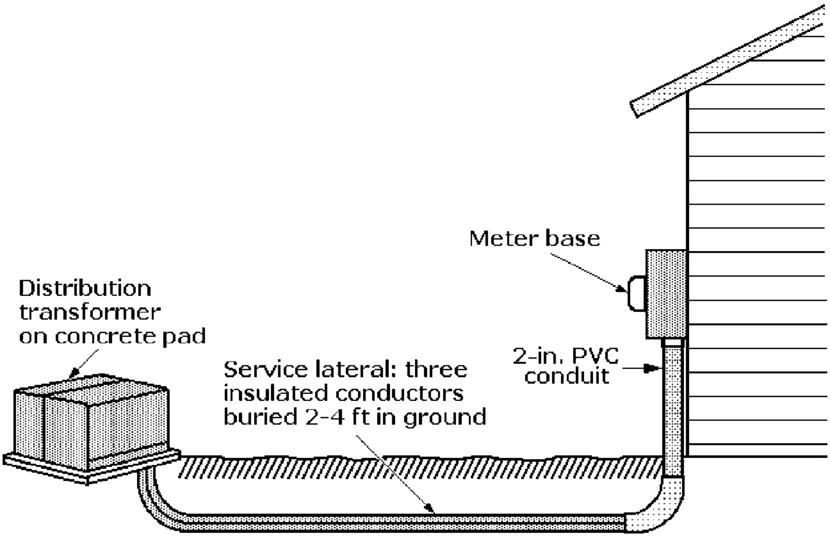


Figure 5-7 Underground service provides electric power from a pad-mounted transformer via a service lateral to the service point.

secondary distribution line that reaches a residential area, for either underground or overhead service, is a single-phase, high-voltage conductor. It usually reaches an aboveground *pad-mounted transformer* that transforms this voltage to 120/240 V AC. The electrical schematic for a pad-mounted, single-phase transformer is identical to that shown in Fig. 5-2. These transformers, like overhead transformers, are located in positions where they can serve many customers.

The pad-mounted transformer distributes 120/240 V AC to the meter base via a buried cable or *service lateral.* The approved cable for underground service is underground service entrance (USE) cable, a modified form of SE cable. It has three insulated conductors because the neutral/grounding conductor must be insulated.

In an underground feed, the two insulated "hot" conductors and grounded neutral conductor are run from the pad-mounted transformer back underground either direct-buried or in conduit. When the cable reaches the foundation of the building being served, it must be brought up through a length of conduit from below grade to the meter base.

The definitions of the terms *service entrance* and *service point* are modified when they to apply to underground electrical service. (See Figs. 3-8 and 3-14 for more technical details on overhead transformers.)

UNDERGROUND SERVICE CONNECTIONS AND GROUNDING

More details about the installation of an underground service lateral for 200-A service are given in Fig. 5-8. Here again, all dimensions and limits are those approved by NEC 2002. The details for 175- and 100-A underground service are identical except for the lower ratings of their USE cable. Underground service must be properly grounded, and the details are identical to those required for overhead service, as shown in Fig. 5-6.

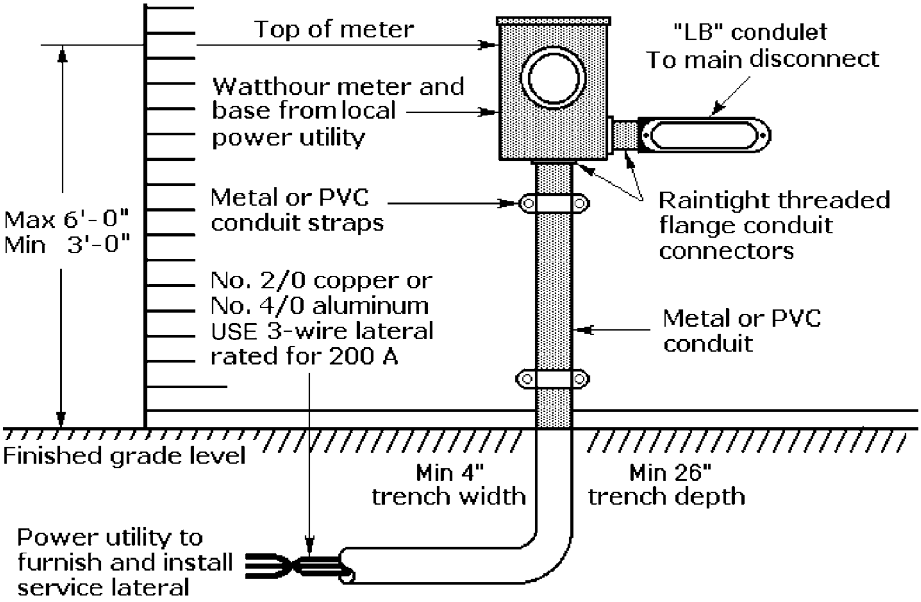


Figure 5-8 **Underground service lateral rated for 200 A: layouts for 100 and 175 A are similar, but they have lower-rated underground service entrance (USE) cables.**

The options available for installing an approved ground in accordance with NEC requirements are discussed in detail later in this chapter.

Service Entrance Cable

Type SE (service entrance) cable contains two separate insulated wires and a bare grounding cable. It conducts power into the home or building from the service drop splices described previously. SE cable is available in three different styles: U, R, and USE. All are rated for 600 V. SE cable is covered in NEC 2002, Article 338, "Service-Entrance Cable: Types SE and USE." This brief descriptive information is supplemented by more technical details in Chap. 6 of this handbook.

Type SE cable has a flame-retardant, moisture-resistant covering. Its installation requirements are in NEC Article 230, "Services."

Type USE cable is for underground use. It has a moisture-resistant covering, but flame-retardant covering is not required. It can emerge from the ground outside the terminations in meter bases or other enclosures where protected in accordance with NEC 2002, Section 300.5(D), "Protection from Damage."

- *U-style SE* cable is flat and approved only for above-ground use. It has two insulated conductors and a multistranded braid that encloses the two insulated conductors. The jacket is flame-retardant and moisture-resistant, and has sun-resistant properties.

- *R-style SE* cable is round and approved only for above-ground use. It contains three insulated conductors and a grounding wire. The conductors are wrapped in glass-reinforced tape and enclosed in a polyvinyl chloride (PVC) jacket.
- *Style USE* (underground service entrance) cable is intended for underground service. Its individual conductors, which can be buried or in conduit, are insulated with cross-linked polyethylene that is moisture-resistant but not flame-retardant.

Watthour Meter Bases

Lengths of overhead or aerial (SE) cable extending from the weatherhead are clamped to the copper bus bars within the meter base, as shown in Fig. 5-9. These bus bars provide power for the watthour meter. Both the meter base with bus bars and the watthour meter are furnished by the electric power utility, but they must be installed by the owner's electrical contractor. The meter base is a watertight metal box, normally mounted on an outside wall of the home or building being served.

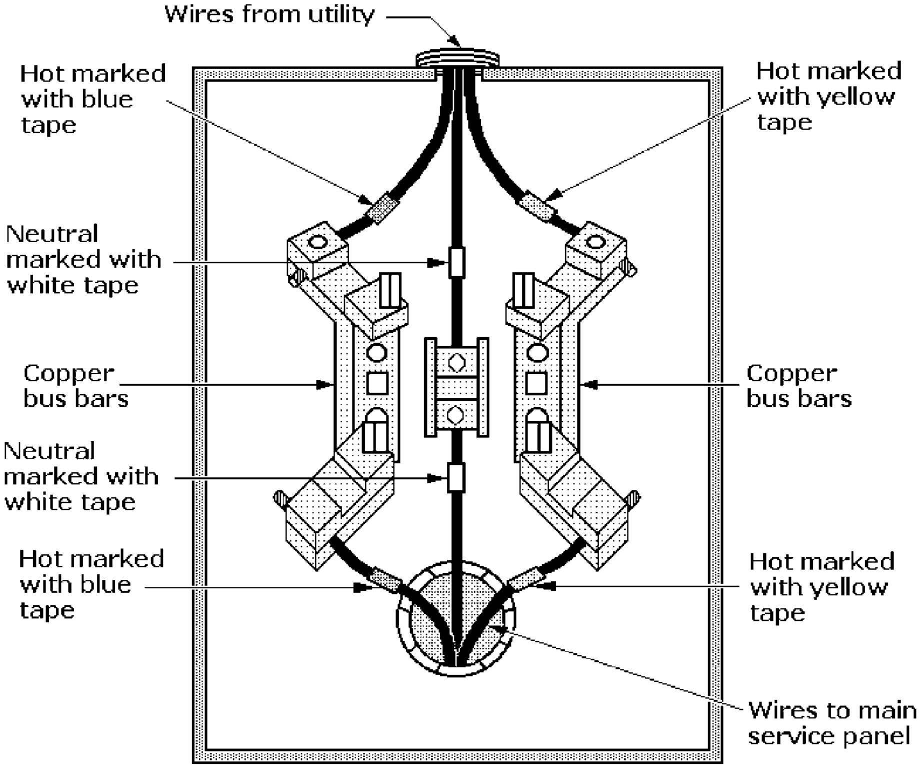


Figure 5-9 Overhead service to a meter base: color-coded tapes identify wires going into and out of the watthour meter.

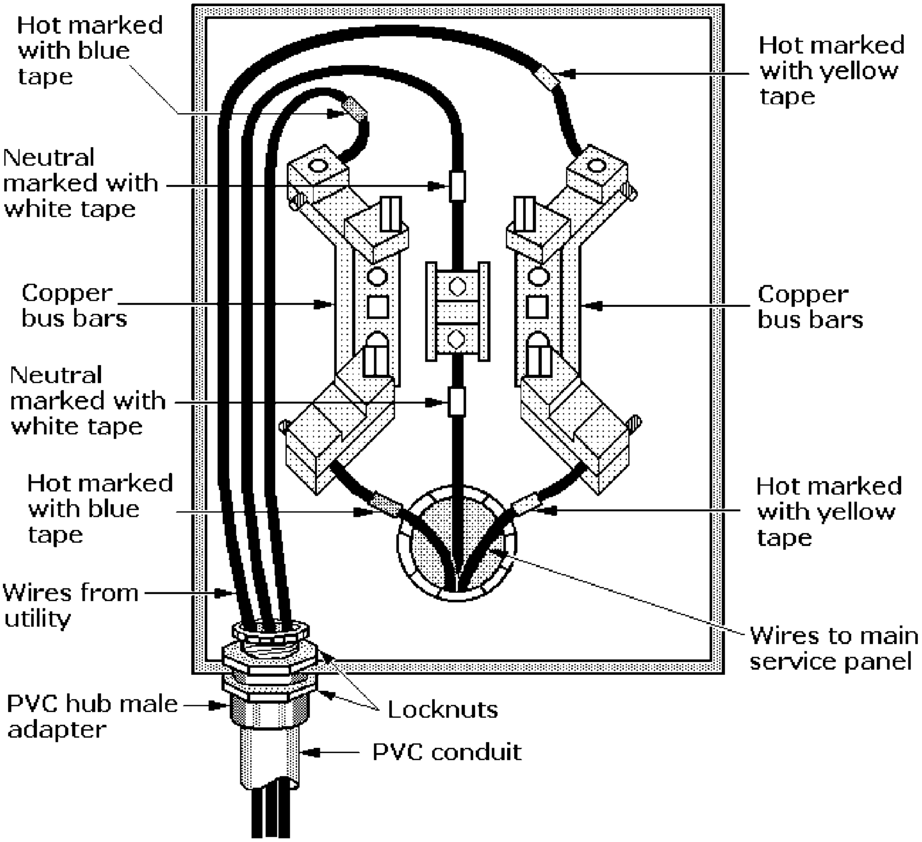


Figure 5-10 **Underground service to the meter base: color-coded tapes identify wires going into and out of the watthour meter.**

The configuration of the copper bus bars within the meter base is standardized. The bus-bar terminal clamps are widely separated to provide adequate insulation. The three wires on one end of a second length of SE cable are clamped to the opposing terminals of the bus bars, as shown in the figure, and the other end is extended to the loadcenter. Because of the serious consequences, different colored tape identifies the three wires entering and leaving the meter base, to avoid mistakes in hooking up the wires.

The USE cable connections inside the meter base from an underground service lateral or buried feed are shown in Fig. 5-10. As in Fig 5-9, the incoming wires are clamped to the top ends of the meter bus bars, but because they enter the meter base from the bottom of the box, the extra lengths of wire must be bent around inside the box to make those connections. Again, as in the overhead situation, another length of service entrance cable is clamped to the lower ends of the bus bars and the other end is extended to the loadcenter. The “hot” and neutral/grounding conductors are also color-coded with tape to avoid mistakes in hooking up the wires.

Loadcenters (Main Service Panels)

Many different names are given to the electrical panels that accept the service entrance wires from the meter base and distribute power to branch circuits within the home or building. The terms *main service panel, panelboard,* and *loadcenter* are used interchangeably and have the same meaning. NEC 2002 refers to them as panelboards, but the electrical industry and electricians generally call them either main service panels or loadcenters. The term loadcenter will be used here because it is simpler and more descriptive than the alternative terms.

Panelboards, as defined by NEC 2002, are metal enclosures for mounting overcurrent-protective devices such as fuses and circuit breakers positioned upstream of all branch circuits in the distribution of power within the building for lighting, appliance, and other loads. Panelboards are classified by the NEC in two general categories: lighting and appliance branch-circuit panelboards and power panelboards.

A *power panelboard* is defined as a panelboard having 10 percent or fewer of its circuits assigned to lighting and appliance branch circuits that are protected at 30 A or less, for which neutral connections are provided.

By contrast, a *lighting and appliance branch-circuit panelboard* is defined by the NEC as one having more than 10 percent of its circuits assigned to lighting and branch circuits that are protected at 30 A or less, for which neutral connections are provided. The NEC also limits the number of overcurrent-protection devices (branch-circuit poles) to a maximum of 42 in any one cabinet. When more than 42 poles are required, separate enclosures are required.

All panelboards not defined as lighting and appliance panelboards by the NEC are classified as power panelboards. They are restricted only to enclosure dimensions with standard heights and widths. NEC 2002, Article 408, "Switchboards and Panelboards," covers the requirements for switchboards, panelboards, and distribution panels for the control of light and power circuits. The article includes such topics such as the classification of panelboards, the number of overcurrent devices on one panelboard, and the overcurrent protection for them. It also covers the location and grounding of panelboards and their construction.

The loadcenter is the distribution center for all branch circuits, and it receives incoming power from the SE cable. Figure 5-11 is an electrical schematic for a single-phase, three-wire loadcenter wiring scheme typical of those for residential electrical service. It is the same as Fig. 5-2 except that more details about how the power is distributed have been added. The two parallel bus bars A and B carry the "hot" 240 V AC from the distribution transformer. The 120 V AC is obtained by making connections across either "hot" bus A or B to the neutral (grounded) bus. The lighting load, indicated by the letter L, represents one of many 120-V AC branch circuits that can be obtained from this connection. Similarly, the motor load indicated by the letter M represents one of the 240-V AC branch circuits connected across the two "hot" buses A and B.

Figure 5-12 is an electrical schematic for a three-phase, four-wire loadcenter wiring scheme typically used for commercial and light industrial electrical service. It has

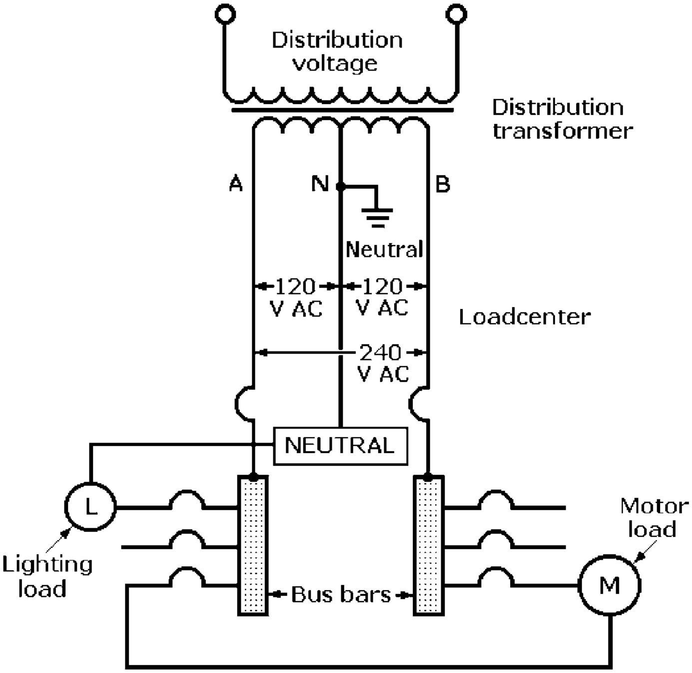


Figure 5-11 **Schematic diagram for a single-phase, three-wire loadcenter.**

three parallel "hot" buses, A, B, and C. The voltage between any two of these buses is 208 V AC from the distribution transformer. The 120 V AC can be obtained by any connection between one of the three "hot" buses and the neutral (grounded) bus. Again, as in the previous figure, the lighting load, indicated by the letter L, represents one of many 120-V branch circuits that can be obtained from these connections. Similarly, the motor load indicated by the letter M represents one of the 208-V branch circuits connected across the two "hot" buses A and C.

The loadcenter contains a heavy-duty circuit breaker also called the *main breaker* or *disconnect breaker.* (If it is a switch, it is called the *disconnect switch.*) Its primary purpose is overcurrent protection because it limits the total amount of current entering the building. These devices are usually located at the top of the loadcenter. All electric power entering a building passes through this breaker or switch. In an emergency such as a fire, earthquake, or violent storm, either the circuit breaker or a switch can be operated manually to cut off all power instantly.

The rating of the main breaker or disconnect switch is set by the current-carrying capacity of the service entrance cable. The main circuit breaker senses the amount of current flowing into the loadcenter panel and automatically disconnects the incoming power from the buses if their current ratings are exceeded. For example, if a home or building has a 200-A loadcenter and the load suddenly exceeds 225 A, the breaker will open, cutting off all power. The amperage rating of the circuit breaker is printed on it.

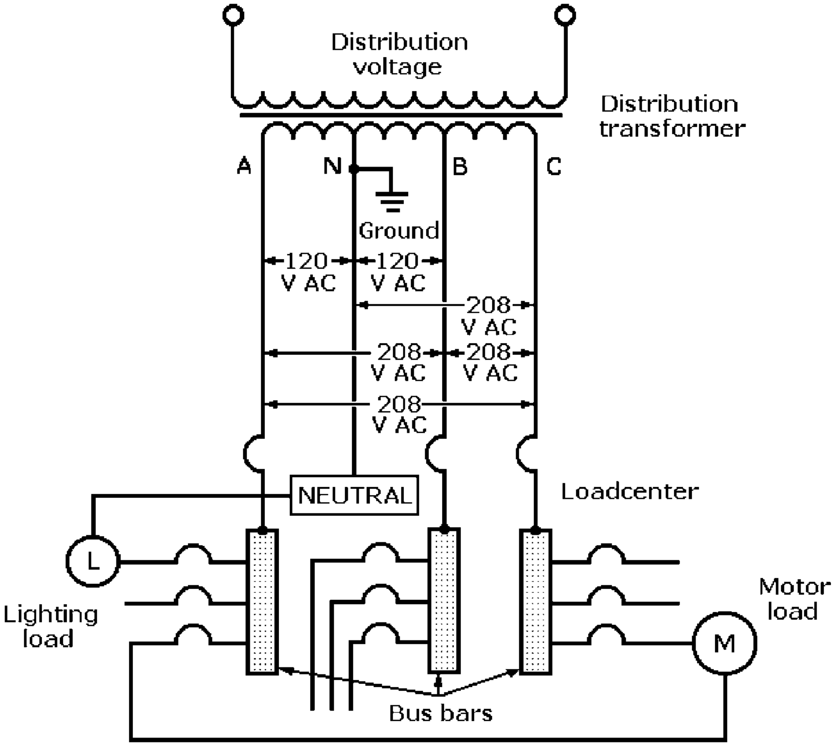


Figure 5-12 Schematic diagram for a three-phase, four-wire loadcenter.

LOADCENTER ENCLOSURE

The loadcenter enclosure contains the circuit protection devices (today almost exclusively circuit breakers) and their related “hot” and neutral bus bars as well as one end of the grounding wire. A typical loadcenter enclosure, as shown in Fig. 5-13, is made of cold-rolled steel and has three main parts: front cover, inner cover or dead front, and backpan. The National Electrical Manufacturers Association (NEMA) and the Underwriters Laboratories Inc. (UL) have established guidelines for the construction of these electrical enclosures.

The NEMA Type 1 enclosure, for general-purpose indoor use, is suitable for most applications where unusual service conditions do not exist. It provides protection for persons who might make accidental contact with the “hot” wires and buses within the enclosure. It also protects the circuit breakers and branch-circuit wiring from dust and dirt. The NEMA Type 3R enclosure for outdoor use also provides personnel protection, but in addition protects the internal electrical equipment from falling rain or sleet and damage from external ice formation. These enclosures have protective gaskets inside their front covers to seal them against inclement weather.

A loadcenter can be flush-mounted within a wall or surface-mounted on a wall. A flush-mounted loadcenter is recessed within an opening in a wall, usually fastened

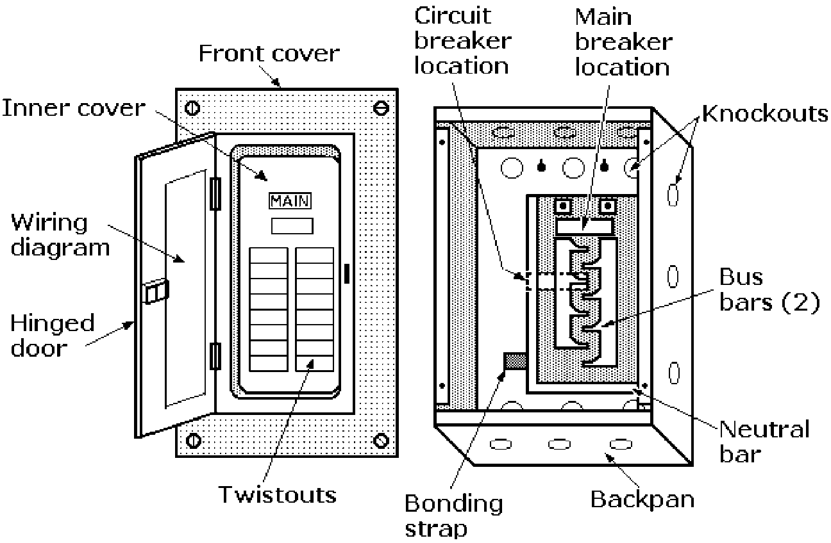


Figure 5-13 Loadcenter consisting of a front cover with a door and a backpan, where connections are made for incoming and branch wiring to the circuit breakers.

between joists. By contrast, a surface-mounted loadcenter is fastened to the outside of the wall, usually concrete or cinder block, with masonry anchor bolts.

Loadcenters classified by the NEC as lighting and appliance branch-circuit panelboards provide for the insertion of class CTL overcurrent devices. This is the UL designation for its "circuit limiting," a requirement that limits the number of circuits within a lighting and appliance branch-circuit panelboard.

The shallow metal box of the loadcenter that is the supporting surface for all mounted bus bars and fittings is called either the *backpan* or the *backpanel.* The "hot" and neutral bus bars and main and branch circuit breakers are mounted within the backpan. The bus bars are extensions of the incoming power cables that provide mechanical support for mounting the branch circuit breakers.

BACKPAN/PANELBOARD

Figure 5.14 is a more detailed view of the backpan/panelboard of a loadcenter. The "hot" bus takes the power from the main circuit breaker and distributes it to two parallel copper or aluminum strips or "legs" that run down the center of the panel. These "hot" bus legs are located immediately below the main circuit breaker terminals. Each "hot" leg includes a row of projections whose ends are bent outward to form *tabs* or *stabs* to accept circuit breaker contacts and lock them into position.

Each leg receives the same voltage with respect to neutral, but it acts like an independent power source. The current in each leg of the "hot" bus is obtained from alternate sides of the utility transformer, as shown in the transformer schematic diagram

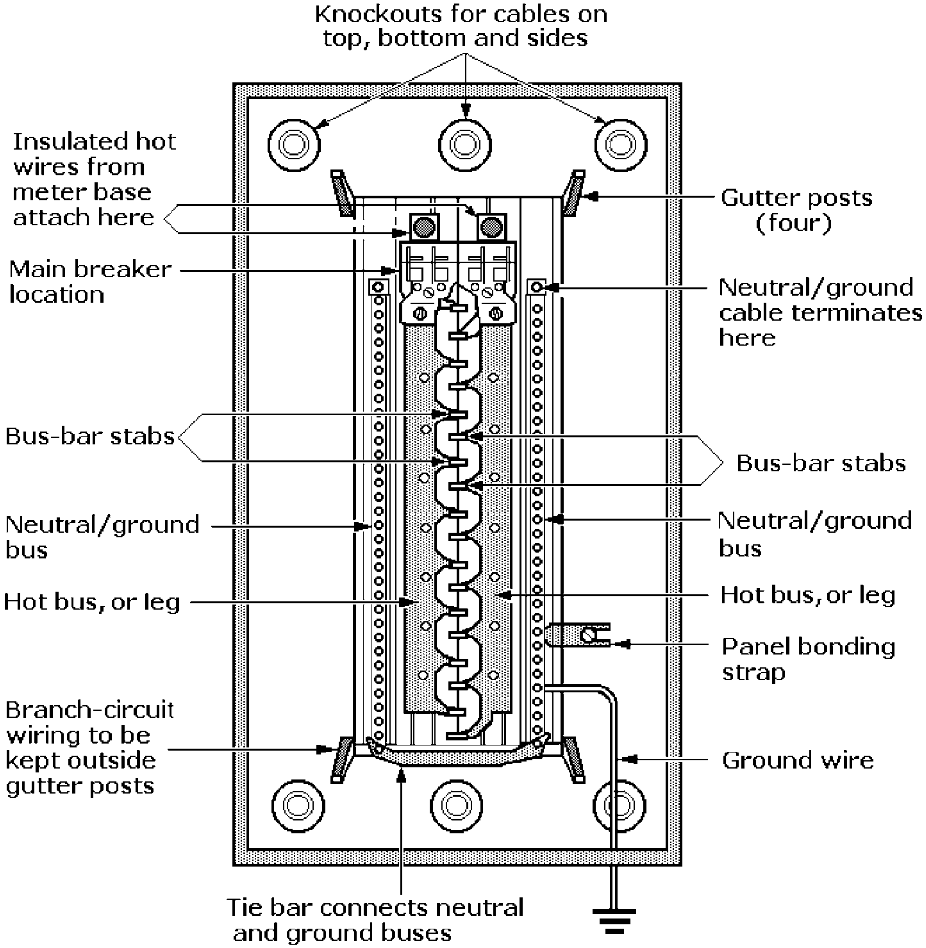


Figure 5-14 Backpan includes buses for terminating the "hot," neutral, and ground wires, and space for installing circuit breakers and wiring branch-circuit connections.

Fig. 5-2 and the loadcenter schematic diagram Fig. 5-11. The voltage between the legs is 240 V AC, and the voltage from each leg to neutral ground is 120 V AC.

The *gutter* of the loadcenter is the space in the backpan on both sides of the neutral ground buses where all branch-circuit wiring is positioned before being connected to the circuit breakers. *Gutter posts* are the plastic studs positioned at the four corners of the neutral/ground buses on the panel to prevent the wires from interfering with or overlapping the buses. They set limits for the wire bundles that will occupy the gutters on both sides of the buses and guide them into their proper positions. The posts also assure that all branch-circuit wiring is run vertically on both sides of the neutral bus, away from the main breaker terminals.

The NEC does not permit wires to cross over the circuit breakers from one gutter to the other except in special cases, where they must be enclosed by a separate section of insulating conduit. The two hex-screw lugs immediately above the main breaker location are for connecting the two “hot” wires in the SE cable from the watthour meter base. A lug at the top of one neutral/ground bus connects the bare neutral wire from the meter base to that bus, and the second parallel bus is usually connected electrically and mechanically to the first bus by a conductive tie bar.

There are legs of a neutral /ground or common-return bus outside of each main bus leg. These strips, which act as ground reference points, are made of aluminum. Each strip contains a large number of tapped holes, each containing a screw. The neutral and ground wires from branch circuits are fastened to these buses with screws in the strips.

Most panel manufacturers put a neutral lug next to the main breaker, convenient as long as the incoming power enters from the top. However, the neutral lugs on some panels can be removed and reattached at other locations on the neutral /ground bus. This feature permits the installer to connect the neutral wire from the meter close to its point of entry to the panel. It also eliminates the need for winding the wire around the inside of the panel, taking up space and interfering with the branch-circuit wiring.

Although the neutral is grounded at the utility pole, an additional ground is made by the installer at the loadcenter to a grounded rod with a solid 4- or 6-AWG copper wire. For additional protection, a bonding screw is installed, connecting the neutral/grounding bus to the metal frame of the loadcenter.

The bonding screw, called the *panel bond,* grounds the metal so that it will not become a conductor if a “hot” wire touches it. In addition, grounding wires from every receptacle and appliance, as well as all neutral wires, are connected to the neutral/ground bus. If the panel has a conductive tie bar that connects the two buses, it can be removed so the panel can be converted to a subpanel with a neutral isolated from ground.

CALCULATING THE LOAD

The electrical load of a residence or building should be sized to determine a safe amperage rating for the service entrance cable, meter base, and main service panel or loadcenter. It requires a computation of the general lighting load based on floor area and allowances for appliance outlet circuits as well as a tabulation of major appliance loads such as washing machines, dishwashers, and clothes dryers. The values for these can be determined from nameplate ratings or taken from tables such as Table 5-1. For the purposes of these computations values in watts (W) can be considered equivalent to values in volt-amperes (VA).

Highly detailed examples of how to make service calculations are published in Annex D of NEC 2002 with cross-references to Article 220, “Branch-Circuit, Feeder, and Service Calculations.” The annex includes sample calculations for single-family homes with variations in floor area and different mixes of major electrical loads. It also includes calculations for stores, multifamily dwellings, mobile homes, motors, and generators. The calculations for all homes are made in essentially the same way, but those with centralized air conditioning and electric home and hot water heating will have significantly higher electric loads than those with oil or gas home and water heating, and perhaps a few portable air-conditioning units.

TABLE 5-1 TYPICAL WATTAGE FOR LIGHTING AND APPLIANCES WITH STARTING VALUES EQUAL TO RUNNING VALUES FOR SYSTEM LOAD DETERMINATION

APPLIANCE	AMPERES[a]	RUNNING/RATED (W)
Air conditioner large (1)	20 (240 V)	4800
Air conditioner, small (1)	15	1800
Clothes dryer	33 (240 V) + 4 (120 V)	8400
Clothes iron	10	1200
Coffee maker	7	850
Computer, desktop	8	960
Dishwasher (2)	12	1440
Dehumidifier	6	720
Drill, electric, small (2)	4	500
Fan (ceiling) (3)	4	480
Fan (furnace, 1/3 hp) (3)	5	600
Fan (portable) (3)	0.6	72
Freezer (3)	4	500
Garbage disposer	6	720
Hair dryer (2)	5–10	1500
Heater (baseboard, 10 ft)	10 (240 V)	2400
Heater (portable)	8	1000
Heater (water, 50 gal)	19 (240 V)	4500
Lamps, incandescent	0.25–1.7	30–200
Microwave oven (4)	6.6 (240 V)	1500
Radio, AM/FM	0.4	50
Range, electric per element	6.5 (240 V)	1500
Refrigerator (3)	5	600
Stereo system	2.5	300
Stove, electric, per element	6.5 (240 V)	1500
Television (color, large)	5	600
Television (color, small)	1	120
Toaster	7	850
Vacuum cleaner (2)	9	1080
Washing machine (2)	10	1220
Water heater, electric	20 (240 V)	4800

[a] All voltages are 120 V AC unless otherwise indicated.

NOTES: To estimate starting/surge wattage:
(1) Multiply running/rated value by 1.6.
(2) Multiply running/rated value by 1.25.
(3) Multiply running/rated value by 3.0.
(4) Multiply running/rated value by 1.5.

A simplified calculation is presented here to convey the concepts, but readers are urged to study Article 220 and Annex D before making calculations for an actual project.

Consider a single-family home with a floor area of 2000 ft^2, exclusive of cellar, attic, and open porches. It has a 12-kW range, a 1.8-kW dishwasher, a 8.4-kW clothes dryer, and a 72-kW garbage disposer. Oil is used for home and water heating, so their load is the operation of fractional horsepower fan and pump motors included in the appliance load. Loads in watts (W) are entered as volt-amperes (VA).

The general lighting load is calculated as floor area multiplied by 3 VA per ft^2:

$$2000 \text{ ft}^2 \times 3 \text{ VA/ft}^2 = 6000 \text{ VA}$$

General load

General lighting	6,000 VA
Three 20-A appliance circuits at 1,500 VA	4,500 VA
Laundry circuit	1,500 VA
Range (at nameplate rating)	12,000 VA
Dishwasher	1,800 VA
Clothes dryer	8,400 VA
Garbage disposer	720 VA
Air-conditioning units	4,000 VA
Total	38,920 VA

Application of a demand factor Because all loads do not operate at the same time, accept the first 10,000 and take 40 percent of the remainder:

First 10 kVA of general load @ 100%	10,000 VA
Remainder of general load @ 40% (28,920 × 0.4)	11,568 VA
Total general load	22,568 VA

Calculated load for service Net computed load for 120/240-V, three-wire, single-phase service:

$$\frac{22{,}568 \text{ VA}}{240 \text{ V}} = 94 \text{ A}$$

This installation could get by with a 100-A loadpanel, meter base, and service entrance cable, but 200 A would provide a better safety margin and permit load increases.

SIZING THE LOADCENTER

The amperage rating of the loadcenter is determined by the size of the building and the anticipated electrical load. The meter base, loadcenter, and SE cable must be sized for the same amperage rating. The lowest-rated loadcenters are rated for 100 A, but some are made with ratings up to 800 A. Loadcenters with 200-A ratings are now most commonly ordered for new home construction, but 400-A units are increasing in popularity.

Because of increasing electrical loads, year-round single-family home loadcenters should not be rated for less than 200 A today. (Exceptions might be made for summer vacation cottages or cabins.) Load calculations might indicate a load of only 150 A, but the possibility of increased loading must be considered. If a loadcenter is undersized or is running close to its maximum load, the heat generated within the cabinet could trip the main circuit breaker.

In situations where the load is estimated at more than 200 A—for example, 220 A—two options are available: install both a 200-A and a 100-A loadcenter, or install a 300-A loadcenter. If two loadcenters are to be installed, the second should be installed next to first one, with parallel SE cables coming directly from the meter base bus bars, which have lugs or clamps that permit parallel-service wiring.

There are three reasons for installing two loadcenters rather than one large one.

1. Difficulty in installing the wiring: A 200-A cable is difficult to bend and install, but 400-A cable is even more difficult to bend and install.
2. Low availability of 300- and 400-A main circuit breakers.
3. Space limitations of a single loadcenter: Two loadcenters with more wiring space avoid cramming a large number of branch-circuit wires inside a single large cabinet.

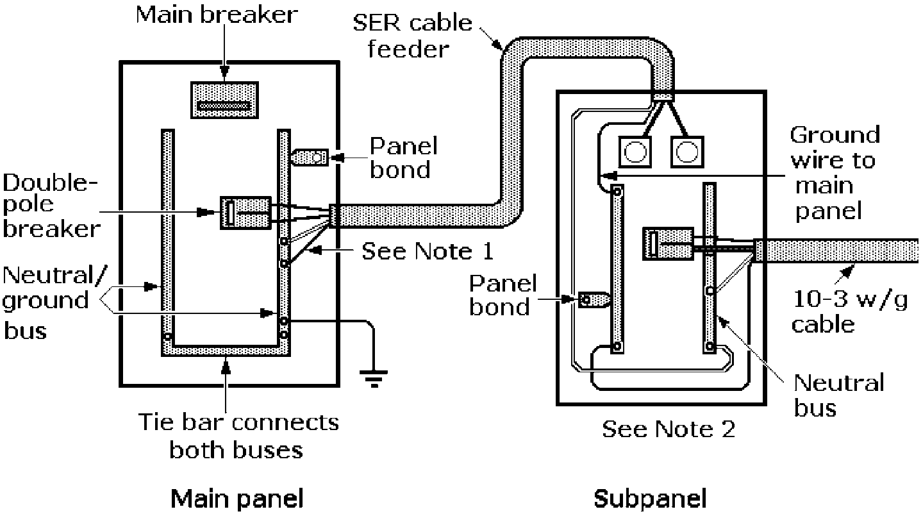
To avoid installation problems, a careful estimate should be made of the number of branch circuits required before specifying the size of the loadcenter. For example, a 200-A loadcenter that can contain from 8 to 40 circuits is typically designated as 40/40. In this case, the first figure refers to the number of tabs or stabs for installing full-size circuit breakers and the second figure refers to the number of available circuits if two-in-one or dual breakers are used.

A loadcenter designated 30/40 indicates that it can hold 30 full-size breakers for 30 circuits. However, 40 circuits can be obtained with the 30 tabs if dual breakers are intermixed with full-size breakers, usually at locations near the bottom of the buses.

In situations where the number of branch circuits exceeds the rated capacity of the main panel or loadcenter, a subpanel can be used. The diagram Fig. 5-15 illustrates the method for connecting a main panel to a subpanel. Both neutral and ground wires can connect to the same bus. Because the ground and neutral buses are separated to keep neutral current off the grounding system, a main breaker is not required in the subpanel.

BALANCING THE LOAD

A balanced electrical load is wired in the loadcenter so that current on one 240-V “hot” bus or leg is equal or close to the current on the other “hot” bus, canceling out any current in the neutral bus. This balancing calls for determining the loads on each leg and organizing the circuit breakers in the panel so that, as far as is practical, com-



Notes:
1. Both neutral and ground wires of cable can connect to same bus.
2. Because ground and neutral buses are separated to keep neutral current off grounding system, main breaker is not required.

Figure 5-15 Wiring layout for adding a subpanel to a main panel.

parable loads operating at the same time are on opposite phases or buses. This is easier to understand by referring to Fig. 5-11, a simplified schematic for a single-phase, three-wire loadcenter.

Balancing lowers heat buildup in the wire terminals within the loadcenter and ensures a higher safe load on the panel. If a loadcenter and main circuit breaker are rated for 200 A but the wiring permits a 300-A load on only one “hot” bus, the circuit breaker will trip. However, if the load is split or balanced, the current will be only 150 A on each leg and this will be within the 200-A rating.

The circuit breaker tabs on each “hot” bus are arranged in opposite phases. This permits single-phase branch circuit breakers with the same rating to be installed on opposite phases to cancel each other out. By contrast, double-pole breakers are connected across both “hot” buses of the panel, so their current will balance automatically.

In general, breakers with the same ratings for loads that will be operating at the same time should be put on opposite phases. For example, if two 5-A loads are put on the same phase, current in both the neutral and on one service entrance “hot” bus will add up to 10 A. However, if they are put on opposite phases, 5 A will flow through each bus but will cancel out to 0 A in neutral.

Even if current on the neutral bus is not canceled, it will carry the difference between the loads on the opposite phases. For example, if a 10-A load is on one phase and a 6-A load is on the other, the current through the service entrance neutral will only be 4 A; if they were both on the same phase, the neutral current would be 16 A.

Miniature Circuit Breakers

This chapter focuses on the widely used miniature circuit breakers rated for 240 V or less. Unlike the higher-voltage circuit breakers discussed in Chap. 3, they are smaller and lower-rated versions of industrial-grade molded-case circuit breakers rated for 600 V or less. These miniature breakers, called *air circuit breakers,* are based on thermal, magnetic, or combined thermal-magnetic principles. They are now almost exclusively installed in all new residences, small businesses, and offices as well as updates of existing older electrical systems. They are rated for amperes, voltage, and short-circuit or fault-current interruption.

Miniature circuit breakers perform the dual functions of a switch and a fuse. They can open a circuit for safety or maintenance reasons simply by switching their toggle levers to the OFF position. As substitutes for fuses, they provide automatic circuit protection and need not be replaced after a dangerous overcurrent has passed or a short circuit has been corrected.

The *ampere rating* defines the maximum current the circuit breaker can carry without tripping. For typical miniature circuit breakers this rating is 15 to 125 A. In residential applications, single-pole breakers protect 20-V branch circuits, and two-pole breakers protect 240-V branch circuits.

The *voltage rating* of a circuit breaker can be higher than the circuit voltage, but never lower. The *fault current interruption rating* (or *short-circuit interrupting rating*) is the maximum available fault current that could be expected from the overhead or pad-mounted distribution transformer outside a residence. If the transformer can produce 10,000 A of current, each breaker in the loadcenter should be rated for at least 10,000 A. While residential breakers have ratings of 10,000, 22,000, 42,000, and 65,000 A, the available fault current for most single-family homes rarely exceeds 10,000 A.

Each miniature or branch circuit breaker, as shown in the cutaway view Fig. 5-16, includes a bimetal strip or element. When this strip is heated to its threshold tempera-

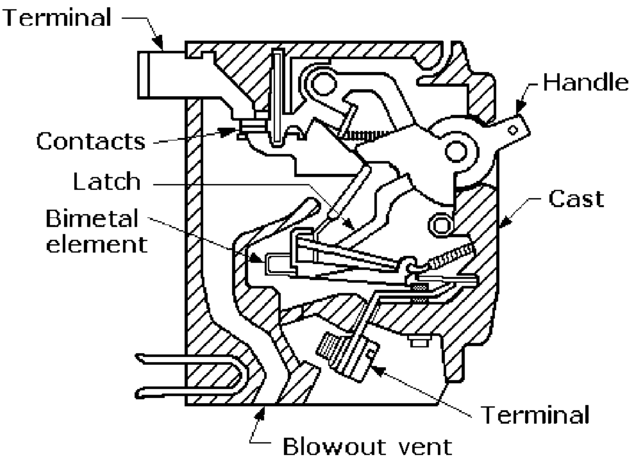


Figure 5-16 Internal view of a thermal circuit breaker.

ture, it bends enough to unlatch a mechanism and open the breaker's electrical contacts. When the contacts open, the toggle on the circuit breaker automatically switches to the OFF position. This, in turn, opens the branch circuit.

These small circuit breakers can be reset manually after they have tripped. As with fuses, the ampere rating of the breaker must match the ampacity of the circuit it protects. These circuit breakers are also called *plug-in breakers,* because they are connected to the loadcenter by plugging them into the bus-bar tabs or stabs.

A high-quality thermal circuit breaker will open a 10,000-A fault at 240 V AC in 40 to 50 ms. Under simple overload conditions, the deflection of a bimetal thermal sensing element within the circuit breaker causes the circuit to open when a preset temperature threshold is reached. Rising temperature in a bimetal element is caused principally by load current (I^2R) heating. The thermal element also factors in the heating or cooling effects caused by nearby heating or cooling sources (furnaces or air conditioners), as well as changes in the ambient temperature.

The size of the bimetal thermal element and its configuration, shape, and electrical resistivity determine the current capacity of a circuit breaker. The most common element is a "sandwich" of two or three different metals. The low-expansion side, for example, might be Invar, the center might be copper or nickel, and there is a wide choice of metals for the high-expansion side.

Some thermal circuit breakers rated for 5 A or lower contain heater coils adjacent to or in series with the bimetal element. These heater coils compensate for the lower anticipated heating action of a fault in a low-current circuit. They augment element self-heating to maintain the temperature of the thermal element closer to the preset threshold temperature, to speed up the trip response in the presence of overcurrent.

Some miniature thermal circuit breakers also contain a magnetic element to accelerate tripping in the presence of an exceptionally fast rising overload. That condition increases current flow fast enough to create a magnetic field in a small electromagnet or solenoid that pulls in a mechanical linkage to unlatch the contacts and trip the breaker before the bimetal element can respond and deflect. The basic elements of a thermal-magnetic circuit breaker are shown in the simplified diagram Fig. 5-17.

The normal condition of the circuit breaker is illustrated in Fig. 5-17*a.* The bimetal element in these breakers responds the same way to overcurrent as the element in a simple thermal breaker. As shown in Fig. 5-17*b,* the bimetal element deflects in proportion to the heating effect of the current passing through the wire in close proximity to it. As in thermal breakers, the bimetal element will open a 10,000-A fault at 240 V AC in 40 to 50 ms. The bending element unlatches the contact mechanism, opening the contacts.

By contrast, the small solenoid magnetic element has a few turns of low-resistance wire in series with the wire adjacent to the thermal element, which has little effect on the impedance of the breaker. In the presence of rapidly rising current, a magnetic field forms around the solenoid, causing it to pull in the trip bar, which unlatches the contacts and opens them. This element responds 4 times faster than the bimetal element, or in about 10 ms.

Molded-case and miniature circuit breakers are designed to operate in elevated-temperature environments such as those encountered inside a breaker panel carrying

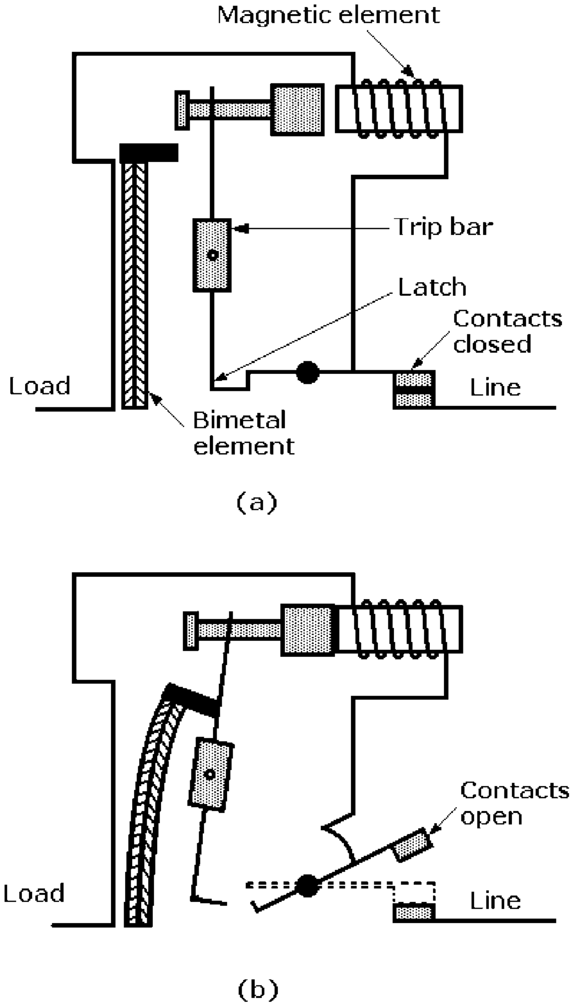


Figure 5-17 Thermal-magnetic circuit breaker trip latch operation: (*a*) normal; (*b*) overcurrent condition.

load. If the panel door is left open for a long period of time or is removed, the interior of the panel will cool to a lower temperature. This additional cooling will allow the breaker's thermal element to exceed its rated continuous current. This could mean that the load it is protecting could overheat.

Circuit breaker manufacturers have different methods for attaching their breakers to the "hot" bus bars. Most breakers have some form of notch on one end of their lower surfaces and conductive clips on the other ends. Typical loadcenter "hot" bus bars have projections alternating from the inner sides of the bars. As stated earlier, the ends of these projections are bent outward at right angles to form stabs. The breakers are installed by hooking the notch at one end under a rail and pressing the conductive clips down over the stabs to make low-resistance contacts with the "hot" bus bars.

Single- and double-pole breakers are most widely used in loadcenters. Single-pole units, rated for 120/240 V AC, are designed to be plugged onto a single bus stab to obtain 120 V between one of the "hot" bus legs and the neutral bus, as shown in Fig 5-14. These breakers are available in ratings from 15 to 70 A, but ratings of 15 and 20 A are most commonly used in homes. They are available in 1-in.-wide full-size, dual 1-in. widths, and half-size $^1/_2$-in. widths.

Some single-pole units are UL listed as HACR type, for air-conditioning, heating, and refrigeration equipment service, as well as being UL listed for SWD (switching duty) for switching 120-V AC fluorescent lighting loads.

Two-pole breakers are rated 120/240 or 240 V AC. Standard sizes are plugged onto two adjacent stabs to obtain 240 V between both parallel "hot" bus bars. They are available with 10- to 125-V ratings. These breakers have a single common trip, and many are HACR type. Some circuit breaker applications by current rating are

- 15 and 20 A: Protection of baseboard heaters and pumps
- 30 A: Protection of water heaters, dryers, and air-conditioning equipment
- 40 to 50 A: Protection of ranges and stoves
- 50 A or more: Protection of electric heaters

Three-pole breakers rated for 240 V require three spaces for contact with three stabs, and they also have common toggle trips. They are typically listed as HACR type for use with air-conditioning, heating, and refrigeration equipment.

The number of single-pole circuit breakers that can be installed in a loadcenter is limited by the number of stabs on the bus bars. For example, a loadcenter with six stabs can accommodate 12 full-size, single-pole branch circuit breakers that are each 1 in. wide.

If the stab is notched, half-size branch circuit breakers can be used. Half-size circuit breakers allow two single-pole circuit breakers to be installed in the space originally intended for a 1-in.-wide full-size breaker. Each half-size unit is only $^1/_2$ in. wide. Where they are allowed by the local electrical code, these breakers function as well as full-size breakers and offer the added convenience of a more compact installation.

Some local inspectors do not allow half-size circuit breakers because it is possible that they could overload the loadcenter or unbalance the system. To balance the loads, circuit breakers must be evenly allocated by current rating to each side of the stab.

It is important that the maximum continuous amperes and available fault current be known when specifying loadcenters and overcurrent protection devices. There are two ways to meet this requirement: full-rating or series-rating method.

- *Full-rating method:* Circuit protection devices are specified with ratings equal to or greater than the available fault current. For example, if a building has 22,000 A of fault current available at the service entrance, every circuit protection device must be rated at 22,000 A.
- *Series-rated method:* The main upstream circuit protection device must have an interrupting rating equal to or greater than the available fault current of the system. Downstream devices connected in series can be rated at lower values. For example, a building with 20,000 A of available fault current might have the breaker at the service entrance rated for 20,00 A and additional downstream breakers rated at 10,000 A.

GFCI Circuit Breakers

The NEC requires that ground-fault circuit interrupters (GFCIs) be installed in many different rooms and locations in both public and private buildings. They are now required in bathrooms, kitchens, appliance rooms or spaces, and garages. In addition, they are required in basements, near swimming pools, hot tubs, or fountains, and in outdoor receptacles. While these requirements are most commonly met with GFCI dual receptacles, they can also be met with GFCI branch circuit breakers.

GFCI circuit breakers and receptacles protect persons from ground faults. These are typically caused by "hot" conductors with inadequate insulation coming in contact with an ungrounded metal object such as an appliance cabinet. If the metal surface is not electrically grounded, a *ground fault* will be created. Any person touching that metal object while standing on a conducting surface (for example, a wet floor) could get a fatal electrical shock because his or her body has effectively become the grounding conductor.

The current required to trip a standard circuit breaker is many times greater than the amount needed to inflict a fatal shock. It was clear that smaller, less expensive, and more sensitive GFCI circuits were needed because early GFCI circuits were clumsy and expensive. However, later versions that included solid-state electronics were small and could be mass-produced cheaply. A more complete discussion of ground faults and GFCI circuit operation is presented in Chap. 6.

To comply with UL Standard 943, Class A, a GFCI must trip in the presence of a ground fault as small as 5 mA (±1 mA) within about 25 ms. The NEC requires that GFCI protection be available in the locations previously listed. This can be accomplished by installing approved GFCI receptacles at those locations. Alternatively, GFCI circuit breakers in the loadcenter can protect downstream standard receptacles in branch circuits serving locations where GFCI protection is required.

GFCI circuits are now included in GFCI receptacles and miniature circuit breakers. GFCI circuit breakers have the same outline dimensions and are installed in the loadcenters in the same way as standard units. The only visible difference is that they have two built-in leads. Available in ratings from 15 to 60 A, the 15- and 20-A units are the most popular. Their amperage ratings must match the amperage ratings of the wire gauge of the branch being protected. One of the two leads of the GFCI circuit breaker is connected to the load neutral and the other, identifiable by its black-and-white stripe, is connected to the neutral bus to establish a zero reference.

The disadvantage of GFCI circuit breakers is that after a ground fault has been detected, a GFCI circuit breaker will disable the entire branch circuit. The branch circuit will remain inoperative until someone finds and corrects the fault and then goes to the loadcenter to reset the circuit breaker manually. This can be awkward and time-consuming. By contrast, under the same circumstances a GFCI receptacle will disable only itself and any standard receptacles downstream of it, but not the entire branch circuit. After correcting the fault, the protected receptacles can be reactivated manually simply by pushing the reset button on the face of the GFCI receptacle.

The NEC 2002 requirement that all outside outlets be GFCI-protected can be met with GFCI receptacles, but they are vulnerable to water from rain, snow, lawn sprinklers, and condensation. Consequently, if used outdoors they must be protected by gasketed metal or plastic weatherproof enclosures. An advantage of GFCI circuit breakers is that they can protect outside receptacles without the need for weather protection.

Fuses Rated for 60 A or Less

Fuses are safety devices that protect electrical systems from overloads and short circuits by interrupting the current flow in the circuit. There are many different kinds of fuses, ranging from those rated for thousands of amperes for protecting electrical equipment from generators to distribution lines down to those rated for less than 100 A for protecting electronic circuit boards.

Most residential loadcenters installed before 1965 were designed to accept fuses for branch circuits rated for less than 50 A. The standard fuses had screw-in-type Edison bases for protecting 120-V AC power and lighting circuits. General-purpose household fuses rated up to 30 A contain a conductive metal alloy ribbon that melts or “blows” if an overload condition occurs. Cartridge fuses were used to protect 240-V AC appliance circuits and the main shutoff of the loadcenter.

The main disadvantage of these fuses is that they are one-time-only (OTO) devices that must be replaced if blown. It was recognized that replacing blown fuses is a time-consuming chore that presents an electrical hazard for all those persons not familiar with electric circuits. Also, replacing a blown fuse with one having a higher rating can result in overheating in the circuit it was intended to protect. This could result in a fire or damaged or destroyed appliances and other electrical devices.

As a result of the shortcomings of standard plug fuses, the NEC now requires that comparably rated circuit breakers be installed in all new construction. However, many different ratings and styles of standard fuses are readily available for replacing blown fuses in older service panels.

The rating of the fuse should match the amperage rating of the wire gauge in the branch circuit it is protecting. For example, a circuit using No. 12 AWG copper conductors has an ampacity of 20 A, so the fuse must also be rated for 20 A.

The most common household plug fuses rated for 60 A and less are

- W series: fast-acting, general purpose
- S and T series: time-delay, dual-element
- SL and TL series: time-delay, loaded-link

W SERIES GENERAL-PURPOSE FUSES

General-purpose, fast-acting plug fuses with Edison bases, as shown in Fig. 5-18*a,* are available in ratings from $^1/_2$ to 30 A, 125 V AC. Their fuse elements are simple metal links that quickly open when a short circuit or significant overcurrent occurs. These fuses are suitable for the protection of lighting and other nonmotor circuits.

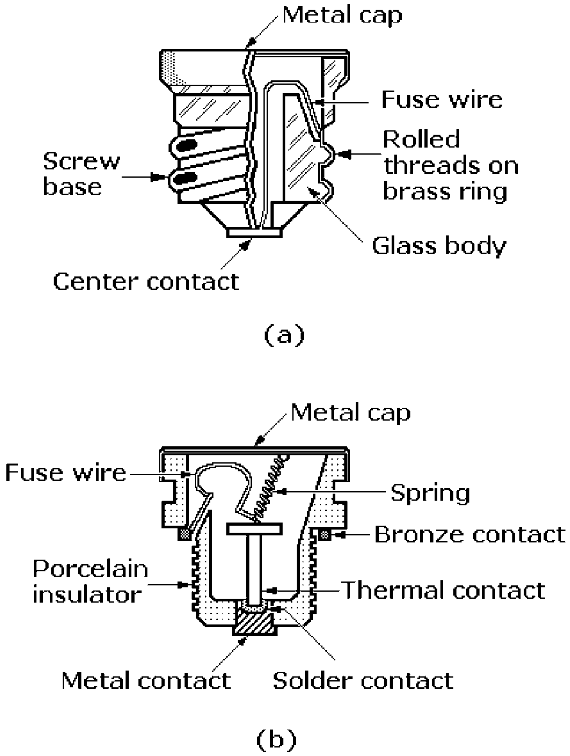


Figure 5-18 **Plug fuses: (*a*) general-purpose Edison-base W series; (*b*) time-delay rejection-base S series.**

The momentary current surge caused by a motor at start-up can cause nuisance blowing if these fuses are used to protect motors. Series W fuses rated to 20 A have glass bodies, and those rated for 25 and 30 A have ceramic bodies. Metal rings with formed threads are attached to the fuse bodies to fit the base threads of fuse sockets. The NEC permits Edison-base fuses as replacements only in existing fused service panels. Fuses rated 15 A and less in 120-V AC circuits have hexagonal windows, while those with ratings of 20, 25, and 30 A have round windows.

S AND T SERIES TIME-DELAY FUSES

S series time-delay, dual-element fuses have ratings of $^1/_4$ to 30 A, and T series fuses have ratings of $^3/_{10}$ to 30 A, 125 V AC. These fuses were developed for circuits that include motors. S and T fuses are all-purpose fuses that function like two fuses in one. Each fuse contains a simple link element that blows for short circuits and dangerous overloads and a series-connected element that lets harmless motor overload starting currents pass without opening. The T series fuse can replace an Edison-base W series fuse where a time-delay feature is desired.

All Edison-base fuses have the same physical size and threads, so they can be easily confused—a 15-A fuse can easily be replaced with a 30-A fuse. This can lead to dangerous circuit underprotection. To overcome this problem, fuse adapters with *rejection bases* were developed for S series fuses. The adapters screw into the threads of standard fuse sockets, and once screwed in, they cannot be removed. The rejection-base fuses are then screwed into the adapters. These adapters are now required by the NEC to prevent accidental insertion of the wrong size fuse. The three ranges for screw-base adapters are 0 to 15 A, 16 to 20 A, and 21 to 30 A. An S series fuse with a rejection base is shown in Fig. 5-18*b*. It has ceramic threads that screw into the fuse adapter. S series fuses are required in all new service panels that permit the use of fuses for protection up to 125 V AC.

SL AND TL SERIES TIME-DELAY FUSES

The SL and TL series time-delay, loaded-link fuses are modified S and T fuses with ratings of 15 to 30 A, 125 V AC. They are intended for use with motors because they allow 5 times their rated current to flow for up to 6 s. This permits brief overload currents to pass without needlessly opening the circuit. A heat-absorbing metal bead in the fusible metal link permits the time delay. Fuses in the TL series, like those in the T and W series, have Edison bases, but the SL series fuses have rejection bases.

CARTRIDGE FUSES

Cartridge fuses represent the oldest form of fuse construction still in use today. There are two basic styles, ferrule and knife-blade. *Ferrule fuses,* available in ratings of 10 to 60 A, are typically used to protect 120/240-V AC appliance circuits. Both fast-acting and time-delay versions are available. These fuses consist of fiber tubes with metal caps on both ends. This permits them to make electrical contact with the circuit being protected by snapping them into end clips on fuse holders in the protected circuits.

A fusible metal strip is connected axially inside the fiber tube between both metal end caps or ferrules, and is embedded in fire-resistive powder. As in other fuses, the fusible strip vaporizes or blows in the presence of overloads and short circuits.

Knife-blade fuses are generally used for main circuit protection in fused loadcenters. General-purpose versions with ampere ratings of $^1/_8$ to 600 A are available with voltage ratings to 600 V AC. Dual-element, time-delay versions permit a 10-s delay at 500 percent of rated current. They are rated at 1 to 600 A and up to 600 V AC. Made basically the same way as ferrule-style fuses, the blades on their end caps permit them to make more secure contact with their metal clips when inserted in protected circuit fuse holders.

Grounding Electrical Service

Article 250, “Grounding,” of NEC 2002 covers the general requirements for grounding and bonding electrical circuits. Grounding is one of the most important, but least understood, considerations in designing electrical systems. Grounding refers to techniques for making low-resistance connections from wiring and electrical equipment to earth or ground. This connection can be a wire making a direct connection to a grounding electrode buried in the earth, or it can be a connection to some other approved ground such as a metal cold-water pipe or metal reinforcing bar projecting from a concrete foundation or footing. NEC 2002 requires that two approved grounding methods be used, but warns against the use of metal gas pipe for grounding.

Grounding provides protection for personnel, equipment, and circuits by eliminating dangerous or excessive voltages in the system. Under certain conditions, higher than normal voltages can occur at points in an electrical system or in electrical equipment connected to the system. Proper grounding ensures that these overvoltages are channeled to earth or ground.

The two elements in electrical system grounding are wiring system and equipment grounding. *Wiring system grounding* is the grounding of one of the wires of the electrical system, such as the neutral, to limit overvoltages on the circuit. Overvoltages can be caused by lightning or accidental contact with other circuits carrying higher voltages than the grounded circuit. In addition, grounding one of the wires of the system limits maximum voltage to ground under normal operating conditions. Also, a circuit with a grounded conductor can have an automatic circuit-opening device installed if a potentially dangerous ground fault should occur on one of its ungrounded conductors.

Equipment grounding is the permanent and continuous bonding together of all metal parts of equipment enclosures such as conduit, boxes, cabinets, motor frames, and lighting fixtures that are not intended to carry current and their connection to a system grounding electrode. The bonding or interconnection of metal enclosures provides a low-impedance path for fault-current flow while permitting enough current to flow to blow the fuses or open the circuit breakers protecting the circuit. This permits the installation of GFCI circuits which open automatically in the presence of a ground fault. They prevent the accidental conduction of voltages by metal enclosures, which can present a possibly fatal shock hazard to personnel who touch the equipment.

NEC 2002, Article 250, defines *effective grounding path* and establishes mandatory requirements for grounding circuits. There are three required characteristics of grounding paths that must be satisfied by the installer.

1. Every ground path must be "permanent and continuous." This can be verified visually and no specific continuity test is specified.
2. Every grounding conductor must have the "capacity to conduct safely any fault current likely to be imposed on it." This is met by adequate sizing of grounding conductors.
3. The impedance of the fault-ground path over the raceways or equipment grounding conductors must be "sufficiently low" for enough current to flow to open the circuit breaker of the fuse nearest the fault on its line side. (No specific instructions are given as to the best test method to determine what is "sufficiently low impedance.") The installer is burdened with the responsibility for determining that value.

One section of Article 250 gives the conditions under which AC circuits operating at less than 50 V must be grounded, and another states that all AC wiring systems from 50 to 1000 V must be grounded so that the maximum voltage to ground does not exceed 150 V. It is required that the following systems or circuits have one conductor grounded:

- 120-V, two-wire
- 240/120-V, three-wire (neutral grounded)
- 208/120-V, three-phase, four-wire, wire-connected (neutral grounded)
- Where the grounded conductor is uninsulated

Other systems operating at higher voltages must be grounded if the neutral conductors are used as circuit conductors. Neutrals must be grounded to assure that maximum voltage to ground does not exceed 150 V.

As stated earlier, in 120/240-V single-phase service, one end of the bare wire cable in the service drop that supports the two "hot" wires from the pole-mounted transformer is spliced to the utility pole's grounding network and the other end is spliced to the ground wire within the SE cable. After the other end is connected to a copper bus bar in the meter base, an extension from that bus bar extends to the main circuit disconnect breaker on the power and lighting loadcenter.

The configuration of "hot" conductive and neutral legs in the loadcenter provides a safe means for splitting the 240 V AC to yield 120 V AC between the two phases A and B and the neutral conductor. Both of the 240-V phases derived from the secondary winding of the transformer are ungrounded, but the neutral is a grounded conductor.

If only 240-V AC loads were connected, the neutral conductor would carry no current. However, with the arrangement of conductive legs and neutral conductor within the loadcenter providing 120-V AC power, the neutral carries the unbalanced load and becomes a current-carrying conductor. For example, if phase A carries 60 A and phase B carries 50 A, the neutral conductor would carry only 60 A − 50 A = 10 A. This is why the NEC allows the neutral conductor in an electric service to have a smaller wire gauge than ungrounded conductors.

GROUNDING ELECTRODE SYSTEMS

The rules for the grounding electrode arrangement required at the service entrance of the premises or in a building or other structure fed from another service are covered in NEC 2002, Section 250.50, "Grounding Electrode Systems," Section 250.52, "Grounding Electrodes," and Section 250.52(A), "Electrodes Permitted for Grounding." Generally, all or any of the electrodes listed below, if they are available on the premises, must be bonded together to form the "grounding electrode system."

- *Metal cold-water pipe* with at least 10 ft of its length buried in the ground. The connection must be made to the water pipe at a point less than 5 ft from where the water pipe enters the building. The cold-water pipe is now considered the least acceptable electrode, and is the only one that may never be used by itself as the sole electrode. It must always be supplemented by at least one "additional" grounding electrode. Any one of the other electrodes listed below is acceptable as the sole grounding electrode.
- *Metal frame of a building,* provided the frame is effectively grounded (embedded in earth and /or buried in concrete if it is effectively grounded).
- *Concrete-encased electrode* within and near the bottom of a concrete foundation or footing in direct contact with the earth. The electrode must consist of at least 20 ft

of one or more steel reinforcing bars or rods of not less than $^1/_2$-in. diameter, or at least 20 ft of bare copper conductor not smaller than No. 4 AWG.

- *Ground ring encircling the building or structure,* buried directly in the earth at least $2^1/_2$ ft down. The ground ring must be at least 20 ft of bare No. 2 or larger copper conductor. (It is expected that the conductor will have to be much longer than 20 ft to encircle the building.)
- *Rod and pipe electrodes* that are not less than 8 ft long.
- *Plate electrodes* with surface areas of at least 2 ft^2 made of iron or steel plates at least $^1/_4$ in. thick. Electrodes of nonferrous metal at least 0.06 in. thick are also approved.

NEC 2002, Section 250.52(B), "Electrodes Not Permitted for Grounding Electrodes," states that neither metal underground gas piping systems nor aluminum electrodes can be used as grounding electrodes.

In most residential structures, the only suitable grounding electrode on the premises is the cold-water pipe, but it must be supplemented by an additional electrode.

The components of a typical residential electric service and the approved connection methods for grounding two electrodes are shown in Fig. 5-19. Three conductive wire connections from the neutral/ground bus complete the ground wiring. One, called the *grounding jumper,* is clamped to the cold-water pipe, a second is clamped to the first ground rod, and the third connects the two ground rods together. The underground metal water pipe shown is in direct contact with the earth for more than 10 ft, making it an acceptable electrode.

GROUND ROD INSTALLATION

A typical "made" ground rod consists of an 8-ft length of rod or pipe that must be driven at least 8 ft into the ground. If a rock barrier is encountered before the rod is 8 ft in the ground, it can be driven at an angle of not more than 45° from the vertical. However, if the rock surface is so close to grade level that it is not possible to drive 8 ft of the rod in the earth even at the angle up to 45°, it is acceptable to dig a 2½-ft-deep trench and position the rod horizontally within the trench. In all options, the upper end of the rod must be flush with or below ground level unless the above-ground end and conductor clamp are suitably protected by an enclosure.

GROUND ROD/PLATE CHARACTERISTICS

The 8-ft length of metal rod, pipe, or plate electrode must have a resistance to ground of 25 Ω or less. If it has a resistance to earth greater than 25 Ω, it must be supplemented by an additional "made" electrode in parallel and spaced at least 6 ft away. However, there is no requirement that the resistance of the second electrode have a resistance to earth of less than 25 Ω. Even greater spacing is better for rods longer than 8 ft (1.44 m), because the combined resistance to ground is reduced.

In many locations, power company specifications and/or local building codes require two electrodes regardless of their resistance to ground, because of the poor conductivity of the soil. Also, in some locations the grounding rods must be copper

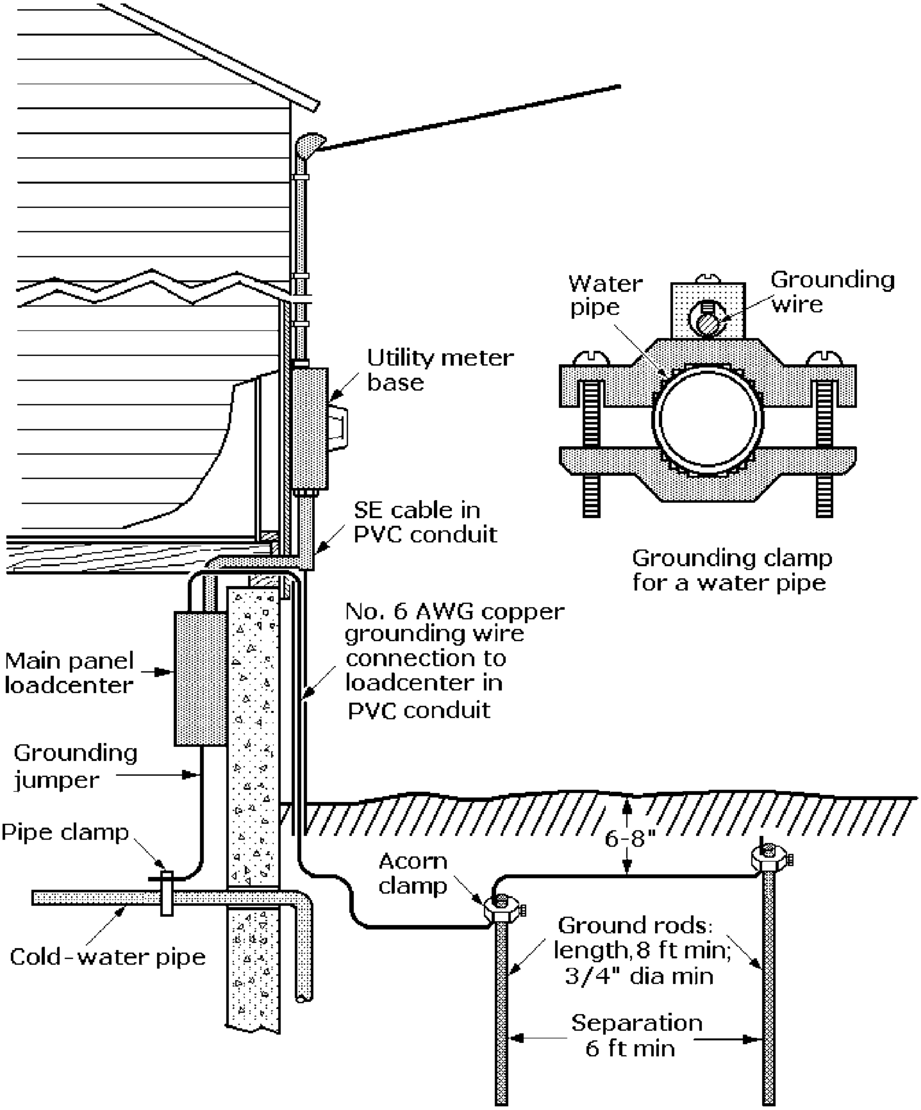


Figure 5-19 Typical service entrance grounding system. A second grounding rod can lower ground resistance in dry soil.

and at least $^1/_2$ in. in diameter. NEC 2002 does not allow grounding rods to be made from aluminum, but it allows grounding rods with any of the following characteristics:

- $^1/_2$-in.-min.-diameter stainless steel or other nonferrous rod
- $^5/_8$-in.-min.-diameter iron or steel rod
- $^3/_4$-in.-min.-diameter pipe or conduit with a galvanized or other metal-plated coating for protection against corrosion

BONDING THE GROUNDING ELECTRODE SYSTEM

When two or more of the grounding electrodes described in NEC 2002, Section 250.52, are to be combined into a grounding electrode system, the size of the bonding jumper between pairs of electrodes must not be smaller than the size of the grounding electrode conductor indicated in NEC 2002, Table 250-66. Table 5-2 is a short form of this table, but it does not include the notes about multiple service entrance conductors or situations where there are no service entrance conductors. A ground rod or other "made" electrode that supplements a water pipe electrode does not require a conductor larger than No. 6 AWG copper or No. 4/0 AWG aluminum or copper-clad aluminum for a bonding jumper that is the only connection.

INSTALLING GROUND CONDUCTORS

The grounding conductor that connects the loadcenter neutral bus to the water pipe and grounding electrodes must be made of conductive material that is resistant to any corrosive substances that exist at the site, or must otherwise be suitably protected against corrosion. The material can be either copper, aluminum, or copper-clad aluminum, solid or stranded, coated or bare. The conductor must be in one continuous length, without a splice or joint, with the following exceptions:

- If the connection is a bus bar, splices are permitted.
- Where a service consists of more than a single enclosure, it is permissible to connect taps to the grounding electrode conductor, provided that the taps are made within the enclosures.

TABLE 5-2 GROUNDING ELECTRODE CONDUCTORS FOR AC SYSTEMS

SIZE OF LARGEST UNGROUNDED SERVICE ENTRANCE CONDUCTOR OR EQUIVALENT AREA FOR PARALLEL CONDUCTORS (AWG/kcmil)		SIZE OF GROUNDING ELECTRODE CONDUCTOR (AWG/kcmil)	
COPPER	ALUMINUM OR COPPER-CLAD ALUMINUM	COPPER	ALUMINUM OR COPPER-CLAD ALUMINUM
2 or smaller	1/0 or smaller	8	6
1 or 1/0	2/0 or 3/0	6	4
2/0	4/0 or 250	4	2
Over 3/0 through 350	Over 250 through 500	2	1/0
Over 350 through 600	Over 500 through 900	1/0	3/0
Over 600 through 1100	Over 900 through 1750	2/0	4/0
Over 1100	Over 1750	3/0	250

Data from NEC 2002, Article 250, Table 250.66, p. 70-107.

- The grounding electrode conductor may also be spliced an any location with irreversible compression-type connectors approved for the purpose, or they may be welded by an exothermic process.

The size of grounding conductors is governed by the size of the largest service entrance conductor or its equivalent in parallel conductors.

Ground Testing

Every metal conduit, BX cable, box, and cover should be at ground potential, 0 V. Equipment that is not self-grounding through its plug should have its metal cover or cabinet connected to ground with the approved wire size. With the main power off, an ohmmeter should read 0 Ω when used to check the resistance from a metal plumbing pipe to all grounded points (socket terminals, outlet and switch plates, BX shields, conduit, appliance cabinets, etc.).

Ground resistance must be low to provide good protection for equipment and personnel against overvoltages due to lightning discharges or accidental line faults. Moisture in the soil or other factors cause differences in ground in resistance in different locations. Ground resistance measurements can be made with a special Megger, similar to those used for testing insulation in high megohm ranges (hi-pot testing), but modified to test for low readings such as leakage current and potential gradient along a distance from the ground rod. Figure 5-20 is a schematic diagram for the connection of a Megger ground tester and its principle of operation.

It is necessary to use separate potential and current reference grounds so that the Megger readout represents only the resistance associated with the ground rod being tested. Conversion circuitry is needed in the ground tester for producing AC current in the earth because if DC current were used, the moisture in the earth could produce electrolytic polarization at the electrodes that would degrade the measurement.

Temporary Electrical Service

Temporary electrical power and lighting are permitted by NEC 2002, Article 527, “Temporary Installations,” during the construction, remodeling, maintenance, repair, or demolition of buildings, structures, equipment, or similar activities. Among the “similar activities” are traveling carnivals or exhibits, holiday decorative lighting, or emergency situations that might call for powerful floodlights. Temporary installations of holiday decorative lighting, for example, are permitted for up to 90 days.

The electrical contractor is responsible for furnishing temporary power to the job site in new construction work. The temporary installation must meet Occupational Safety and Health Administration (OSHA) regulations and the NEC requirements and must have the cooperation and approval of the local electric utility. Utilities charge for

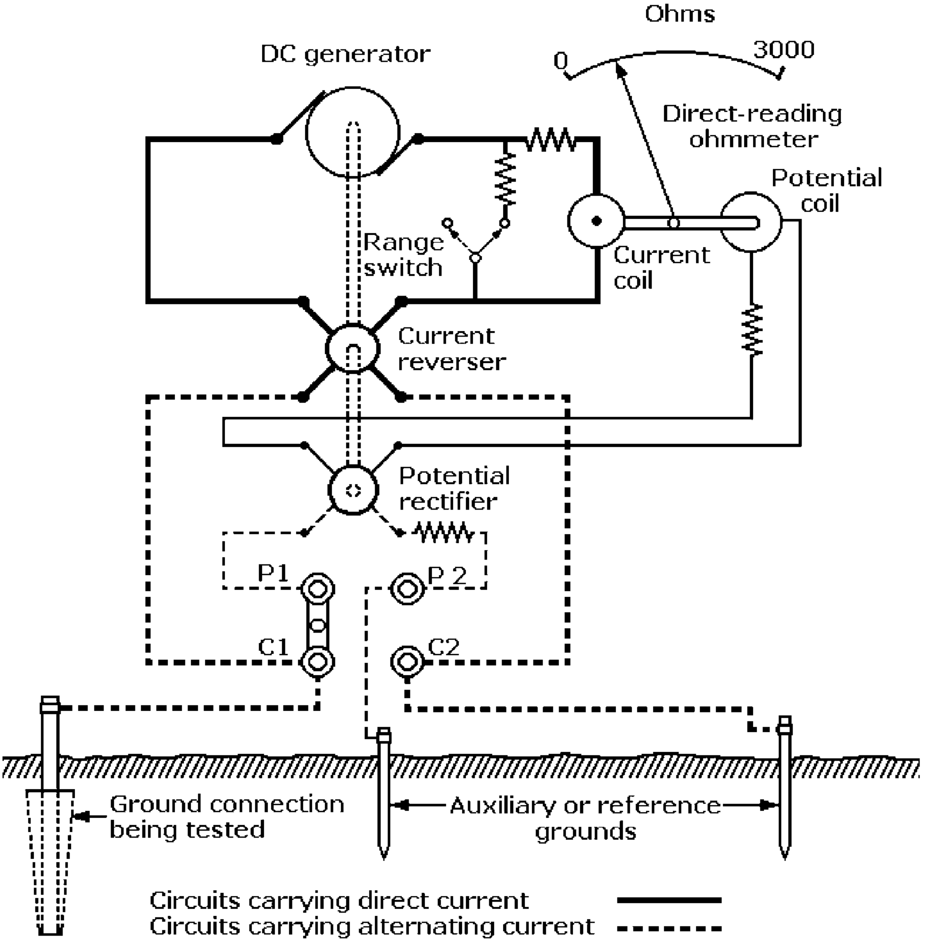


Figure 5-20 Schematic of a Megger ground resistance tester.

hooking up power lines to the temporary service and removing their power lines, connectors, and other related fittings needed to make the connection. The contractor/owner must pay the utility in advance and must pay for the electric current consumed, based on the appropriate service classification.

NEC 2002, Article 527, covers feeders, branch circuits, receptacles, disconnecting means, lamp and accidental damage protection, and device terminations. Emphasis is placed on GFCI protection for personnel and grounding provisions.

Many contractors build their own temporary service entrance assemblies to minimize the time and effort required to set up and remove temporary electrical service. Figure 5-21 illustrates a temporary installation assembly rated for 200 A, and Fig. 5-22 illustrates a temporary installation assembly rated for 100 A. The completely wired assemblies consist of rigid poles with weatherheads, conduit, service entrance (SE)-type cable, meter bases, meters, and appropriate grounding connections. These assemblies

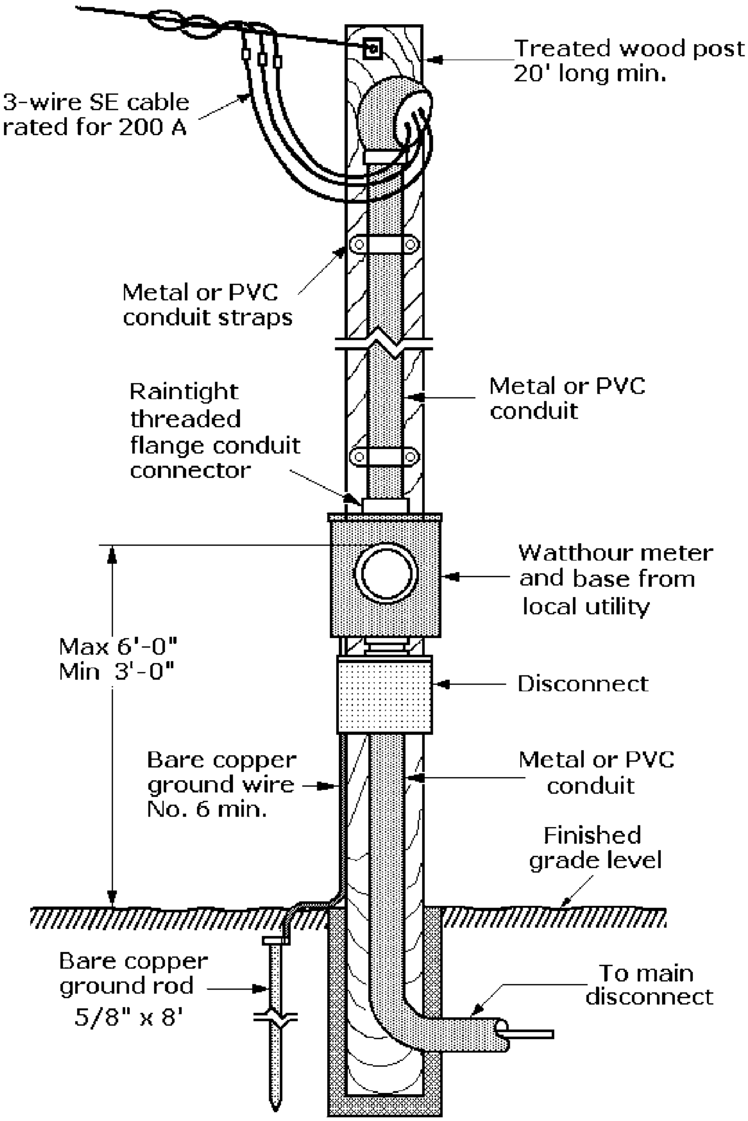


Figure 5-21 Temporary service entrance assembly rated for 200 A with SE cable protected by conduit to the meter base.

can be self-supporting, fastened to existing utility poles, or fastened to the structure of the building under construction. The assemblies are constructed so that they can easily be moved from site to site. In the figures the temporary service is routed underground, but where adequate overhead space permits, the service might be overhead. A major East Coast public utility, for example, specifies a treated pole, minimum Class 7, or equivalent, set in solid earth where no building exists. The contractor/customer is required to provide substantial and adequate support for the pole, guyed if necessary.

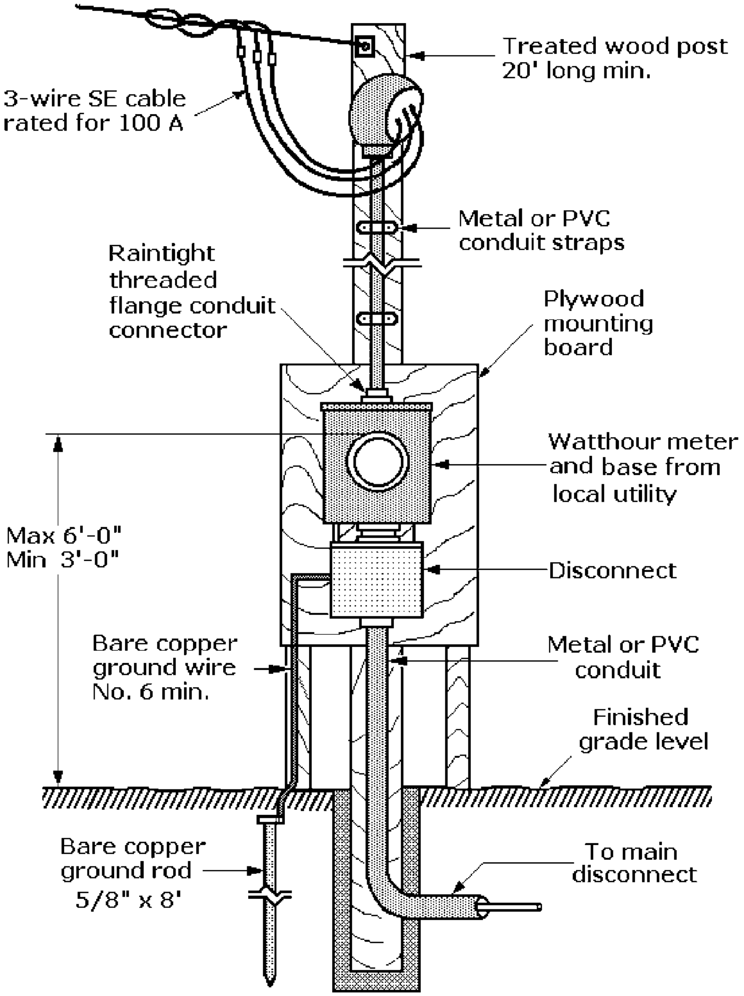


Figure 5-22 **Temporary service entrace assembly rated for 100 A with SE cable exposed to the meter base.**

This support can be a 4- × 6-in. timber securely attached to the framing of a building (not a contractor's mobile field office) and extending no more than 3 ft above the support if unguyed or 8 ft if guyed.

Glossary of Electrical Service Terms

Service: The conductors and equipment for delivering electric energy from the serving utility to the wiring system of the premises served.

Service cable: Service conductors made up in the form of a cable.

Service conductors: The conductors from the service point to the service disconnecting means.

Service drop: The overhead service conductors from the last pole or other aerial support to and including the splices, if any, connecting to the service entrance conductors at the building or other structure. Also called a *triplex.*

Service entrance conductors, overhead system: The service conductors between the terminals of the service equipment and a point usually outside the building, clear of building walls, where joined by tap or splice to the service drop.

Service entrance conductors, underground system: The service conductors between the terminals of the service equipment and the point of connection to the service lateral.

Service equipment: The necessary equipment, usually consisting of a circuit breaker(s) or switch(es) and fuse(s) and their accessories, connected to the load end of service conductors to a building or other structure, or an otherwise designated area, and intended to constitute the main control and cutoff of the supply.

Service lateral: The underground service conductors between the street main, including any risers at a pole or other structures or from transformers, and the first point of connection to the service entrance conductors and a terminal box or meter or other enclosure, inside or outside the building wall. Where there is no terminal box, meter, or other enclosure, the point of connection is considered to be the point of entrance of the service conductors into the building.

Service point: The point of connection between the facilities of the serving utility and the premises wiring. Also called the *point of entry.*

Triplex: See *service drop.*

Weatherhead: A spherical metal cap mounted at the top of the service entrance conduit to protect the entrance of the service drop and prevent corrosion caused by rain or snow entering the conduit, meter socket, and service equipment. Also called a *service head.*

6

WIRE, CABLE, AND CIRCUIT COMPONENTS

CONTENTS AT A GLANCE

Overview
Insulated Wire Conductors
Wire Insulation and Cable Coding
Service Entrance Cables
Nonmetallic Cables
Metal-Clad Cables
Communications Cables
Metal and Nonmetallic Conduit
Conduit Bodies and Fittings
Electrical Boxes
Outlet Box Wiring
Wall-Mounted AC Switches
Lamp Dimmers and Fan Controls
Motion/Occupancy Sensors
Wall-Mounted Receptacles and Plugs
Ground-Fault Circuit Interrupters
Isolated-Ground Receptacles
Locking Receptacles and Plugs
Pin-and-Sleeve Devices
Wire Mesh Cable Grips
Glossary of Wiring Device Terms

Overview

This chapter focuses on the standard wire, cable, and electrical devices used in homes and offices, with emphasis on branch circuits. Many different kinds of standard wire and cable are available for use in 120/240-V AC branch-circuit wiring. Wire is defined as a single solid or twisted copper or aluminum conductor with or without insulation, and cables for power and lighting typically consist of two or more insulated wires and a bare ground wire with a protective jacket. There are also untwisted and twisted wire pairs for telephone service and coaxial cables for TV and Internet reception.

Conduit is tubing or pipe that encloses and protects wires and cables. It can be metal or nonmetallic, and rigid or flexible. In outdoor locations, conduit protects the enclosed wires or cable above ground from rain, snow, condensed moisture, and abrasion as well as accidental severence during excavation or trench digging. It is also used to protect buried cable. Short lengths of conduit are used under concrete sidewalks to make it easier to pull wires or cable under those obstructions. In addition, short lengths are used to protect wire or cable as it emerges from the ground to a meter base or other enclosure.

Conduit bodies are fittings that permit electrical metallic tubing (EMT) conduit to be joined in straight lengths or in 90° turns. Many different kinds of conduit connectors and couplings are available for coupling or connecting similar or dissimilar conduit. These products are made from materials such as zinc-plated steel, malleable iron, aluminum, die-cast zinc, and nylon.

Junction and pull boxes provide access points for pulling and feeding conductors into a raceway system. Their use is mandatory in conduit runs where the number of bends between outlets exceeds the maximum permitted by the National Electrical Code (NEC). Conduit is also used inside homes or buildings to protect wiring or cable from moisture, dust buildup, or abrasion.

Wall switches are designed for mounting inside wall-mounted outlet boxes and before being covered with decorative wallplates. Standard switches are available in all specification grades with ratings of 120/240 V AC, and some industrial and commercial grades are rated for 347 and 600 V AC. Switches can be single-pole, three-way, or four-way, and they can include pilot lights, lighted handles, and locks.

Conventional dimmers are wall-mounted devices for reducing the illumination levels of incandescent lamps. Other versions with different internal circuits are designed for dimming fluorescent lamps or controlling the speed of fans. Dimmers can change the illumination levels in a room and can help to conserve energy.

Motion or occupancy sensors are switches that can turn on lights or other appliances automatically when a person enters a room, and turn them off when the person leaves. The most popular motion-sensing technologies are passive infrared (PIR) and ultrasonic. These sensors are also used in security systems to warn of intruders inside or outside homes or buildings.

General-purpose duplex straight-blade receptacles are the familiar electrical outlets most often seen in homes and offices. They are designed to accept two- or three-prong plugs on line cords. Ground-fault circuit-interrupter (GFCI) receptacles, now required by the NEC in many areas of a home, protect persons from electric shock should a bare or abraded conductor come in contact with an exposed metal object.

Locking-type plugs and receptacles are widely used in industry to clamp line cords from heavy-duty power tools securely in their receptacles. They can preventing possible injury to operators or damage to property if the plugs are accidentally pulled from their receptacles. Pin-and-sleeve devices are heavy-duty connectors for distributing electric power in industrial plants. They include plugs, receptacles, inlets, and connectors.

Insulated Wire Conductors

The American Wire Gauge (AWG) is used in the United States to identify specific wire diameters. The AWG values for wires commonly used to conduct 120/240-V AC and communications signals in homes and offices are illustrated in Fig. 6-1.

Ampacity, a word coined by combining the terms *ampere* and *capacity,* expresses the current-carrying capacity of wires and cables in units of amperes. It is important in the selection of wire and cables for various applications because it signifies maximum safe current-carrying capacity for conductors.The numbers used to identify wire diameter and ampacity are inversely related to AWG sizes. For example, 10 AWG wire has an ampacity rating of 30 A, No. 12 AWG wire has an ampacity rating of 20 A, while No. 14 AWG wire has a lower ampacity rating of 15 A, all for use in 120/240-V circuits.

On the other hand, relatively fine No. 16 and No. 18 AWG wires are not given ampacity rating because, as low-voltage or signal-level conductors, they are incapable of carrying useful power.

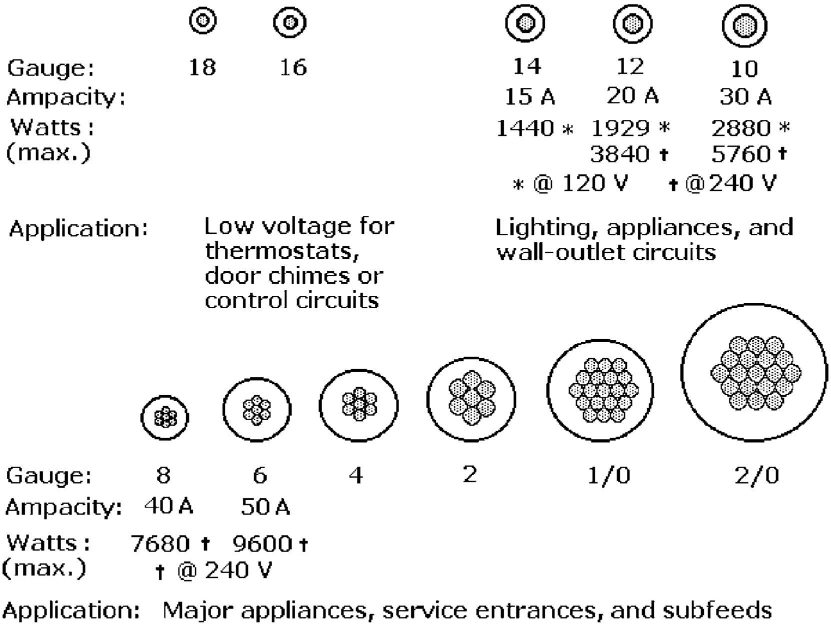


Figure 6-1 Cross sections and ratings of common copper wire gauges.

The ampacity of insulated wire, solid or stranded, depends on its gauge, metal composition, and the thermal properties of its insulation. Copper is preferred for electrical conductors because of its high conductivity, ductility, and resistance to corrosion, but aluminum and copper-clad aluminum wire are approved for some applications.

The classification of insulation, either thermoplastic or thermoset, generally determines its suitability for use under various ambient conditions. Thermoplastic materials, typically plastic resins, soften and flow when they are heated and subjected to pressure, but they become rigid when cooled. Thermoset materials, by contrast, are initially set or cured when heated, but after curing they will not soften, flow, or distort. Some kinds of insulation are approved for wire only if it is to remain in a dry environment, preferably within a building, but other insulating materials have been formulated to stand up to environments that are dry and damp, dry and wet, or wet, and still other materials can withstand extreme temperatures. For example, some insulated wire can perform effectively only up to 60°C (140°F), while others can perform effectively at temperatures as high as 90°C (194°F).

All modern electrical wire insulation is rated as flame-retardant, but only a few of these insulation materials are capable of remaining effective insulators following long-term exposure to sunlight (ultraviolet radiation), ozone, or nuclear radiation.

A letter code has been established to simplify the selection of the optimum insulated wire for specific tasks while considering operating temperatures and application environments. A knowledge of this code will permit the user suffucient background information to make the best selection. Examples of these code designations are RHH, THHN, TW, and XHHW.

Copper and aluminum wire are identifiable on sight by their color—reddish brown for copper and silver for aluminum. However, it is difficult to identify copper-clad aluminum wire on sight without making a clean cut through the wire to examine the core. On the other hand, even experts have trouble identifying wire insulation. For this reason, manufacturers print an identification code directly on the wire insulation, giving:

- The trade name of the insulation
- The wire’s maximum operating temperature
- Environments for safe application (dry, damp, wet, or combinations of these)
- Insulation properties (e.g., flame-retardant and moisture- and/or heat-resistant)

Table 6-1, excerpted from Table 310.13 of NEC 2002, translates the insulation codes printed on the most commonly used insulated wires for electrical power power conduction. (To keep the table short and easier to read, codes identifying special-purpose insulated wire were omitted.)

Table 6-2, excerpted from Table 310.16 of NEC 2002, gives the ampacity values of copper, aluminum, and copper-clad aluminum wires from 14 to 4/0 AWG, with a wide range of insulations indicated by their manufacturing code types such as RHW, THHW, or XHHW. The maximum temperatures at which these insulated wires can function effectively are classified into three groups: 60°C (140°F), 75°C (167°F), and 90°C (194°F).

TABLE 6-1 IDENTIFICATION OF INSULATION CODES ON COMMON ELECTRICAL WIRES

TRADE NAME	TYPE LETTER	MAX. OPERATING TEMP.	APPLICABLE LOCATIONS	INSULATION
Thermoset	RHH	90°C 194°F	Dry and damp	
Moisture-resistant thermoset	RHW	75°C 167°F	Dry and wet; ozone-resistant when > 2000 V applied	Flame-retardant, moisture-resistant thermoset
Moisture-resistant thermoset	RHW-2	90°C 194°F	Dry and wet	Flame-retardant, moisture-resistant thermoset
Heat-resistant thermoplastic retardant	THHN	90°C 194°F	Dry and damp (for use in conduits)	Flame-retardant, heat-resistant thermoplastic
Moisture- and heat-resistant thermoplastic	THHW	75°C 167°F 90°C 194°F	Wet Dry	Flame-retardant, moisture- and heat-resistant thermoplastic
Moisture- and heat-resistant thermoplastic	THWN	75°C 67°F	Dry and wet (for use in conduits)	Flame-retardant, moisture- and heat-resistant thermoplastic
Moisture-resistant thermoplastic	TW	60°C 140°F	Dry and wet	Flame-retardant, moisture-resistant thermoplastic
Thermoset	XHH	90°C 194°C	Dry and damp	Flame-retardant thermoset
Moisture-resistant thermoset	XHHW	90°C 194°F 75°C 167°F	Dry and damp Wet	Flame-retardant, moisture-resistant thermoset
Moisture-resistant thermoset	XHHW-2	90°C 194°F	Dry and wet	Flame-retardant, moisture-resistant thermoset

The letter translations are:

H indicates a maximum allowable temperature of 75°C; if not present, the maximum is 60°C.
HH indicates a maximum allowable temperature of 90°C.
HHW indicates a maximum allowable temperature of 90°C for dry locations and 75°C for wet locations.
N indicates a nylon sheath around the thermoplastic insulation.
R indicates thermoset insulation.
T indicates thermoplastic insulation.
W indicates suitability for wet and dry locations.
X indicates cross-linked polyethylene thermoset insulation.
−**2** indicates allowable temperature of 90°C, wet or dry.

Source: NEC 2002, Article 310, Table 310.13, pp. 70-138 to 70-141.

TABLE 6-2 ALLOWABLE AMPACITIES OF INSULATED CONDUCTORS

	TEMPERATURE RATING OF CONDUCTOR						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types RHH, RHW-2, THHN THHW, THW-2, THWN-2, USE-2, XHH, XHHW, ZW-2, XHHW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	
SIZE (AWG or kcmil)	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			SIZE (AWG or kcmil)
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14	20	20	25	—	—	—	—
12	25	25	30	20	20	25	12
10	30	35	40	25	30	35	10
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	115	3
2	95	115	130	75	90	100	2
1	110	130	150	85	100	115	1

1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
CORRECTION FACTORS							
AMBIENT TEMPS.		**For ambient temperatures other than 30°C, multiply the allowable ampacities shown shown above by the appropriate factor shown below**					
˚C	**˚F**						
21–25	70–77	1.08	1.05	1.04			
31–35	87–95	0.91	0.94	0.96			
41–45	105–113	0.71	0.82	0.87			
51–55	123–131	0.41	0.67	0.76			
61–70	141–158		0.33	0.58			

Conditions: No more than three current-carrying conductors in raceways, cables, or buried directly in earth; based on ambient temperature of 30°C (86°F).
Source: NEC 2002, Table 310.16, p. 70-144.

The first half of Table 6-2 gives the values for copper wire separately from those for aluminum and copper-clad aluminum in the second half. The ampacity ratings for aluminum and copper-clad aluminum are identical for all guages and temperatures. Many of the same insulations are used on both copper and aluminum wires. Examination of the table reveals that all insulated copper wire gauges have higher ampacity ratings than comparable aluminum wire gauges for all insulations.

Table 6-2 assumes that not more than three of the current-carrying conductors listed are located in one raceway or cable or buried together directly in the earth. A selection of correction factors for five ambient temperature ranges, from 21–25°C (70–77°F) to 61–70°C (141–158°F), was taken from NEC 2002, Table 310.16. It will permit reasonable estimates to be made of the ampacity values of individual insulated wires at temperatures above and below the base ambient temperature of 30°C (86°F). The complete NEC table includes 10 ambient temperature ranges, from 21–25°C (70–77°F) to 71–80°C (159–176°F), for more precise ampacity estimates.

NEC 2002, Table 310.16, also includes wire gauges from 250 to 2000 AWG. A footnote reference to NEC 2002 Article 240.4(D) limits the maximum current permitted in selected wires as follows:

- 14 AWG copper wire shall not exceed 15 A.
- 12 AWG copper wire shall not exceed 20 A.
- 10 AWG copper wire shall not exceed 30 A.
- 12 AWG aluminum and copper-clad aluminum wire shall not exceed 15 A.
- 10 AWG aluminum/copper-clad aluminum wire shall not exceed 25A.

Wire Insulation and Cable Coding

INSULATED WIRE CODING

The wire manufacturers' wire markings give:

- Wire gauge
- Maximum voltage rating
- Insulation code (R for thermoset, T for thermoplastic, X for cross-linked polyethylene thermoset)
- Maximum temperature code (H for 75°C, HH for 90°C, nothing for 60°C)
- Abbreviation for sheath if present (e.g., N for nylon)

The identification codes for wires with thermoplastic insulation approved for use in conduit are given in Fig. 6-2*a* for THHN and in Fig. 6-2*b* for THWN.

CABLE IDENTIFICATION AND CODING

Cables are identified by their wire gauge and the number of insulated wires they contain. In addition, all cables have a grounding wire. The codes printed on the jackets of

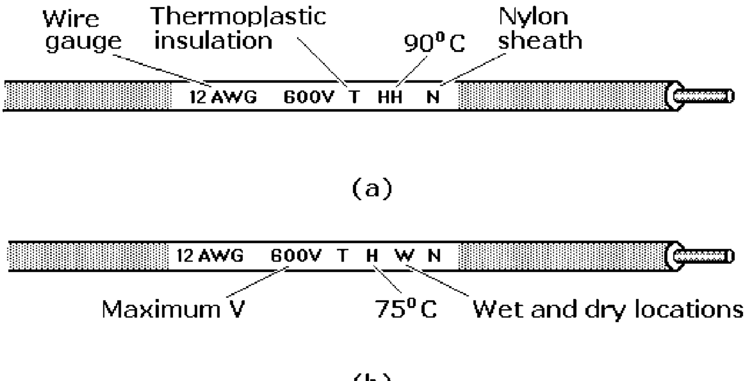


Figure 6-2 **Codes printed on the thermoplastic insulation identify the wire as suitable for use in conduit: (*a*) THHN; (*b*) THWN.**

the major classes of cable for lighting and power applications, service entrance (SE), nonmetallic (NM or Romex), underground feeder (UF), flexible armored (BX or AC), and metal-clad (MC) are given in Fig 6-3.

The code for SE cable shown in Fig. 6-3*a* provides the following information:

- Cable type (e.g., service entrance)
- Insulation code
- Maximum voltage rating
- Number and gauge of "hot" conductors
- Number and gauge of ground conductors
- UL listing
- Year of manufacture

The codes on nonmetallic (NM) and underground feeder (UF) cable, as shown in Fig. 6-3*b* and *c,* provide the following information:

- Wire gauge
- Number of conductors
- Presence of ground wire (W/G)
- Function (e.g., nonmetallic sheath or underground feeder)
- Maximum operating temperature (H for 75°C, HH for 90°C, none for 60°C)
- Identification of sheath, if present (e.g., N for nylon)

Service Entrance Cables

Service entrance cable, type SE, as shown in Fig. 6-3*a,* conducts power into the building from the splice with the utility's service cables. Standard SE cable has two

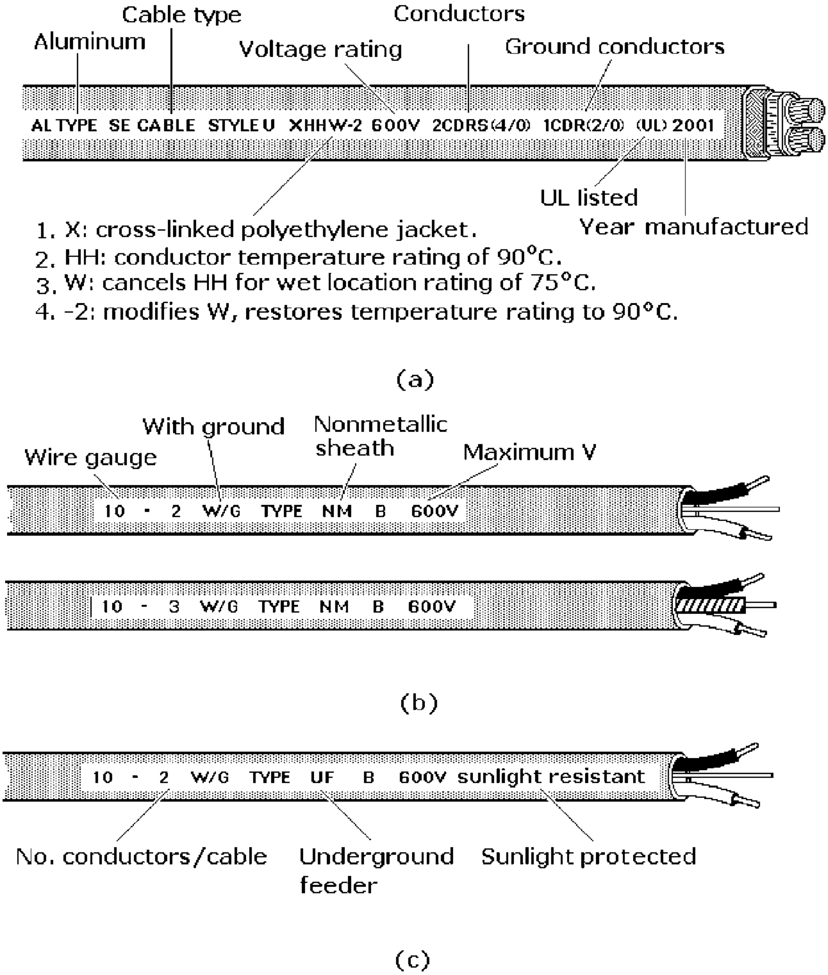


Figure 6-3 **Codes printed on the jackets of cables identify them as: (*a*) service entrance (SE), (*b*) nonmetallic (NM), and (*c*) underground feeder (UF).**

insulated conductors and a bare ground wire. It is approved for powering 240-V AC heat pumps and electric furnaces, but it cannot be used where an insulated neutral is required. Two of the insulated cables are for the 240-V AC load and a return neutral is for the 120-V AC load. SE cable is available in three different styles, U, R, and USE, all rated for 600 V AC. The letter X on the insulation indicates that it is cross-linked polyethylene.

NEC 2002, Article 338, "Service-Entrance Cable: Types SE and USE," covers the use, installation, and construction specifications for SE and USE cable.

Service entrance cable, type SE, style U, is a flat cable approved only for above-ground use. It has two insulated conductors. Both are black, but one might have a red stripe for phase identification. The neutral is multistranded braid enclosing the two insulated conductors. Conductors and braid are wrapped in glass-reinforced tape and jacketed in polyvinyl chloride (PVC) pipe. The jacket is flame-retardant, moisture-resistant, and has ultraviolet-resistant properties. It is available in AWG 6 and larger. U-style SE cable cannot be used to power 120/240-V AC appliances such as electric dryers and stoves, because these appliances require three insulated conductors and ground.

Service entrance cable, type SE, style R, is round cable that contains three insulated conductors and a grounding wire. As with style USE cable, it is approved only for above-ground use. The conductors are wrapped with glass-reinforced tape and enclosed in a PVC jacket. It is available in AWG 6 and larger. R-style SE cable is approved to feed 120/240-V AC loads such as electric clothes dryers and ranges, because it has three insulated conductors with an additional bare grounding conductor.

Service entrance cable, type USE, is intended for underground service or for use within conduit. It contains individual conductors that can be buried or placed in a conduit. The conductors are insulated with cross-linked polyethylene. This cable is available in AWG 6 and larger.

Nonmetallic Cables

Cables labeled 12/2 WG contain two insulated AWG 12 wires and a grounding wire. Some commonly used cables suitable for use in 120/240-V circuits are described below.

Nonmetallic sheathed cable, type NM, shown in Fig. 6-3*b,* is widely used for indoor wiring in dry locations such as bedrooms, family rooms, or kitchens. NM cable, also called Romex, is available in a wide range of wires sizes with either two or three insulated wires and a bare ground wire. Insulated and bare wires in NM cable are protected with paper insulation and a thermoplastic jacket. This cable is sold as rolls in boxes of 25 to 250 ft of cable.

NEC 2002, Article 334, "Nonmetallic Sheathed Cable: Types NM, NMC, and NMS," covers the use, installation, and construction specifications of nonmetallic sheathed cable.

Underground feeder cable, type UF, shown in Fig. 6-3*c,* is used for wiring in damp or wet locations including outdoor lighting circuits. It has two insulated wires and a bare ground wire that are embedded in a white or gray solid-core vinyl sheathing to protect against dampness or water seepage. Most local electrical codes allow UF cable to be buried directly in the ground, and it is also suitable for use indoors in such locations as laundry rooms or built-in basements where the humidity can be high.

NEC 2002, Article 340, "Underground Feeder and Branch-Circuit Cable: Type UF," covers the use, installation, and construction specifications for UF cable.

Large appliance cable has either two or three insulated wires and one bare ground wire embedded in a white or gray solid-core vinyl sheath. This cable is intended for powering kitchen ranges, clothes dryers, and water or other electric heaters rated for 30 to 50 A that require No. 8 or 6 AWG wire. Its construction is similar to NM cable, but its stranded copper wires make the cable easier to bend.

Metal-Clad Cables

Flexible armored cable, type AC, shown in Fig. 6-4*a,* also called BX or Greenfield cable, has either a steel or aluminum armor sheath that serves as a grounding pathway. Its conductors are insulated with thermoplastic and individually wrapped with a waxed paper jute. Available with from one to four conductors, it has a No. 16 AWG aluminum bonding wire inside its jacket that runs its entire length and contacts the metal armor to reduce its grounding resistance. Any short-circuited current flows through the metal sheath back to the loadcenter.

NEC 2002, Article 320, "Armored Cable: Type AC," covers the use, installation, and construction specifications for AC cable.

Metal-clad cable, type MC, shown in Fig. 6-4*b,* has either interlocking armor like AC cable or a smooth corrugated-tube armor. Standard MC cable has either three or four insulated No. 6 AWG or larger conductors. The bundle of conductors is wrapped in paper or plastic. However, it is also available with more smaller-gauge conductors and one bare grounding wire.

NEC 2002, Article 330, "Metal-Clad Cable: Type MC," covers the application and construction specifications for MC cable, and NEC 2002, Article 332, "Mineral Insulated, Metal-Sheathed Cable: Type MI," covers the use, installation, and construction specifications for type MI cable.

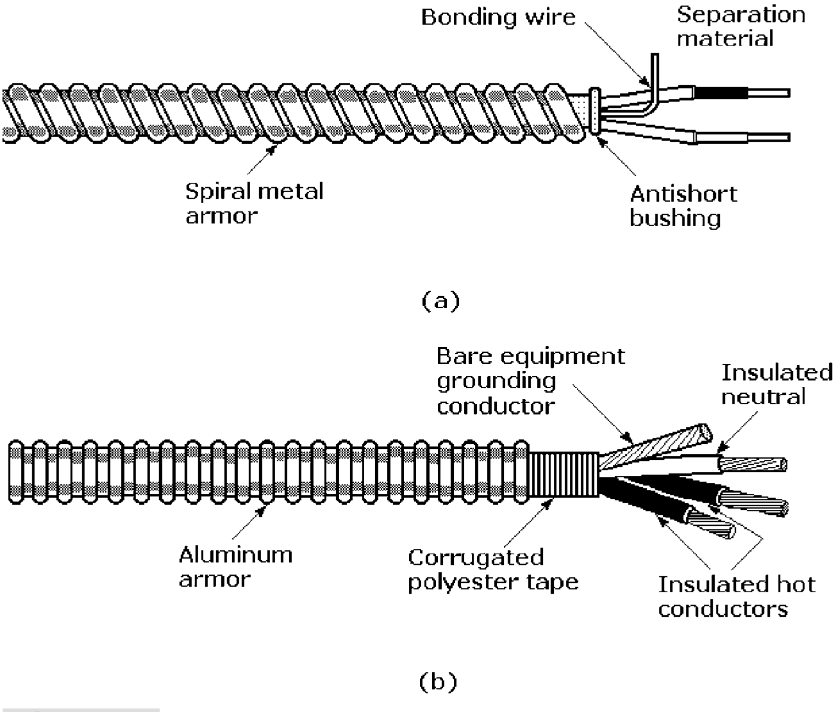


Figure 6-4 **Metal-clad cables: (*a*) flexible armored (AC); (*b*) metal-clad (MC).**

Communications Cables

Communications cables are made to carry audio, video, and data signals for telephones, TVs, and computers. These specialized cables are generally installed the same way as power cables.

Coaxial cable can carry TV, video, and data signals. Its central conductor is insulated by a dielectric material which is covered by conductive wire braid or metal foil and then an insulating jacket. Coaxial cable is available in lengths up to 25 ft.

Telephone cable (also called station wire) can carry audio or voice signals between telephones and answering machines, and data for fax machines and computer modems, over the wired dial-up public telephone system. It is available in the following cables:

- Quad or four-wire, four-color (green, red, black, and yellow)
- Six-wire, six-color (green, red, black, yellow, white, and blue) wires configured as three twisted-wire pairs
- Eight-wire, six-color (blue, red, green, and brown) banded wire, configured as four twisted-wire pairs

These cables are discussed in greater detail in Chap. 9.

Metal and Nonmetallic Conduit

Indoor metal and nonmetallic conduit can keep dust and moisture out of wiring and protect it from mechanical abrasion. Short sections can protect wiring close to the floor used to power washing machines and clothes dryers in damp basements. These sections must be anchored to masonry walls where there are no wood studs for supporting them. Conduit is also used as vertical ducting between floors to ease the task of pulling power and communications cables through floors. It will also protect all power and communications cables in warehouses and other unoccupied storage buildings where there are no dry internal walls or ceilings.

THHN and THWN wire with thermoplastic insulation are approved for use in conduit. THHN wire, rated for a maximum operating temperature of 90°C (194°F), can be used in both damp and dry locations, while THWN wire, rated for 75°C (167°F), can be used in both wet and dry locations. Service entrance (SE) cable, underground feeder (UF) cable, and nonmetallic (NM) cable can also be installed in conduit.

METALLIC CONDUIT

Metallic tubing, type EMT, is light, thin-wall metal conduit used primarily to protect indoor wiring from physical abuse. It is easy to install, but its thin walls provide only marginal protection from abuse. EMT is available in 10-ft lengths with diameters of $^1/_2$, $^3/_4$, 1.0, $1^1/_2$, and 2.0 in. EMT $^1/_2$-in.-diameter conduit can hold up to six No. 14 AWG wires, five No. 10 AWG wires, or two No. 8 AWG wires.

NEC 2002, Article 358, "Electrical Metallic Tubing: Type EMT," covers the use, installation, and construction specifications for EMT and associated fittings.

Intermediate metallic conduit, type IMC, has thicker walls than EMT and is galvanized so it is approved for exposed outdoor use, but it can also be used indoors where greater protection against abuse is desired. IMC is connected with watertight threaded or compression fittings, and is available in 10-ft lengths with $^1/_2$- and $^3/_4$-in. diameters.

NEC 2002, Article 342, "Intermediate Metal Conduit: Type IMC," covers the use, installation, and construction specifications for IMC and associated fittings.

Rigid metal conduit, type RMC, is actually pipe and provides the greatest protection for wiring, but it is expensive and requires threaded fittings. It is approved for use in industrial, large commercial, and public buildings under all atmospheric conditions and occupancies. Ferrous raceways and fittings protected from corrosion only by enamel paint are approved only for indoor use and in places not subject to corrosive influences.

NEC 2002, Article 344, "Rigid Metal Conduit: Type RMC," covers the use, installation, and construction specifications for RMC and its fittings.

Flexible metal conduit, type FMC, is approved for use in exposed and concealed locations where rigid conduit is difficult to install. FMC is used to connect permanently wired appliances such as water heaters, electric space heaters, and clothes dryers, because it is easy to bend.

NEC 2002, Article 348, "Flexible Metal Conduit: Type FMC," covers the use, installation, and construction specifications for FMC and its fittings.

Liquidtight flexible metal conduit, type LFMC, is approved for exposed or concealed locations where conditions of installation, operation, or maintenance require flexibility or protection from liquids, vapors, or solids. These conditions are defined in NEC Secs. 501.4(B), 502.4, 503.3, and 504.20. LFMC is also permitted in other hazardous locations where specifically approved, and by Sec. 553.7(B).

NEC 2002, Article 350, "Liquidtight Flexible Metal Conduit: Type LFMC," covers the use, installation, and construction specifications for LFMC and associated fittings.

NONMETALLIC CONDUIT

Electrical nonmetallic tubing, type ENT, is a nonmetallic round raceway that is corrugated. It is made of plastic that is resistant to moisture and chemical atmospheres, and is also flame-retardant. ENT can be bent by hand with reasonable force to fit it in the direction desired for the length of the run. It is available with diameters of $^1/_2$ to 2 in.

NEC 2002, Article 362, "Electrical Nonmetallic Tubing: Type ENT," covers the use, installation, and construction specifications for ENT and associated fittings.

Rigid nonmetallic conduit, type RNC, is approved for many different locations that are dry, damp, and wet as well as those subject to severe corrosive influences from chemicals. It can also be used in concealed locations within buildings or underground.

NEC 2002, Article 352, "Rigid Nonmetallic Conduit: Type RNC," covers the use, installation, and construction specifications for RNC and associated fittings.

Nonmetallic underground conduit with conductors, type NUCC, is approved for direct burial underground and encasement or embedding in concrete or cinder fill.

Under certain conditions it can be buried in underground locations where it will be subject to severe corrosive chemicals.

NEC 2002, Article 354, "Nonmetallic Underground Conduit: Type NUCC," covers the use, installation, and construction specifications for NUCC with conductors.

Liquidtight flexible nonmetallic conduit, type LFNC, is approved for use where conductors must be protected from vapors, liquids, or solids and where flexibility is required for installation, operation, or maintenance. Users are cautioned that some types of LFNC can become brittle in extreme cold and therefore susceptible to damage from physical contact.

NEC 2002, Article 356, "Liquidtight Flexible Nonmetallic Conduit: Type LFNC," covers the use, installation, and construction specifications for LFNC and associated fittings.

Polyvinyl chloride (PVC) is a plastic resin used for extruding nonmetallic conduit in diameters up to $1^1/_2$ in. If the conduit is treated to resist ultraviolet light, it is approved for use where it is continuously exposed to the sun. Unlike metal conduit, PVC conduit does not corrode when it is in contact with water or damp soil, and it does not need to be painted. It can protect buried wires transitioning from below ground to above-ground destinations. PVC conduit and fittings can be joined together to form assemblies with a solvent glue similar to that used for PVC plumbing pipe. Because it is nonconductive, a grounding wire is required within the PVC conduit. If used underground, it must be buried at a depth of at least 18 in., but if it is covered by a concrete slab, the depth can be shallower.

Conduit Bodies and Fittings

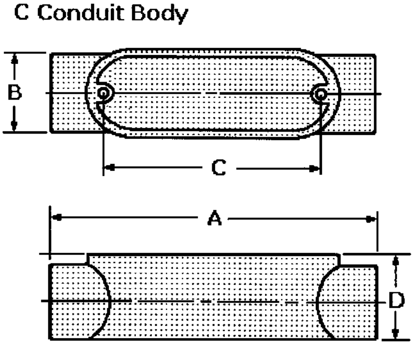
CONDUIT BODIES AND COVERS

Conduit bodies are tubular hardware units with openings at each end to admit EMC conduit and cavities that are large enough to give the installer access to the ends of wires or cables so they can be pulled out and easily be redirected if necessary. These bodies are available in different sizes and are made to perform such functions as joining two sections of conduit to form either straight lengths or 90° bends.

Figure 6-5 illustrates six different conduit body styles and two different gasketed cover styles for body cavities, all with tables giving the dimensions of those styles for mating with standard conduit. Conduit bodies have threaded ports or openings for conduit and tapped holes for the screws to fasten the covers over the cavities to form watertight seals when wire or cable arrangement is complete.

Conduit bodies are especially useful for making right-angle bends in stiff, heavy conductor bundles or cable such as service entrance (SE) cable. For this reason they are widely used in making service entrance connections. Conduit bodies are standard commercial hardware items made from malleable iron or copper-free aluminum. The iron bodies can be galvanized or painted with enamel to prevent rusting.

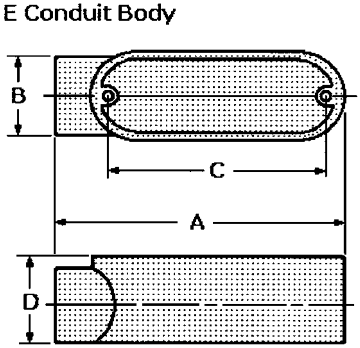
Sections 314.5, 314.16, and 314.17 of NEC 2002, Article 314, "Outlet, Device, Pull, and Junction Boxes; Conduit Bodies; Fittings; and Manholes," cover the



Dimensions (inches)
C Conduit Bodies

Conduit size	A	B	C	D
½	5.19	1.31	3.13	1.38
¾	5.75	1.5	3.75	1.63
1	7.06	1.75	4.5	1.88
1¼	8.13	2.5	6	2.5
1½	8.13	2.5	6	2.75
2	10	3.13	8.06	3.44

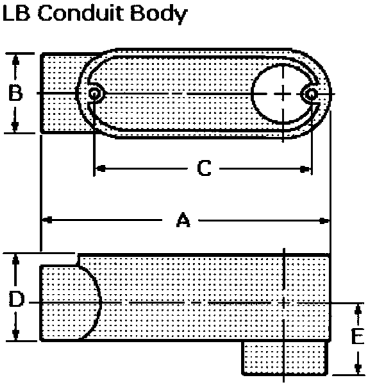
Dimensions and characteristics of C conduit bodies.



Dimensions (inches)
E Conduit Bodies

Conduit size	A	B	C	D
½	4.5	1.31	3.16	1.38
¾	5.19	1.5	3.25	1.63
1	6.25	1.75	4.5	1.88

Dimensions and characteristics of E conduit bodies.



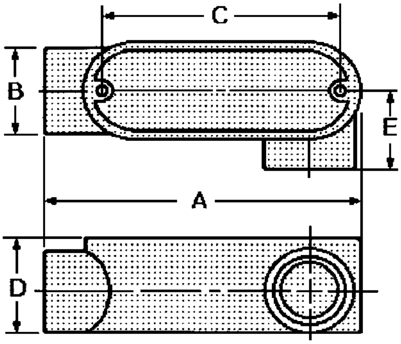
Dimensions (inches)
LB Conduit Bodies

Conduit size	A	B	C	D	E
½	4.5	1.31	3.16	1.38	1.5
¾	5.19	1.5	3.25	1.63	1.63
1	6.25	1.75	4.5	1.88	2.09
1¼	8.06	2.5	6.06	2.53	2.22
1½	8.06	2.5	6.06	2.75	2.38
2	10	3.13	8.13	3.44	2.63
2½	13	4.44	10.5	4.44	3.88
3	13	4.44	10.5	4.44	3.88
3½	15.75	5.5	13.25	5.5	4.56
4	15.75	5.5	13.25	5.5	4.59
5	20.25	7.38	16.19	7.25	5.25

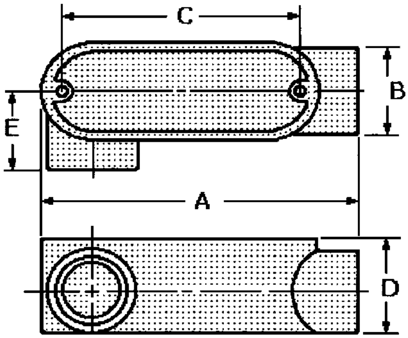
Dimensions and characteristics of LB conduit bodies.

Figure 6-5 Dimensions and characteristics of LB conduit bodies and covers.

LL Conduit Body



LR Conduit Body

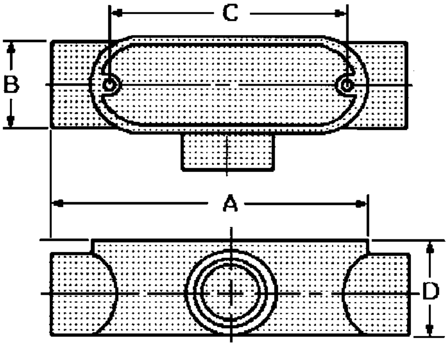


Dimensions (inches)
LL and LR Conduit Bodies

Conduit size	A	B	C	D	E
½	4.5	1.31	3.16	1.38	1.5
¾	5.19	1.5	3.25	1.63	1.63
1	6.25	1.75	4.5	1.88	2.09
1¼	8.06	2.5	6.06	2.53	2.22
1½	8.06	2.5	6.06	2.75	2.38
2	10	3.13	8.13	3.44	2.63

Dimensions and characteristics of LL and LR conduit bodies.

T Conduit Body



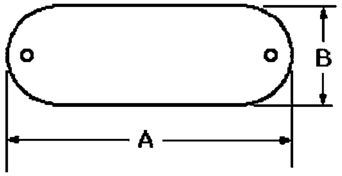
Dimensions (inches)
T Conduit Bodies

Conduit size	A	B	C	D	E
½	5.19	1.31	3.13	1.38	1.56
¾	5.75	1.5	3.75	1.63	1.63
1	7	1.75	4.5	1.88	2.13
1¼	8.69	2.5	6	2.38	2.25
1½	8.13	2.5	6	2.75	2.5
2	10	3.13	8.06	3.44	2.19

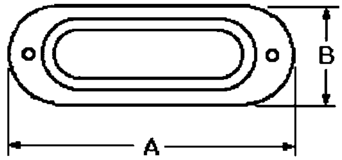
Dimensions and characteristics of T conduit bodies.

Figure 6-5 (*Continued*)

Flat Conduit-Body Cover



Domed-Top Conduit-Body Cover



Dimensions (inches)

Flat Body Covers		Domed Body Covers	
A	B	A	B
3.9	1.31	3.88	1.31
4.63	1.5	4.59	1.5
5.38	1.75	5.38	1.75
7.25	2.5	7.25	2.5
9.5	3.13	9.56	3.13
12.25	4.44	12.25	4.44
14.88	5.5	14.88	5.5
18.25	7.31		

Figure 6-5 (*Continued*)

installation and use of conduit bodies. The maximum number of conductors permitted (fill) in the conduit or tubing to which the bodies are attached is given in Chapter 9, Table 1, of NEC 2002. Conduit bodies must be durably and legibly marked with their volumes by the manufacturer to be approved for containing splices, taps, or other devices.

CONDUIT CONNECTORS, COUPLINGS, AND FITTINGS

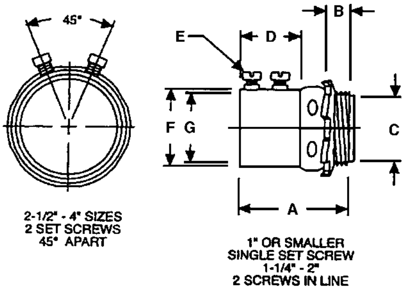
Many different kinds of connectors, couplings, and fittings are made for coupling or connecting similar or dissimilar lengths of conduit and making connections between conduit and various types of electrical boxes. They are made from materials such as zinc-plated steel, malleable iron, aluminum, die-cast zinc, and nylon. Conduit connectors and couplings are made in accordance with Underwriter's Laboratories, Inc. (UL) standards and are also certified by the Canadian Standards Association (CSA). Connections can be made by set screws, compression methods, or screw-down clamps.

Figure 6-6 is a gallery of a representative illustrations of conduit connectors, couplings, and related fittings accompanied by short tables giving their dimensional data. Most of the connectors illustrated are for EMT conduit, but illustrations and tables are given for liquidtight straight and angled connectors, connectors for type B conduit, and connectors for flexible metal conduit and armored cable.

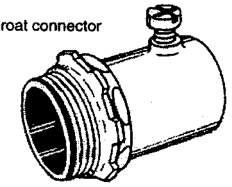
The dimensions given in the tables are based on information provided by several manufacturers and should be used for reference only. A complete directory of commercial conduit fittings is beyond the scope of this handbook. The reader is advised to consult the latest manufacturers' catalogs for styles and dimensions of conduit hardware now being manufactured, because the product offerings are subject to change.

(*Text continues on p. 204.*)

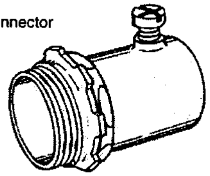
EMT SET SCREW CONNECTORS



Insulated throat connector



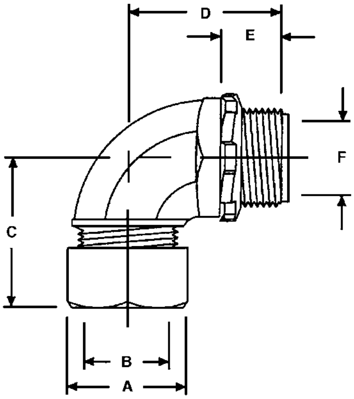
Uninsulated connector



DIMENSIONS (inches)

A	B	Thd. Spec.	C	D	E Set Screw	F	G
1.57	.47	½-14 NPS	.63	.78	Tri-drive, 12-24 x .25 in	2.22	.72
1.63	.34	¾-14 NPS	.81	.91	Tri-drive, 12-24 x .25 in	1.06	.94
.88	.39	1-11½ NPS	1.03	1.16	Tri-drive, 12-24 x .25 in	1.28	1.19
2.34	.63	1¼-11½ NPS	1.38	1.41	Hex Head/Slot .25-28 x .31	1.72	11.22
2.59	.63	1½-11½ NPS	1.58	1.5	Hex Head/Slot .25-28 x .31	1.94	1.75
2.47	.63	2-11½ NPS	2.06	1.78	Hex Head/Slot .25-28 x .31	2.42	2.22
2.94	.94	2½-11½ NPS	2.56	1.88	Hex Head .31-24 x .34	3.22	2.92

EMT SHORT 90° COMPRESSION CONNECTORS



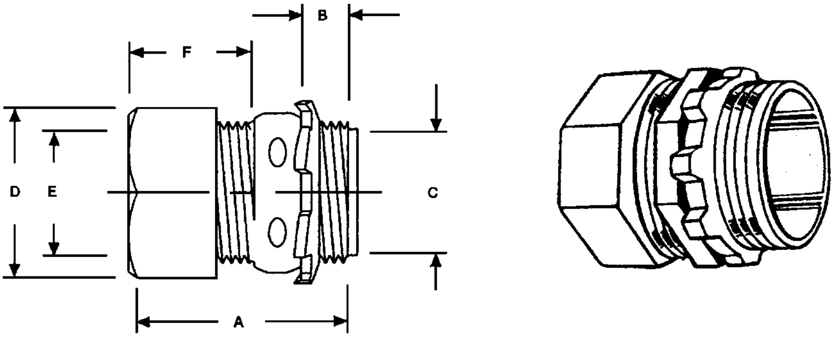
DIMENSIONS (inches)

A	B	C	D
1.13	.78	1.28	1.22
1.38	.94	1.59	1.47
1.67	1.69	1.97	1.56

E	Thread Spec.	F
.5	½-14 NPT	.63
.56	¾-14 NPT	.81
.5	1- 11.5 NPT	1.03

Figure 6-6 Gallery of drawings and dimensions of conduit connectors, couplings, and straps.

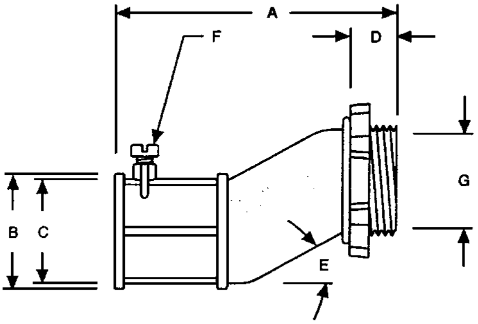
EMT COMPRESSION CONNECTORS



DIMENSIONS (inches)

A	B	Thd. Spec.	C	D	E	F
2.88	.44	½-14 NPS	.63	1.13	.72	1.25
2.75	.44	½-14 NPS	.63	1.38	.94	.94
1.44	.34	¾-14 NPS	.83	1.67	1.17	1.06
2	.39	1-11.5 NPS	1.03	2.19	1.53	.94
2	.56	1¼-11.5 NPS	1.38	2.44	1.75	1.06
2.31	.63	1½-11.5 NPS	1.61	2.88	2.22	1.75
2.5	.63	2-11.5 NPS	2.06	3.94	2.94	1.69

EMT SET SCREW OFFSET CONNECTORS



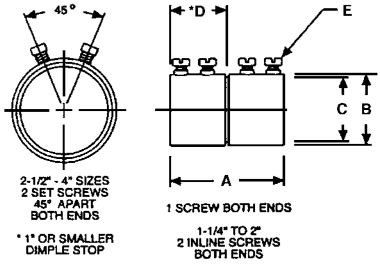
DIMENSIONS (inches)

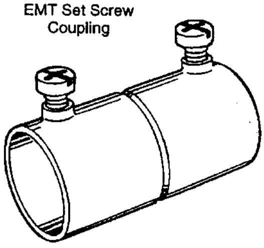
A	B	C	D	E
2.1	.95	.72	.38	30°
3	1.16	.94	.44	30°

F	G	Screw Type
10-24 x .31 in	.63	½ - 14 NPS

Figure 6-6 (*Continued*)

EMT SET SCREW CONNECTORS

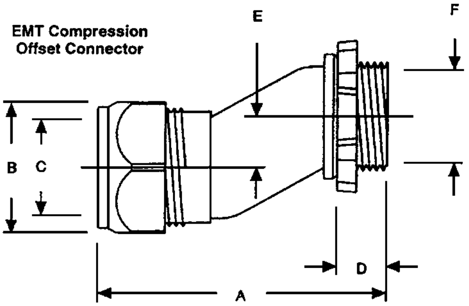




DIMENSIONS (inches)

A	B	C	D	Thread Specs.
1.75	.92	.78	.88	Tri-Drive 12 - 24 x ¼
1.97	1.08	1.31	.97	Tri-Drive 12 - 24 x ¼
1.88	1.28	1.19	.88	Tri-Drive 12 - 24 x ¼
2.69	1.70	1.53	1.30	Hex Head/Slot: ¼ -28x .31 in
2.88	1.94	1.75	1.39	Hex Head/Slot: ¼ -28x .31 in
3.44	2.42	2.22	1.67	Hex Head/Slot: ¼ -28x .31 in
3.86	3.22	2.45	1.5	Hex Head/Slot: .31 in -24x .34 in

EMT COMPRESSION CONNECTORS



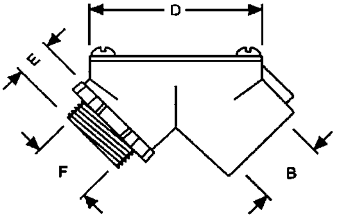
DIMENSIONS (inches)

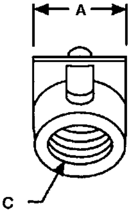
A	B	C	D
2.16	1.09	.72	.38
2.89	1.31	.95	.44
3.03	1.63	1.19	.56

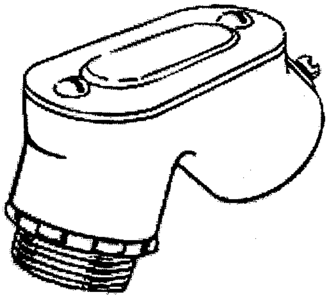
E	F	THD. Spec.
.88	.63	½ - 14 NPS
.75	.81	¾ - 14 NPS
.75	1.05	1 - 11½ NPS

Figure 6-6 (*Continued*)

EMT 90° SET SCREW ELL CONNECTORS



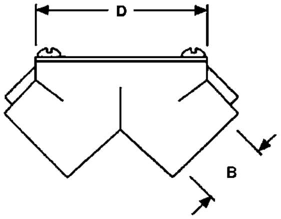


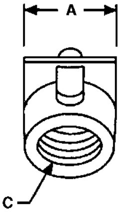


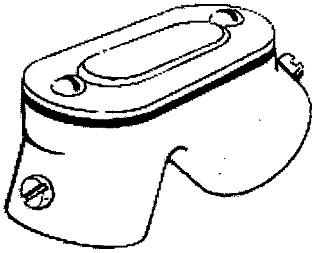
DIMENSIONS (inches)

A	B	C	D	E	F	Screw Type
1.13	.72	10-24 x .31	1.88	.38	.63	¼-14NPS-Slotted
1.34	.94	10-24 x .31	2.19	.44	.81	¼-14NPS-Slotted

EMT 90° SET SCREW ELL COUPLINGS







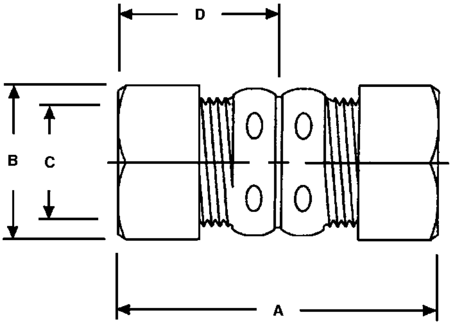
DIMENSIONS (inches)

A	B	C	D
1.13	.71	10-24 x .94	1.88
1.34	.94	10-24 x .94	2.19
1.63	1.19	10-24 x .94	3.13

Screw Type
Slotted, female to female
Slotted, female to female
Slotted, female to female

Figure 6-6 (*Continued*)

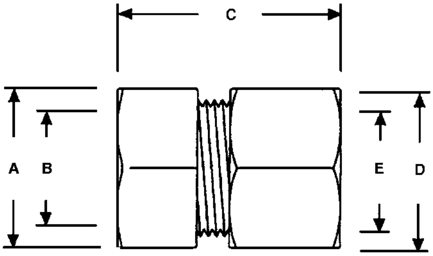
EMT COMPRESSION COUPLINGS



DIMENSIONS (inches)

A	B	C	D
1.66	1.13	.72	.75
1.72	1.38	.94	.69
1.97	1.67	1.17	.94
2.13	2.19	1.53	1
2.56	2.44	1.75	1.13
2.88	2.88	2.22	1.28
4.75	3.94	2.94	2

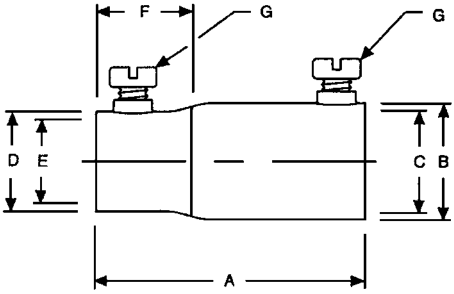
EMT TO RIGID COMPRESSION COUPLINGS



DIMENSIONS (inches)

A	B	C	D	E
1.16	.75	1.34	1.13	.72
1.44	.99	1.53	1.38	.94
1.66	1.22	1.63	1.67	1.17

EMT TO RIGID SET SCREW COUPLINGS



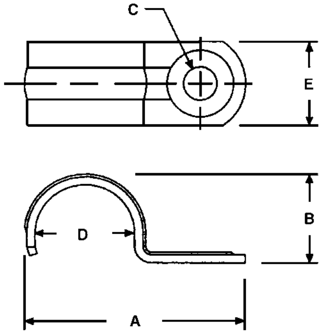
DIMENSIONS (inches)

A	B	C	D	E
2.31	1	.88	.88	.72
2.63	1.25	1.08	1.11	.94
3.16	1.50	1.34	1.34	1.19

F	G
.78	¼ - 28 × 5⁄16 Hex head screw
.84	¼ - 28 × 5⁄16 Hex head screw
1.06	¼ - 28 × 5⁄16 Hex head screw

Figure 6-6 (*Continued*)

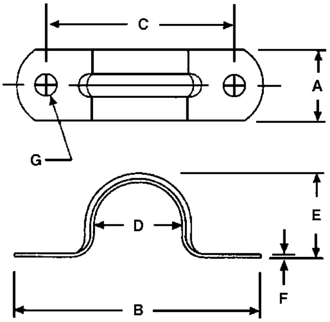
EMT ONE-HOLE PUSH-ON STRAPS



DIMENSIONS (inches)

A	B	C	D	E
1.63	.75	.25	.71	.63
2.19	1	.28	.92	.63
2.56	1.28	.28	1.17	.75
3.13	1.64	.28	1.53	.88
3.63	1.89	.34	1.75	1
4.44	2.39	.34	2.19	1.13
5.31	3.06	.66	2.88	1.25

EMT TWO-HOLE STRAPS

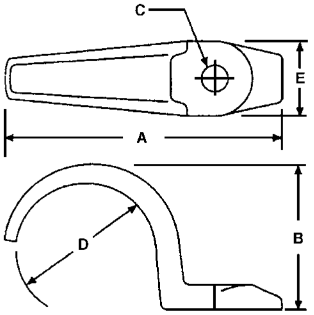


DIMENSIONS (inches)

A	B	C	D
.625	2.140	1.625	.706
.625	2.288	1.715	.922
.750	2.750	2.140	1.163

E	F	G
.750	.032 × .625	.187
1.015	.032 × .625	.187
1.235	.036 × .750	.250

EMT MALLEABLE IRON STRAPS

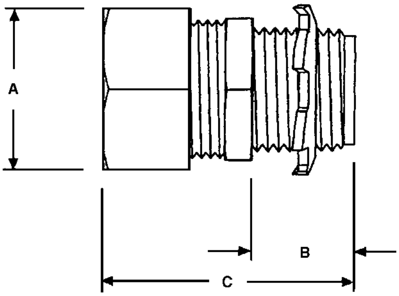


DIMENSIONS (inches)

A	B	C	D	E
6.44	3.28	.66	2.88	1.81
7.50	4	.66	3.50	2
8.13	4.5	.83	4	2.13
8.88	5.56	.75	4.50	2.25

Figure 6-6 (*Continued*)

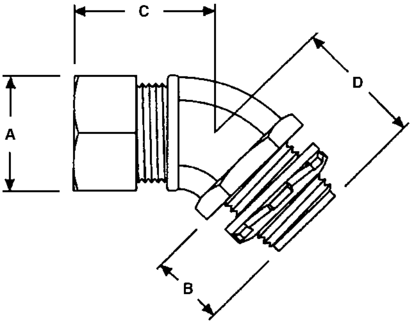
LIQUIDTIGHT STRAIGHT INSULATED/ UNINSULATED STEEL CONNECTORS



DIMENSIONS (inches)

Trade Size	A	B	C
⅜ in	1.06	.59	1.44
½ in	1.19	.59	1.44
¾ in	1.19	.59	1.56
1 in	1.69	.66	1.69
1¼ in	2.06	.63	2.03
1½ in	2.38	.63	2.03
2 in	2.88	.66	2.28
2½ in	3.63	1	3.5
3 in	4.31	1	3.75

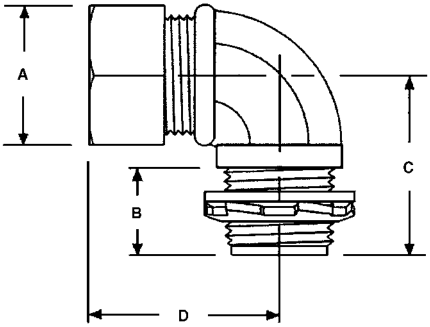
LIQUIDTIGHT 45° INSULATED/ UNINSULATED CONNECTORS



DIMENSIONS (inches)

Trade Size	A	B	C	D
⅜ in	1.06	.59	1.19	1.28
½ in	1.19	.59	1.19	1.28
¾ in	1.38	.59	1.19	1.44
1 in	1.69	.66	1.38	1.53
1¼ in	2.06	.63	1.42	1.69
1½ in	2.38	.63	1.66	2
2 in	2.88	.66	1.69	2.25

LIQUIDTIGHT 90° INSULATED/ UNINSULATED IRON CONNECTORS

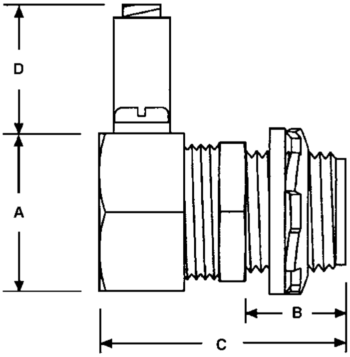


DIMENSIONS (inches)

Trade Size	A	B	C	D
⅜ in	1.03	.56	1.31	1.44
½ in	1.19	.56	1.31	1.44
¾ in	1.38	.59	1.44	1.63
1 in	1.69	.66	1.78	2.19
1¼ in	2.06	.63	1.97	2.50
1½ in	2.38	.63	2.19	2.69
2 in	2.88	.66	2.53	3.25
2½ in	3.63	1	3.13	4.25

Figure 6-6 (*Continued*)

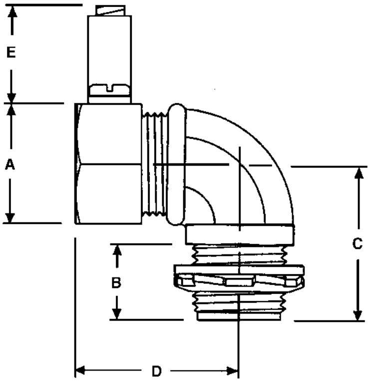
LIQUIDTIGHT STRAIGHT INSULATED IRON CONNECTORS WITH GROUND LUGS



DIMENSIONS (inches)

Trade Size	A	B	C	D
⅜ in	1.06	.59	1.44	.78
½ in	1.19	.59	1.44	.78
¾ in	1.19	.59	1.56	.78
1 in	1.69	.66	1.69	.78
1¼ in	2.06	.63	2.03	.78
1½ in	2.38	.63	2.03	.78
2 in	2.88	.66	2.28	.78
2½ in	3.63	1	3.5	1.17
3 in	4.31	1	3.75	1.17
3½ in	4.75	1	3.75	1.89
4 in	5.31	1	3.75	1.89

LIQUIDTIGHT 90° INSULATED/ UNINSULATED IRON CONNECTORS WITH GROUND LUGS

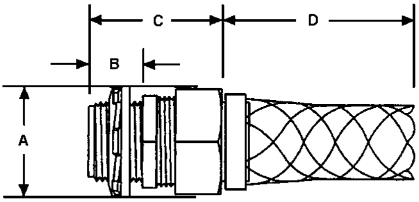


DIMENSIONS (inches)

Trade Size	A	B	C	D	E
⅜ in	1.03	.56	1.31	1.44	.78
½ in	1.19	.56	1.31	1.44	.78
¾ in	1.38	.59	1.44	1.63	.78
1 in	1.69	.66	1.78	2.19	.78
1¼ in	2.06	.63	1.97	2.50	.78
1½ in	2.38	.63	2.19	2.69	.78
2 in	2.88	.66	2.53	3.25	.78
2½ in	3.63	1	3.13	4.25	1.17
3 in	4.31	1	3.69	4.88	1.17
3½ in	4.75	1	—	—	1.89
4 in	5.31	1	4.19	5.63	1.89

Figure 6-6 (*Continued*)

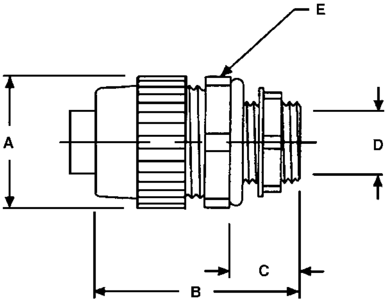
STRAIGHT MESH-INSULATED THROATS



DIMENSIONS (inches)

Hub Size	A	B	C	D
⅛ in	1.06	.59	1.44	3
½ in	1.19	.59	1.44	3.5
¾ in	1.38	.59	1.56	4
1 in	1.69	.66	1.69	5
1¼ in	2.06	.63	2.03	6
1½ in	2.38	.63	2.22	6.75
2 in	2.88	.66	2.28	8

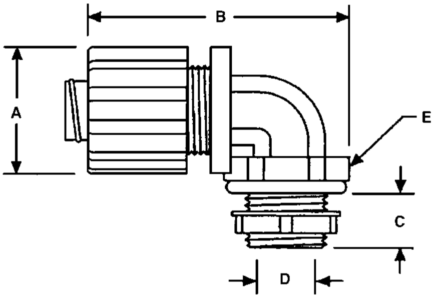
STRAIGHT NYLON CONNECTORS (FOR TYPE B CONDUIT)



DIMENSIONS (inches)

Trade Size	A	B	C	D	E A/C	E A/F
⅜ in	1.14	1.63	.57	.42	1.41	1.30
½ in	1.30	2.14	.57	.55	1.41	1.30
¾ in	1.53	2.22	.58	.74	1.85	1.53
1 in	1.80	2.32	.72	.96	1.94	1.80
1¼ in	2.20	2.15	.74	1.30	2.38	2.18
1½ in	2.49	2.35	.76	1.45	2.63	2.43
2 in	3.05	2.51	.79	1.90	3.13	2.93

90° NYLON CONNECTORS (FOR TYPE B CONDUIT)

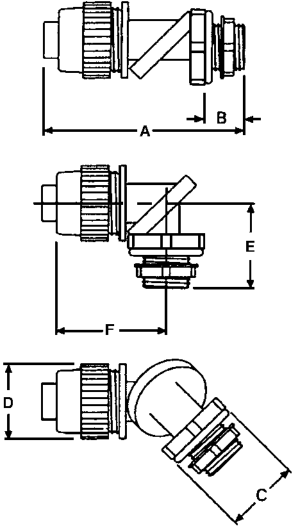


DIMENSIONS (inches)

Trade Size	A	B	C	D	E A/C	E A/F
⅜ in	1.14	2.26	.57	.42	1.41	1.30
1¼ in	2.21	3.57	.74	1.30	2.38	2.18

Figure 6-6 (*Continued*)

MULTIPOSITION NYLON CONNECTORS (FOR TYPE B CONDUIT)

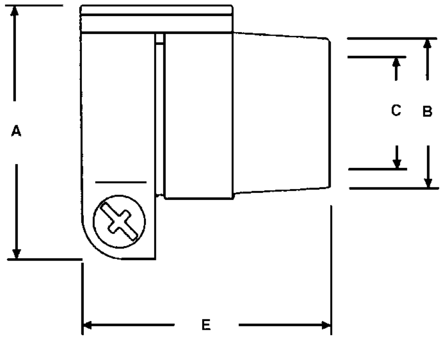


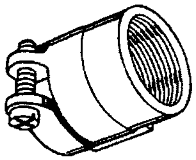
DIMENSIONS (inches)

Trade Size	A	B	C	
			A/C	A/F
½ in	3.27	.57	1.41	1.30
¾ in	3.66	.58	1.65	1.53
1 in	4.00	.72	1.94	1.80

Trade Size	D	E	F
½ in	1.30	1.43	2.00
¾ in	1.53	1.59	2.23
1 in	1.80	1.84	2.30

FLEXIBLE METAL TO EMT CONDUIT CONNECTORS



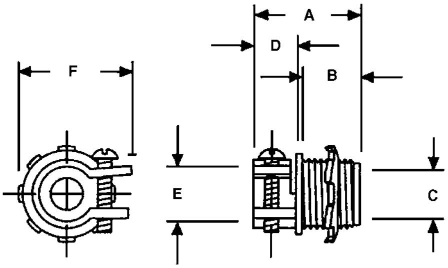


DIMENSIONS (inches)

A	B	C	D	E
1.63	1.03	.75	½ - 14 NPT	1.66
1.88	1.22	.97	¾ - 14 NPT	1.78
2.19	1.5	1.22	1-11.5 NPT	1.81

Figure 6-6 (*Continued*)

STRAIGHT SQUEEZE CONNECTORS (FOR FLEXIBLE METAL CONDUIT)



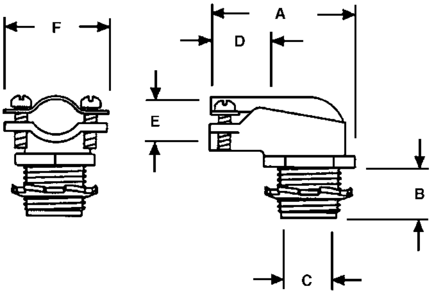
INSULATED / UNINSULATED

A = Overall length
B = Thread length and thread specifications
C = Throat inside diameter
D = Length to conduit stop
E = Clamping range
F = Maximum width of body

DIMENSIONS (inches)

A	B	B Thread Spec.	C	D	E	F
.94	.41	½-14	.34	.41	.53 - .66	1.06
1.44	.41	½-14	.63	.50	.84 - .97	1.38
1.56	.44	¾ - 14	.81	.66	.97 - 1.16	1.59
1.75	.56	1 - 11½	1.03	.56	1.19 - 1.44	1.84
2	.63	1¼ - 11½	1.31	1.19	1.47 - 1.69	2.13

90° SQUEEZE CONNECTORS (FOR FLEXIBLE METAL CONDUIT)



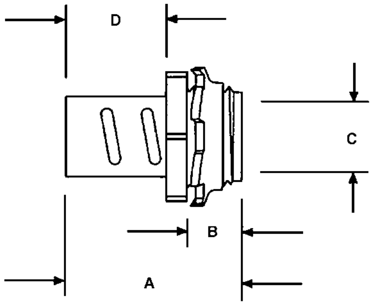
INSULATED / UNINSULATED

A = Overall length
B = Thread length and thread specifications
C = Throat inside diameter
D = Length to conduit stop
E = Clamping range
F = Maximum width of body

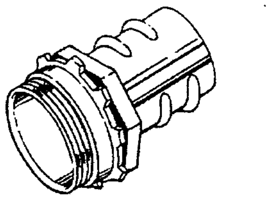
A	B	Thread Specs.	C	D	E	F
2	.56	½ - 14 NPT	.622	.75	.44 to 3.56	1.38
2	.56	½ - 14 NPT	.622	.88		2
2.13	.50	¾ - 14 NPT	.822	1		2.19
2.88	.63	1 - 11½ NPT	1.05	1		3.38
4.88	.63	1¼ - 11½ NPT	1.38	1.06		2.75
5.06	.63	1½ - 11½ NPT	1.61	1.63		3.13
6.5	.66	2 - 11½ NPT	2.07	1.88		3.63

Figure 6-6 (*Continued*)

STRAIGHT SCREW-IN CONNECTORS (FOR FLEXIBLE METAL CONDUIT)



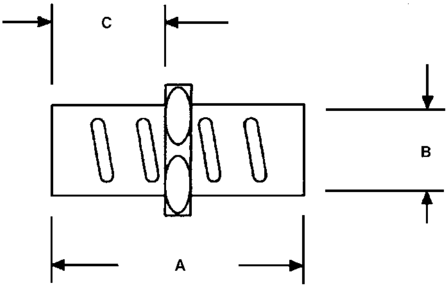
UNINSULATED, DIE-CAST ZINC



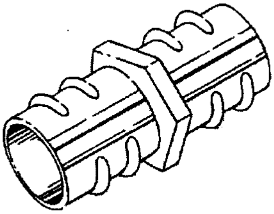
DIMENSIONS (inches)

A	B	Thread Spec.	C	D
1.39	.44	½-14	.56	.78
1.38	.38	½-14	.63	.78
1.59	.50	¾ - 14	.81	.97

STRAIGHT SCREW-IN COUPLINGS (FOR FLEXIBLE METAL CONDUIT)



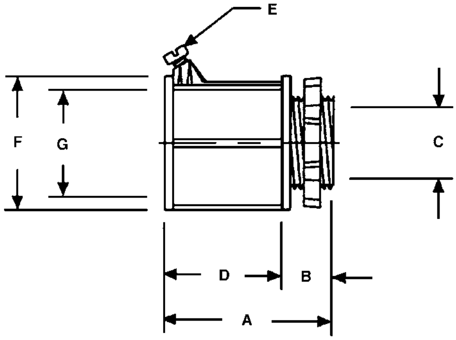
UNINSULATED, DIE-CAST ZINC



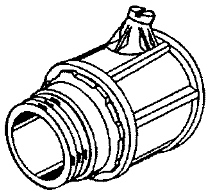
DIMENSIONS (inches)

A	B	C
1.80	.56	.81
1.20	.75	1

STRAIGHT SET SCREW CONNECTORS (FOR FLEXIBLE METAL CONDUIT)



UNINSULATED, DIE-CAST ZINC



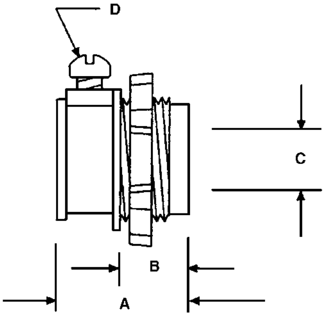
DIMENSIONS (inches)

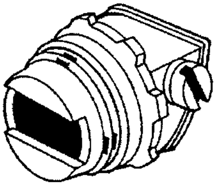
A	B	Thread Spec.	C
1.48	.38	½ - 14	.63

D	E	F	G
1.03	8-32 × ½	1.16	.94

Figure 6-6 (*Continued*)

STRAIGHT SET SCREW CONNECTORS (FOR FLEXIBLE METAL CONDUIT)

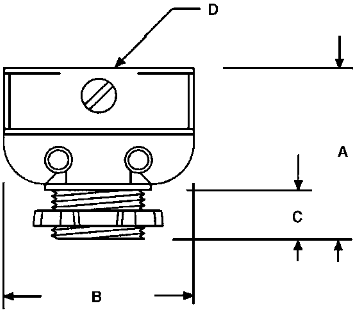


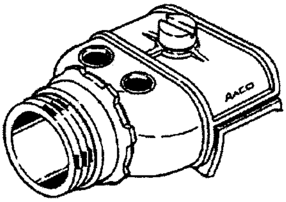


DIMENSIONS (inches)

A	B	C	D
.13	.44	.38	10-24 x ½

DUPLEX CLAMP-TYPE CONNECTORS (FOR FLEXIBLE METAL CONDUITS)

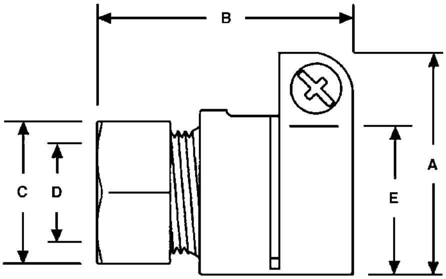


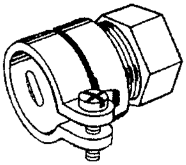


DIMENSIONS (inches)

A	B	C	D
1.56	1.66	.44	.13 -.56

FLEXIBLE METAL TO EMT CONDUIT CONNECTORS



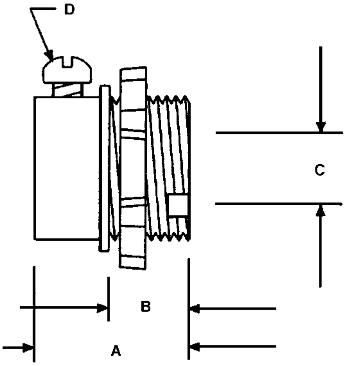


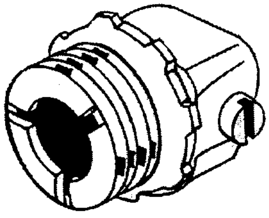
DIMENSIONS (inches)

A	B	C	D	E
1.25	1.31	1.11	.72	.53 - .63
1.50	1.75	1.11	.72	.81 - .94
1.75	1.83	1.38	.94	1 - 1.13

Figure 6-6 (*Continued*)

ARMORED CABLE SET SCREW CONNECTORS

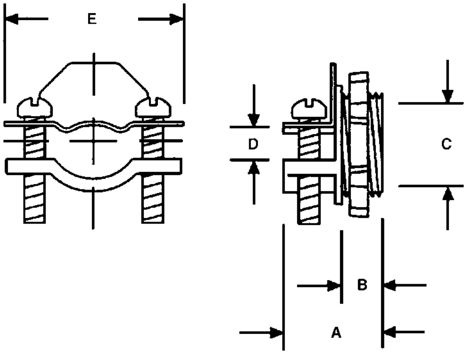


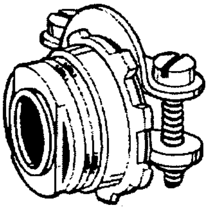


DIMENSIONS (inches)

A	B	C	D
1.06	.59	.34	10-24 × ½

ARMORED CABLE CLAMP-TYPE CONNECTORS





DIMENSIONS (inches)

A	B	Thread Spec.	C
.84	.38	½ × 14	.38

D	E
.16 - .63	1.19

Figure 6-6 (*Continued*)

Electrical Boxes

NEC 2002, Article 314, "Outlet, Device, Pull, and Junction Boxes; Conduit Bodies; Fittings; and Manholes," requires that wire connections or cable splices be contained inside approved metal or plastic boxes. This provision is intended to shield wood building framing members or other adjacent flammable objects from electrical sparks should the wiring be defective. Boxes also protect people from accidental electrical shock and keep moisture and dust out of wire connections or splices.

The outlet, device, pull, and junction boxes that must be sized, selected, and used in accordance with the latest NEC are classified by application. Boxes with supports are required in vertical raceways where the weight of the cable would place excessive strain on the conductor terminals. These conduit-support boxes are common in high-rise buildings, where heavy feeder conductors are used. Most electrical boxes are made from sheet steel and have a painted or galvanized finish, but some are made of cast iron, aluminum, PVC, or clear polycarbonate.

JUNCTION AND PULL BOXES

Junction and pull boxes provide access points for pulling and feeding conductors into a raceway system. Their use is mandatory in conduit runs where the number of bends between outlets exceeds the maximum number permitted by the NEC. Among the many standard commercial products available are the following:

- *Metal surface-mounted pull boxes* finished with gray enamel paint are available with or without knockouts. Widths and heights are from 4 to 24 in., and depths are from 4 to 8 in. These boxes include covers attached with screws.
- *Galvanized metal surface-mounted pull boxes* are available with or without knockouts. Widths and heights are from 4 to 36 in., and depths are from 4 to 12 in. These boxes also include covers attached with screws.
- *Metal junction pull boxes with hinged covers,* finished in gray enamel, are also available with or without knockouts Widths are from $4^1/_2$ to 24 in., heights are from 5 to 12 in., and depths are from 3 to 6 in.
- *Moisture-proof, gasketed boxes* with metal screw-on covers, finished in gray enamel, do not have knockouts. Widths and heights are from 6 to 12 in., and depths are from 4 to 6 in.
- *Double-door metal transformer cabinets,* finished in gray enamel, do not have knockouts. Widths are 36 in., heights are 30 to 36 in., and depths are 10 in.

OUTLET BOXES

The NEC 2002, Article 314, “Outlet, Device, Pull, and Junction Boxes; Conduit Bodies; Fittings and Manholes,” requires that outlet boxes with the correct fittings be installed at the following locations:

- Each conductor splice point
- Each outlet, switch point, or junction point
- Each pull point for the connection of conduit and other raceways
- Transitions from conduit to open cables

A wide variety of standard metal and nonmetallic electrical or outlet boxes are available commercially for installing switches and receptacles, connecting lighting fixtures, and protecting splices. Only the most commonly used boxes and their features are discussed and illustrated in this chapter. These are the rectangular and square metal and plastic boxes for wall switches and duplex receptacles and the octagonal and round electrical boxes for making wire connections to ceiling or wall luminaires. All of these electrical boxes are available in different depths. The boxes used must be deep enough to permit switches and receptacles and their wiring to be inserted and removed easily without crimping or damaging the wires. This applies as well to boxes used to suspend luminaires.

Because so many different manufacturers offer these electrical boxes, the reader is advised to consult the latest manufacturers' catalogs for more details than can be given here. In addition to depth, boxes are available with different numbers of knockouts (KOs) or pryouts (POs) to accommodate different arrangements for switch levers, control knobs, receptacle sockets, or other devices.

Product lines are changed in response to customer demand, and manufacturers drop products lines that are no longer sold in large enough quantities to be profitable. The boxes listed below are readily available in hardware and electrical supply stores today.

Rectangular (3-in. × 2-in.) metal and plastic boxes are intended for installing a single switch or a duplex receptacle. Also called *device boxes,* they are normally mounted vertically in walls by fastening them to wall studs in new construction. A 3-in. × 2-in. rectangular metal switch box with a detachable side is shown in Fig. 6-7. This box has a depth of $2^1/_2$ in. and a volume of 12.5 in.^{3}. Boxes with depths of 2.75 in. have minimum volumes of 14 in.^{3}, and those with depths of $3^1/_2$ in. have minimum volumes of 18 in.^{3}.

These 3-in. × 2-in. boxes can be ganged together with matching boxes to provide a single box with twice the volume. After removing the opposing removable sides of each box, they are fastened together with screws to form one rigid unit. Ganged boxes can accept two switches or two duplex receptacles with their associated wiring.

Rectangular switch boxes are available with the following features:

- Gangable or nongangable
- Depths of $1^1/_2$ to $3^1/_2$ in., 2.56, 2.75, and 3.50 in.
- Nonmetallic (NM) and armored cable clamps

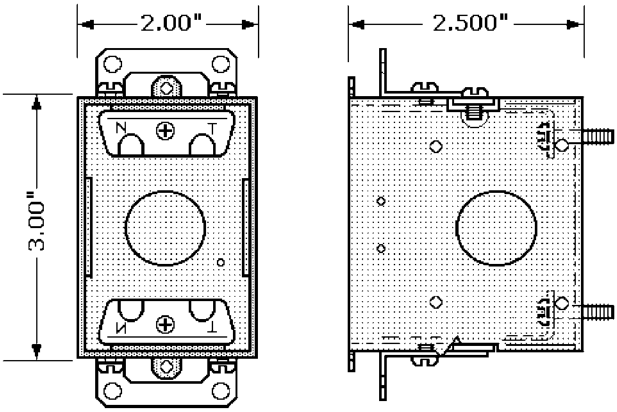


Figure 6-7 Metal 3-in. × 2-in. gangable device box sized for a single switch or duplex receptacle has a volume of 12.5 in.^{3}.

- Beveled back corners on some configurations
- Screw-driven flexible expansion clamps for installing the boxes in drywall cutouts

Metal 4-in. × 2.125-in. utility "handy" boxes are used for mounting switches and receptacles. The box shown in Fig. 6-8 has a depth of 1.875 in. and a volume of 13 in^3. It has six knockouts (KOs), two each on the sides and back. Handy boxes are deep-drawn from a single sheet of steel and galvanized for protection. Some have attached mounting straps. There are also handy boxes with square corners and nine KOs. They are 1.5 in. deep and have volumes of 11.5 in.^{3}.

Plastic $2^1/_4$*-in. ×* $4^1/_4$*-in. rectangular boxes* for mounting switches or duplex receptacles can only be used with nonmetallic (NM) cable. An example of a box with four NM cable clamps is shown in Fig. 6-9. This plastic box, nominally sized 3 in. × 2 in., has a volume of 5.5 in.^{3}. It is intended for use where circuits are being extended in houses with finished walls. A cutout is made in the gypsum wallboard, and the wire or wires to be connected are fished out and clamped within the box. The box is then inserted in the cutout and the swing-out clamps on the top and bottom of the box are extended by turning the screws in the linkage to clamp the box securely to the back side of the wallboard.

These so-called *retrofit boxes* are popular after-market items that can be installed in finished rooms to add new switches or receptacles. Their use avoids removing and later replacing drywall sections to expose the wall studs needed for anchoring the boxes.

However, there are 3-in. × 2-in. plastic boxes with preattached nails in bosses directed at an angle for fastening the boxes to studs in new construction. The NEC requires that all wall switches installed in any of these plastic boxes have grounding screws.

Square metal boxes measuring 4 in. × 4 in. and $4^{11}/_{16}$ × $4^{11}/_{16}$ in. are large enough to gang two switches or two duplex receptacles in one box or to protect cable splices. A 4-in. × 4-in. box with a depth of 1.5 in. is shown in Fig. 6-10. This box has a minimum volume of 21.0 in.^{3}. The box shown has 17 conduit KOs.

Square boxes are also normally mounted vertically in walls by nailing them to studs during original construction. A wide selection of cover plates is available for these

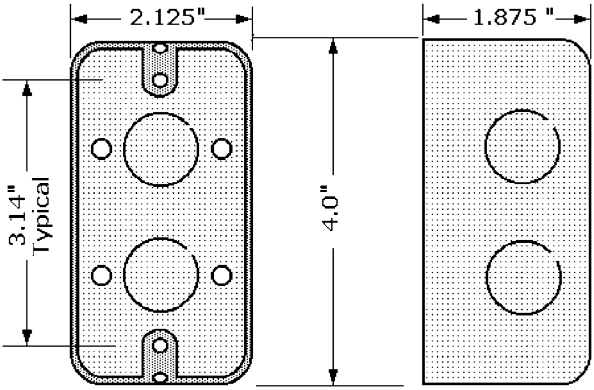


Figure 6-8 Metal utility 3-in. × 2-in. device box has a volume of 13.0 in.^{3}.

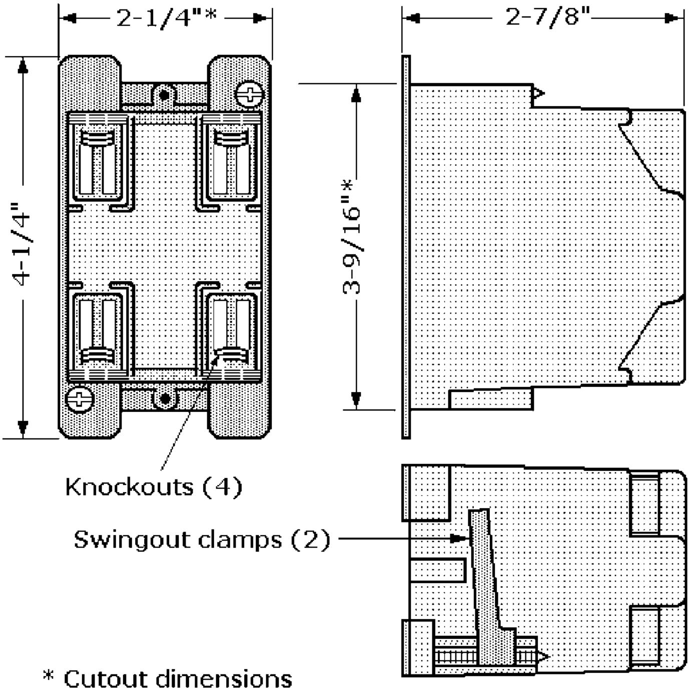


Figure 6-9 Plastic 4-in. × 3-in. switchbox for positioning in a wallboard cutout is fastened with swingout clamps. It has a volume of 5.5 in^3.

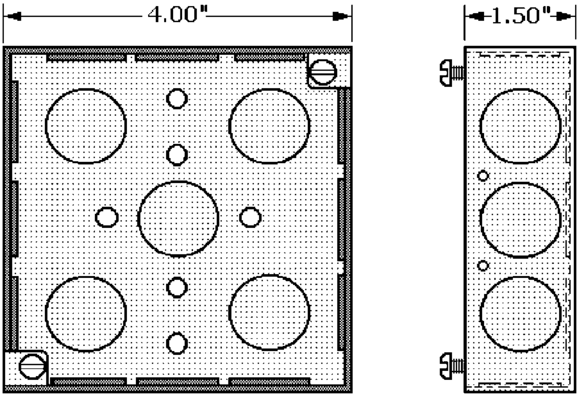


Figure 6-10 Metal 4-in. × 4-in. device box with a volume of 22.5 in.^{3} can contain two switches or duplex receptacles.

boxes, with different cutouts to admit the toggles of strap-mounted switches or to expose both outlets of strap-mounted dual receptacles. Single switches or duplex receptacles can be installed in these boxes if an adapter cover plate with a centrally located cutout is used.

Square 4-in. × 4-in. box depths range from $1^1/_4$ to $2^1/_8$ in. with corresponding minumum volumes from 18 to 30.3 in.^{3}. Another series of square $4^{11}/_{16}$-in. × $4^{11}/_{16}$-in. metal boxes has depths from $1^1/_4$ to $2^1/_8$ in. Their corresponding minimum volumes are from 25.5 to 42.0 in.^{3}. These boxes typically have from 13 to 17 conduit knockouts, mounting straps or brackets, and clamps for nonmetallic armored cable. Molded plastic square 4-in. × 4-in. boxes with fittings for nailing them to wall studs are also available. They must meet the same grounding requirements as all other plastic switch boxes.

Octagonal metal 4-in. × 4-in. boxes, as shown in Fig. 6-11, are intended for containing wire connections for ceiling luminaires. These boxes are conventionally measured diagonally, where their actual dimensions are 4 in., but they have nominal 4-in. dimensions when measured between their flat sides. They can be fastened to ceiling joists or studs with nails or screws, or can be supported by telescoping metal braces that extend to fit between adjacent joists. These boxes are frequently used to support luminaires if there are studs or hickeys in the box, on the box covers, or on cross straps.

Industry standard octagonal metal boxes have depths of $1^1/_4$, $1^1/_2$, or $2^1/_2$ in., with corresponding minimum volumes of 12.5 to 21.5 in.^{3}.

Among the choices available for octagonal metal electrical boxes are

- Five different internal cable clamps and an internal armored cable clamp
- Single- or dual-screw plaster ears
- Five or nine $^1/_2$-, $^3/_4$-, or 1-in. conduit knockouts
- Grounding clips or screws
- Adjustable bar hangers with stud or fastener
- A choice of attached straps or brackets
- 10–32 tapped holes for grounding screws
- Extension rings that add 15.8 in.^{3} to the octagonal box volume

Round ceiling pan boxes with diameters of $3^1/_4$ in. have applications similar to those of octagonal boxes because they can be mounted on walls or ceilings to support light fixtures. Round boxes with depths of 0.5 in. have volumes of 4 in.^{3}, and those with depths of 0.75 in. have volumes of 5.5 in.^{3}. A choice of internal cable clamps is offered with these boxes, and they can accept round covers that fit both round and octagonal boxes. Plastic versions of these boxes are also available.

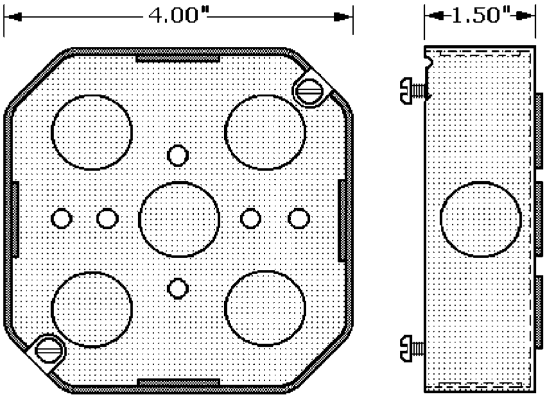


Figure 6-11 Octagonal metal box with a volume of 15.8 in.^{3} can contain wiring for a ceiling luminaire and a yoke or strap with a stud to support it.

Outlet Box Wiring

NEC 2002, Section 314.16, "Number of Conductors in Outlet, Device, and Junction Boxes, and Conduit Bodies," covers the limitations on the contents of any electrical box including conductors or fittings to assure that the boxes will not be overloaded and present a fire or shock hazard. These requirements are based on the cross-sectional area of conductors in relation to the size of the box, fitting, or raceway system. The maximum number of conductors permitted in standard outlet boxes is listed in NEC Section 314.16, and Table 314.16 lists a wide selection of standard metal boxes and states the maximum number of conductors allowed.

- Part (A), "Box Volume Calculations," defines the volume of a wiring enclosure or box. The calculations must take into account the volume of the box as well as the volume of any extensions such as domed covers or extension rings.
- Part (B), "Box Fill Calculations," describes the method for determining how much volume (fill) may be occupied by conductors, clamps, support fittings, devices (switches or receptacles) or equipment, and equipment grounding conductors.
- Part (C), "Conduit Bodies," covers enclosing No. 6 AWG or smaller conductors and requires that the maximum number of conductors be computed. (See also "Conduit Bodies and Fittings," in this chapter.)

Table 6-3 is a simplified table derived from NEC Table 314.16(A) to focus on the dimension and maximum number of conductors for eight common metal boxes. Both Table 6-3 and the NEC table apply only where all the wires in a given box are the same size, and the boxes contain no fittings such as internal cable clamps, luminaire studs, grounding conductors, equipment bonding jumpers, clamps, switches, or receptacles. They also assume that grounding conductors are not part of the wiring within the box. If any of these items is present, a number must be deducted from the number of conductors listed.

NEC Section 314.16 also states that ganged boxes must be treated as a single box with a volume equal to the sum of the volumes of its two sections. The same rules apply to wires in boxes using any wiring method: conduit, EMT, BX, or NM cable.

The following information summarizes the deductions allowed from the specified wire count for each box volume.

- Each conductor coming into a box and connecting to a wiring device counts as one conductor.
- Each strap-mounted device such as a switch or receptacle counts as two wires.
- One or more ground conductors count as a single conductor deduction of the size of the largest ground conductor.
- Isolated ground conductors count as one conductor.
- Unbroken wires running through the box count as one wire.
- Each conductor coming into a crimp or twist-on splice device counts as one wire.
- One conductor deduction must be made for one or two cable clamps. Moreover, even if one clamp is left unused, it counts as one wire.
- Each hickey or luminaire stud in the box counts as one conductor.

TABLE 6-3 ELECTRICAL METAL BOX CONDUCTOR CAPACITIES

BOX TRADE SIZE (in.)		MINIMUM VOLUME (in.^{3})	MAXIMUM NUMBER OF CONDUCTORS IN BOX	
			14 AWG	12 AWG
$4 \times 1^1/_4$	Octagonal	12.5	6	5
$4 \times 2^1/_8$	Octagonal	21.5	10	9
$3 \times 2 \times 1^1/_2$	Device	7.5	3	3
$3 \times 2 \times 2^1/_2$	Device	12.5	6	5
$3 \times 2 \times 3^1/_2$	Device	18.0	9	8
$4 \times 2^1/_8 \times 1^1/_2$	Device	10.3	5	4
$4 \times 2^1/_8 \times 1^7/_8$	Device	13.0	6	5
$4 \times 2^1/_8 \times 2^1/_8$	Device	14.5	7	6

Grounding and pigtail wires are not counted.
Source: NEC 2002, Table 314.16(A), p. 70-166.

The sample calculation here is based on the use of a 3-in. × 2-in. metal device box with a depth of $3^1/_2$ in. As indicated in Table 6-3, a maximum of nine No. 14 AWG conductors are permitted, a requirement that can be met if the fill in the box consists of two 14/2 NM cables, each containing two insulated 14 AWG wires and one bare 14 AWG ground wire, one cable clamp, and one strap-mounted duplex receptacle.

The total is determined as follows:

4 No. 14 AWG insulated wires	4
2 No. 14 AWG ground wires	1
1 strap-mounted receptacle	2
2 cable clamps	1
Total	8

This fill meets the requirements of NEC 2002 Article 314.16.

If for some reason the box will contain conductors with different wire gauges—say, 12 and 14 AWG—Table 314.16(B), “Volume Allowance Required per Conductor,” permits an alternative method for calculating fill. It gives the free space in in.^{3} and cm^3 within the box occupied by conductors sized from 18 to 6 AWG.

Wall-Mounted AC Switches

Standard industrial-specification-grade wall-mounted toggle and locking switches are rated for 120/277 and 347 V AC from 15 to 30 A. Commercial-specification-grade wall-mounted toggle switches are rated for 120/277 V AC for 15 and 20 A, and 120 V AC, but 347-V AC 15-A units are also available. By contrast, most residential-grade toggle switches are rated for 120 V AC, 15 A.

The three types of general-purpose wall-mounted switches available are

- *Single-pole switches* that can control lights from one location.
- *Three way-switches* that can control lights from two different locations. They are always installed in pairs.
- *Four-way switches* that, when used with a pair of three-way switches, can control lights from three or more locations.

Among the many specialized wall switches available commercially are

- *Dimmer switches* that permit illumination levels to be controlled
- *Pilot-light switches* with built-in lamps that glow when lights or appliances are powered by the switch
- *Switch/receptacles* that combine a grounded receptacle with a single-pole wall switch
- *Timer switches* that can be set to turn lights on and off automatically
- *Time-delay switches* that can turn off lights after preset time delays
- *Motion sensor* or *proximity switches* that project wide-angle infrared beams to detect movement over large areas to turn lights on automatically
- *Programmable switches* that include digital controls which can provide four on–off cycles each day to perform various functions

There are standard, miniature, and specialty switches. Switches can be actuated by conventional or flush toggles, rockers, pushbuttons, rotary knobs, or sliding handles. Wall switches can be identified by counting their screw terminals. Single-pole switches have two screw terminals, three-way switches have three screw terminals, and four-way switches have four screw terminals. Most electrical wall switches now include a green-colored grounding screw. The NEC requires that switches be grounded only when installed in plastic boxes, but it is considered good practice to ground all switches for extra protection against electrical shock by "pigtailing" a grounding conductor to a grounding screw.

Many switches can either be side- or back-wired. Switches are back-wired by removing the insulation on the ends of wires to the length indicated by a gauge molded on the back of the switch. The wire ends are then inserted into wire wells that contain clamps to grip the wires. While back-wired connections are fast and easy to make, connections made to screw terminals are generally considered to be more reliable, particularly if the switch is near a refrigerator or other motor-powered equipment. Vibrations transmitted through the floor and walls from this equipment can loosen the wires from the clamps and open the circuit.

Switches have straps to mount them to the electrical boxes. The "ears" on the straps brace the switch against the upper and lower edges of the cutout made in the wallboard for the electrical box.

Switches are manufactured in three general grades: industrial, commercial, and residential. The industrial-grade products are made to be more durable, but the differences between the grade essentially relate to the choice and quality of of the materials used in their construction, and this is reflected in their prices. Regardless of grade, however, all acceptable switches should at least be UL listed, CSA certified where applicable, and meet or exceed NEMA and ANSI standards.

Single-pole switches: A single-pole, industrial-grade AC toggle switch is shown in Fig. 6-12. Rated for 15 A, 120 V AC, it includes a grounding screw and a self-grounding clip. The single-pole wall switch shown in Fig. 6-13*a* is the most popular type of wall-mounted toggle switch. It has two screw terminals and a grounding screw. These switches can control lamps and luminaires, appliances, or receptacles from a single location. Each single-pole switch toggle is marked with ON and OFF. If the switch is mounted correctly, the ON mark will be visible when the toggle in the *up* position.

Three-way switches: A three-way switch is shown in Fig. 6-13*b*. Three-way switches are always installed in pairs so that they can control lights from two separate locations. These switches can be identified by their three screw terminals and absence of ON–OFF markings. The *common screw terminal* is darker in color than the two *traveler screw terminals,* which are functionally interchangeable.

Four-way switches: A four-way switch is shown in Fig. 6-13*c*. It is always installed between a pair of three-way switches. Four-way switches have four screw terminals and no ON–OFF markings. When used with three-way switches, the four-way switch makes it possible to control lights from three or more locations.

Duplex switches: A duplex wall switch is shown in Fig. 6-13*d*. It has two switch levers in a single housing. A duplex switch can control two light fixtures or appliances

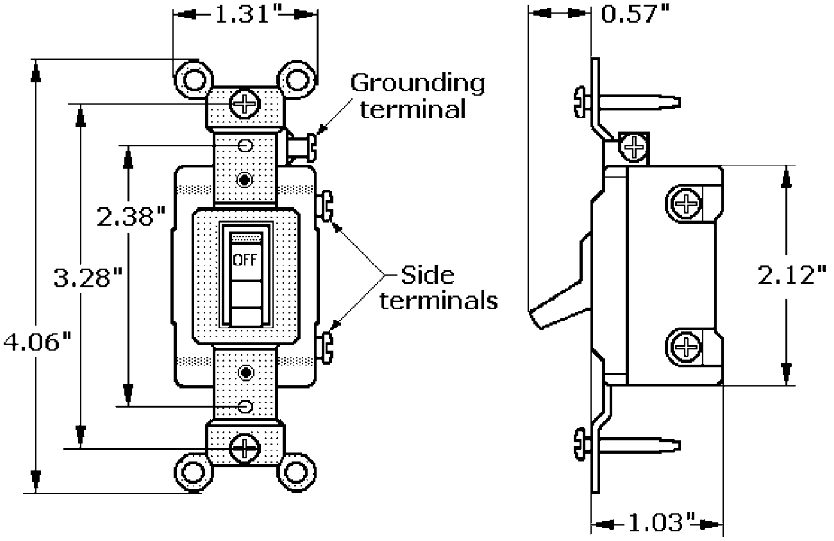


Figure 6-12 Single-pole AC toggle switch rated for 15 A, 120 V AC has two side and one grounding screw terminals.

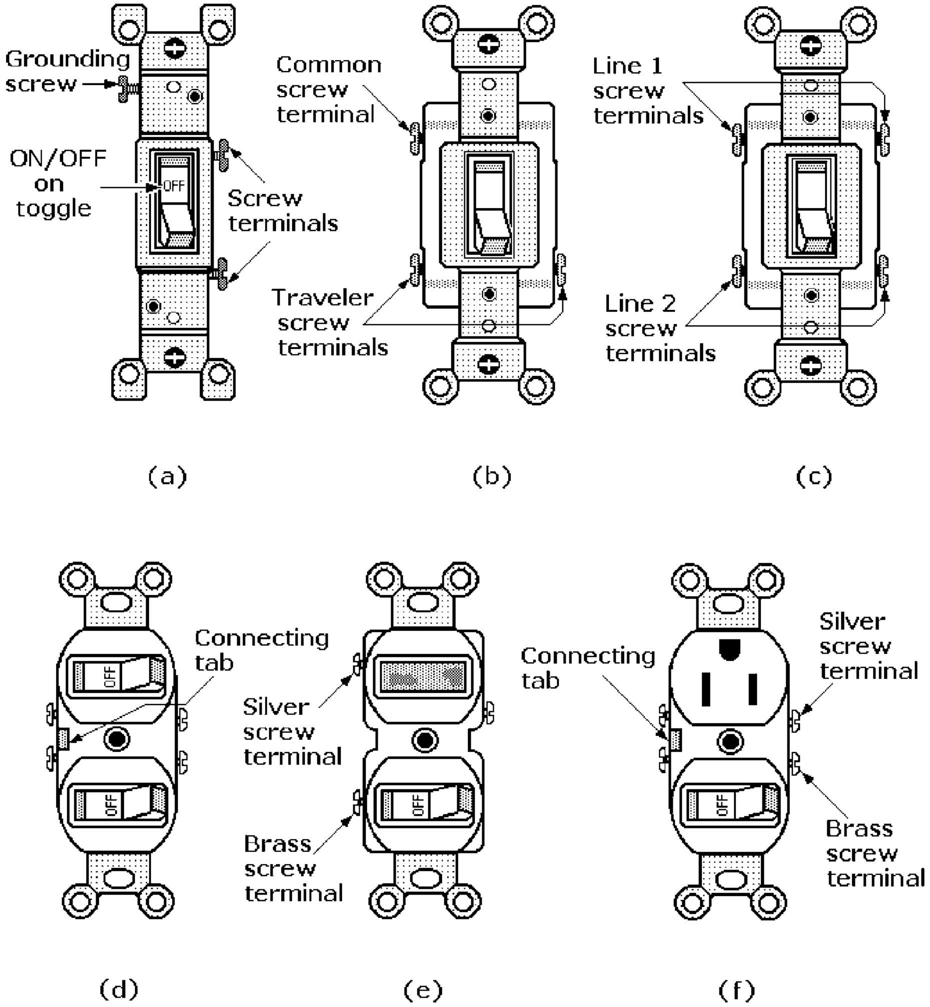


Figure 6-13 Wall switch configurations: (*a*) single-pole; (*b*) three-way; (*c*) four-way; (*d*) duplex; (*e*) pilot-light; (*f*) switch/receptacle.

from the same switch box. Typically both halves of the switch are powered by the same circuit. In these *single-circuit installations,* three black wires are attached to the double switch. The black “hot” wire that brings power into the box is connected to the terminal on the side of the switch with the connecting tab.

The wires carrying power out to other lamps or appliances are connected to the terminals on the side of the switch that *does not* have a connecting tab. The white neutral wires are connected together with a wire connector. The connecting tab of the double switch joining two of the screw terminals can be removed so that each half can control a separate circuit.

Pilot-light switches: A pilot-light switch, as shown in Fig. 6-13*e,* has an internal incandescent lamp or LED in its actuator that illuminates when the switch is connected to an energized circuit and the actuator is in the ON position. Pilot-light switches are usually installed where a controlled luminaire or appliance cannot be seen from the switch location. This switch requires a neutral wire connection, and its switch box must have room to contain two two-wire cables.

Three wires are connected to the switch. The black "hot" wire is connected to the brass screw terminal on the side of the switch body that does not have a connecting tab. The white neutral wires are pigtailed to the silver screw terminal, and the black wire carrying power out to the load is connected to the brass screw terminal next to the tab. Finally, the bare copper grounding wires are pigtailed to the grounded metal box.

Switch/receptacles: The wall switch/receptacle shown in Fig. 6-13*f* combines a grounded outlet with a single-pole wall switch. Three-wire grounded cable is needed to install this device, because it requires a neutral wire connection.

To wire this switch so that the outlet is powered regardless of switch position, the "hot" wire bringing power into the switch box should be connected to the side of the switch with the connecting tab. Then the second "hot" wire carrying power out to the load should be connected to the brass screw terminal on the side of the switch body that *does not* have a connecting tab. The white neutral wire should be pigtailed to the silver screw terminal. The bare copper grounding wires should be pigtailed to the green grounding screw on the switch/receptacle and to the grounded metal box.

This device can also be wired so that the outlet is "hot" *only* when the switch is ON. The hot wires should be reversed so that the "feed" wire is attached to the brass screw terminal on the side of the switch that *does not* have a connecting tab. Finally, the second "hot" wire is attached to the brass screw terminal on the side of the switch that *has* the connecting tab.

Timer switches include electrically powered control dials that can be set to turn lights on and off automatically once each day. These switches are usually used to control both indoor and outdoor luminaires. A switch box containing two cables with neutral wires is required for its installation. Timer switches have three-wire leads: a black wire for connection to the incoming "hot" wire, a red wire for connection to the wire carrying power out to the load, and a neutral wire for connection to the neutral wires of the entering cables. The bare copper grounding wires are pigtailed to the grounded metal outlet box.

Time-delay switches contain spring-driven mechanisms with dials that must be wound manually. The dials can be set to turn off a load after delays ranging from 1 to 60 min. These switches are usually used to turn off luminaires, exhaust fans, and infrared heat lamps in bathrooms or other rooms that are only temporarily occupied. A time-delay switch has two black leads that are connected to the "hot" circuit wires with wire connectors. Because a time-delay switch does not need a neutral wire connection, it can be placed in a switch box containing either one or two cables. If the switch box contains two white neutral wires, they are connected together with wire connectors. The bare copper grounding wires are pigtailed to the grounded metal box.

Programmable switches, used principally for area security, include digital electronic controls and a digital display. They have on/off switches and function keys that permit them to be programmed to provide as many as four on/off cycles per day. These switches do not require neutral wire connections, so they can be installed in boxes containing either one or two cables. The two black wire leads on the switch are connected to the "hot" circuit wires with wire connectors. If the switch box contains two white neutral wires, they are connected together with wire connectors. The bare copper grounding wires are pigtailed to the grounded metal box.

AC manual motor starting switches are heavy-duty switches that provide manual on/off control of single-phase or three-phase AC motors where overload protection is not required or is furnished separately. Typical ratings for single-pole, double-throw switches are 250 V AC, 30 A or 600 V AC, 20 A. Three-pole, three-phase switches have ratings of 600 V AC, 30 A. These switches are used to control machine tools, pumps, fans, and conveyors in industrial and commercial facilities. Switches intended to control motors also have horsepower ratings. Two-pole switches are rated for either 2 or 3 hp, and three-pole switches are rated from 7 to 10 hp.

To qualify for an hp rating, a motor-starting switch is tested at 6 times the full motor load current corresponding to the hp rating marked on the switch. For DC motor load controllers, the test is made at 10 times the full motor load current corresponding to the DC hp rating marked on the switch.

Lamp Dimmers and Fan Controls

Wall-mounted incandescent lamp dimmers are available in at least four different styles, and fluorescent lamp dimmers, low-voltage lighting, and fan controls are available in three of these styles:

- Rotary dimmers
- Slide-action dimmers
- Toggle dimmers
- Digital dimmers

Incandescent lamp dimmers are wall-mounted devices that include a *triac,* which functions like two silicon controlled rectifiers (SCRs) in parallel. As a result, a triac can control DC or full-wave AC. When full-wave AC is applied across the triac terminals, positive and negative gate pulses can control the turn-on time of anode-to-cathode current. By delaying the application of the gate pulses, both load current and power can be reduced.

Delays in positive and negative gate pulses "chop" or delete the fronts of both positive and negative half-cycles of the sinusoidal waveform. This results in a narrowed waveform that reduces the current and therefore power to the load. Delays in application of gate pulses can reduce load current from about 95 to 5 percent of full value.

The distorted waveform resembles a series of positive and negative square waves which introduce step functions to the load. Resistive incandescent lamp loads can tolerate these waveforms, but inductive loads including motors and fluorescent lamp ballasts can be damaged by them. The chopped waveforms cause coils or windings to overheat.

Dimmers are not, as is widely believed, variable resistors or rheostats. Any rheostat capable of controlling 120/240 V AC would be too large and heavy to fit in a standard box. Even if it were housed in a larger metal box, it would dissipate enough power as heat to be a fire hazard.

The delay in gate pulses in incandescent lamp dimmers is adjusted by turning a knob on a rotary switch, which moves a wiper on a slide switch. If the knob is in its OFF position, the triac turns on early in the AC cycle, allowing nearly full current to be sent to the lamp so it shines brightly. By adjusting the knob, the gate pulses can be delayed and the lamp is dimmed. The dimming range is set by the dimmer circuitry. (See also the discussion of triacs in Chap. 3.)

Heat dissipation occurs with triac-based dimmers, but it does not present a problem as it would be with a rheostat. Triac-based dimmers are equipped with metal heat sinks to dissipate any heat built up within their metal device boxes. Although a dimmer can replace a single-pole wall switch in a standard device box, a larger device box is usually recommended. Dimmer switches have larger bodies than standard switches, and the extra space in the box assures more air circulation for heat dissipation.

Fluorescent lamp dimmers control the ballasts of fluorescent and low-voltage luminaires. The two basic types of dimming ballasts are *magnetic* and *electronic.* Magnetic dimming ballasts are step-down transformers that present inductive loads, while electronic dimming ballasts include internal solid-state circuitry, so they are not strictly inductive.

Dimmers designed for fluorescent and low-voltage lighting systems are rated for specific magnetic or electronic ballasts. These dimmer circuits must be compatible with the ballast recommended by the lamp manufacturer, and they should not be used for any other type of fluorescent ballast.

It is important that incandescent lamp dimmers *not* be used to control standard fluorescent lamps, low-voltage lighting, or fan speed because of the potentially destructive effect of the chopped output waveforms from their triac control circuits. However, some compact fluorescent lamps (CFLs) can be controlled by them. Precautions should also be taken to be sure that receptacles are not controlled by incandescent lamp dimmers because of the possibility that fans, vacuum cleaners, power tools, and other motor loads might be plugged into them and damaged.

Fan speed controls: There are two types of wall-mounted fan speed controls, fully variable (full-range) and step control. Both types of controls can be used on conventional ceiling paddle fans, regardless of the number of speeds the fan has. Fan speed is set on its highest setting when the speed control is installed so that it can be varied through its entire speed range. Fan manufacturers often recommend that specific controls be used with their products. Residential fan speed controls for 120 V AC, 60 Hz have ratings from 1.5 to 5 A, and commercial-grade units have ratings to 10 A.

DIMMER AND MOTOR CONTROL SPECIFICATIONS

Rotary dimmers: Lamp illumination or fan speed can be controlled by rotating the knob of a unit such as the one shown in Fig. 6-14*a.* Some of these dimmers also have a push-on/push-off feature initiated by pushing on the knob. All rotary dimmers look the same,

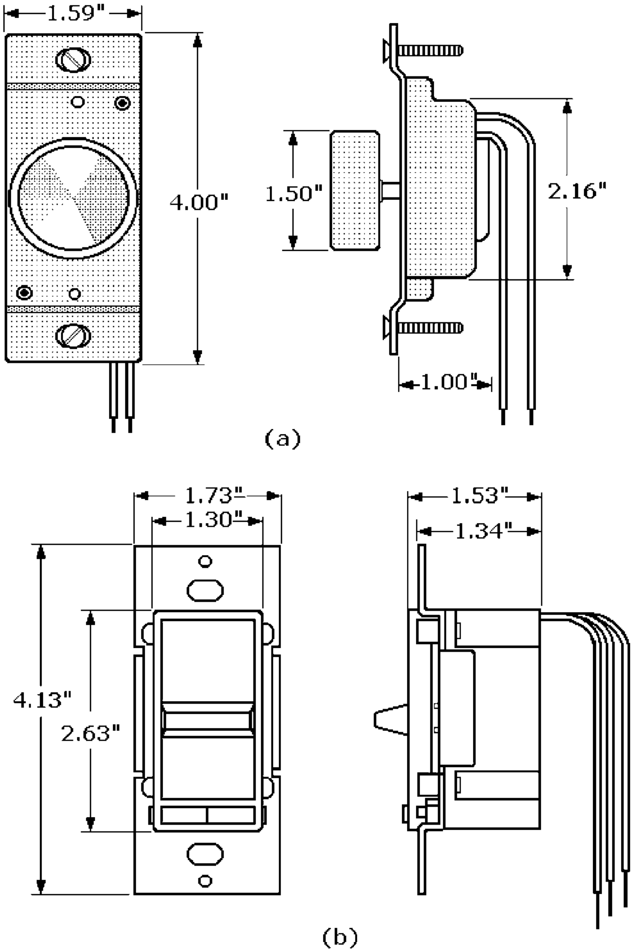


Figure 6-14 **Dimmers: (*a*) rotary and (*b*) slide contain different circuits for dimming incandescent and fluorescent lamps and controlling fan speeds.**

but their internal circuitry can be quite different, and it is important that their intended applications be known. Some ratings for commercially available units are the following.

- Incandescent lamp single-pole and three-way push-on/push-off versions are rated for 300 to 2000 W at 120 V AC.
- Fluorescent lamp single-pole versions for controlling 2 to 12 rapid-start fluorescent lamps with magnetic ballasts are rated for 40 to 480 W at 120 V AC.
- Fan-speed control versions are rated for 1.5 to 5 A at 120 V AC.

Slide-action dimmers control lights or fan speed by moving an actuator on a slide switch. They typically have two controls: a snap-action toggle switch and a sliding potentiometer. The incandescent lamp dimmer shown in Fig. 6-14*b* includes a toggle on/off switch. Some ratings for commercially available units are the following.

- Incandescent lamp single-pole and three-way versions, either with or without preset on/off switches and status lamps, have typical ratings of 600 W at 120 V AC.
- Fluorescent lamp single-pole and three-way magnetic versions with preset on/off switches are rated for 480 or 500 W at 120 and 277 V AC.
- Fan control single-pole and three-way versions with or without preset on/off switches are rated for 1.5 or 5 A.

Toggle dimmers include both single-pole and three-way styles. Incandescent lamp versions are rated for 600 W, 120 V AC. The three-way versions permit dimming from either switch location. They can also be combined with a standard three-way light switch or a second three-way dimmer. Models that include a combination of a toggle-style on/off switch and a digital touch pad are also rated for 600 W at 120 V AC.

Touch-pad dimmers provide full-range dimming for incandescent lamps in response to finger position on the pad. They are typically rated for 600 W at 120 V AC.

Motion/Occupancy Sensors

Motion or occupancy sensors are automatic switches that turn lights or other devices on in the presence of a person or other moving object. The most popular technologies are passive infrared (PIR) sensing and ultrasonic. PIR sensors react to heat emitters such as the human body. They sense occupancy by detecting the difference between the heat emitted from a warm body (human or animal) and the ambient temperature of the room or space where the sensor is located. The output signal from the sensor activates the electronic circuitry that switches on the connected lights or alarms, either audible or silent.

When a PIR sensor, such as the one shown in Fig. 6-15, detects a person entering a room, it automatically switches the connected lights on. A switch of this type can turn on incandescent floodlights or fluorescent lamps with either electronic or magnetic ballasts. After the person (or other heat-emitting body) leaves, and the room remains unoccupied for a selected time interval, the sensor automatically switches the lights or alarm off.

Motion/occupancy sensors with various features are being offered by manufacturers. They are useful for at least three different mutually exclusive reasons:

- They provide convenient “hands-free” light switching for persons entering a room.
- They conserve energy and reduce electric bills by ensuring that controlled lights left on unintentionally in an unoccupied room are turned off.
- They perform a security function by turning lights or an alarm on in the presence of unwanted intruders to warn occupants in the place being protected or startle and perhaps disuade an intruder from trespassing further. (See also Chap. 9.)

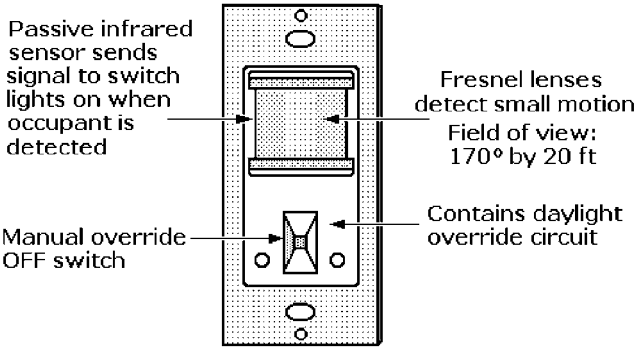


Figure 6-15 **Wall-switch passive infrared (PIR) occupancy sensor detects heat from occupants and switches lamps on.**

Wall-mounted occupancy sensors typically have lens systems with a field of view of 170 to 180°. Most commercial products include the following features:

- A manual switch lever that permits the sensor to be turned on or off.
- A delayed-off time adjustment, which can set the time the lights will remain on after occupants have departed.
- An ambient light override circuit to prevent the lights from turning on in the presence of bright natural light.

Many different versions of PIR occupancy sensors are available for mounting in such locations as enclosed offices, warehouses, hallways, stairways, narrow rooms, libraries, and selected outdoor locations. The simplest PIR sensors are in cylindrical housings with both threaded bases and threaded sockets. An incandescent or fluorescent lamp is screwed into the device, which, in turn, is screwed into a standard ceiling lampholder.

PIR occupancy sensors designed for outdoor installation are enclosed in water-resistant cases and typically have wider fields of view, up to 270°. They are usually housed with one or more floodlights to illuminate residential backyards or commercial storage areas to inhibit intruders.

In locations where the line of sight of a PIR sensor would be blocked, either indoors or outdoors, an ultrasonic occupancy sensor can be installed. These are volumetric motion detectors whose response is based on the Doppler principle. The sensors bounce ultrasonic energy off the objects in the area under surveillance and then measure the time taken for the energy to return. Movement by a person or animal into the area causes the sound waves to return faster than if the space were unoccupied, triggering a detection signal. That signal then activates the circuitry that turns the lights or alarm on. These sensors are most effective when used in open office spaces, conference rooms, enclosed hallways, and large areas of up to 200 ft^3, such as warehouses or retail stores.

Motion sensors with dual sensing technology include both ultrasonic and PIR technologies for turning floodlights on, but only one sensor controls the duration of the illumination. This technology is most effective in classrooms, computer rooms, large conference rooms, and areas where the ability to sense small motions is critical.

The choice of the technology selected depends on factors such as the kinds of activities that occur in the desired coverage area, physical limitations in mounting the sensor, or barriers and obstacles that would obstruct the sensor's coverage within the area.

Wall-Mounted Receptacles and Plugs

The three general classes of receptacles and plugs are:

- Straight-blade nonlocking, for general residential and commercial applications
- Locking-type, primarily for powering heavy-duty power tools
- Pin-and-sleeve devices, for making high-voltage industrial electrical connections

There are also many different specialized receptacles based on the straight-blade nonlocking receptacle design, which include:

- Ground-fault circuit interrupter (GFCI) receptacles
- Isolated-ground receptacles
- Surge-protective receptacles

Appendix A includes the NEMA configurations for straight-blade nonlocking and curved-blade locking plugs and receptacles and their circuit wiring diagrams.

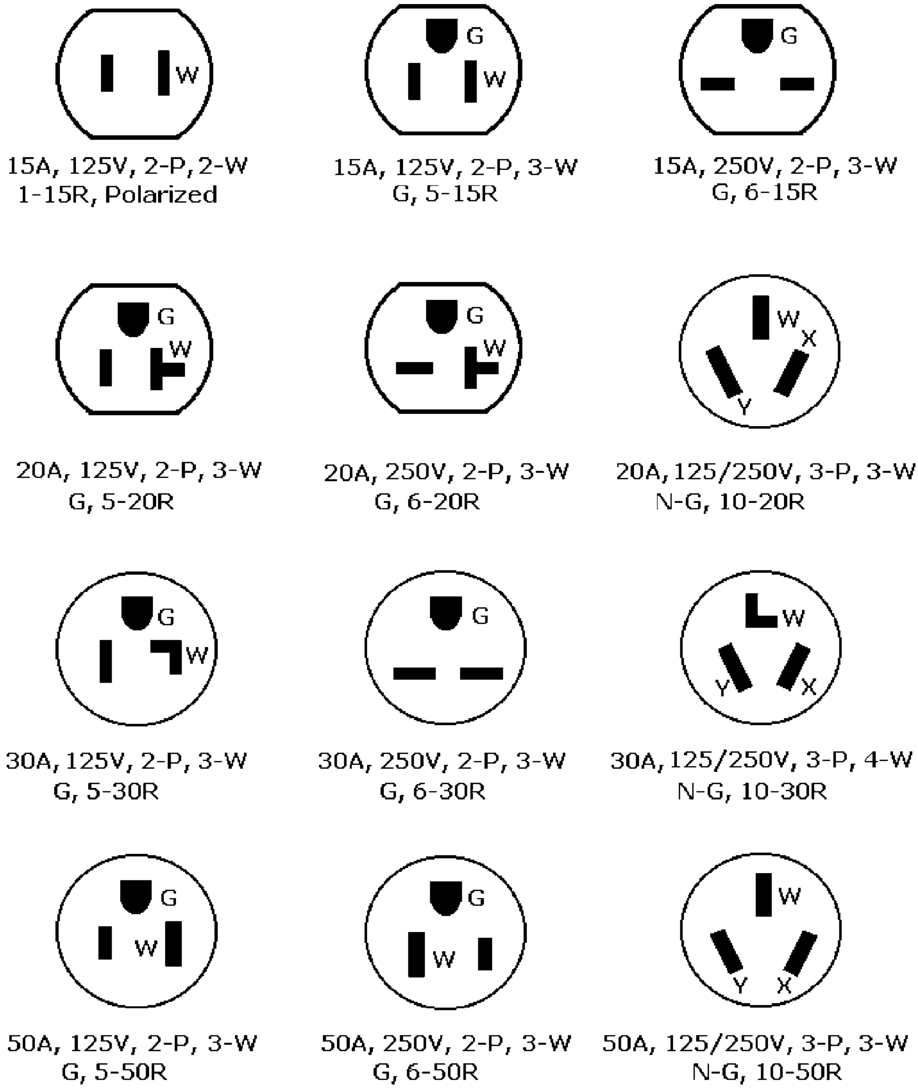
STRAIGHT-BLADE RECEPTACLES AND PLUGS

Straight-blade, nonlocking receptacles are made so that mating plugs can be inserted directly into them to make an electrical connection and they can be easily removed by pulling them straight out. Figure 6-16 illustrates the blade and prong profiles of NEMA straight-blade receptacles with ratings from 15 to 50 A.

The 15-A, 125-V, two-blade (two-pole), two-wire receptacle is no longer approved for new construction. The different widths of the parallel slots to accept a narrow and a wide plug blade were intended to assure that the connection would be polarized. These receptacles were standard for circuits in U.S. homes until about 1958. However, because the white neutral wire did not always ground stray current from loose wires or malfunctioning appliances, a third bare or green insulated copper ground wire was proposed as an additional safety feature, and it became standard on all residential wiring.

The new receptacles had a U-shaped hole to accept a plug prong in addition to the wide and narrow slots to accept the wide and narrow plug blades. The prong in the plug was intended to provide more reliable grounding. It is wired through the line cord to appliances to drain off any leakage current and route it to ground.

The adoption of this three-prong plug-and-receptacle combination led eventually to the acceptance of three-wire branch-circuit cable as the standard. It was found that the



15A, 125V, 2-P, 2-W
1-15R, Polarized

15A, 125V, 2-P, 3-W
G, 5-15R

15A, 250V, 2-P, 3-W
G, 6-15R

20A, 125V, 2-P, 3-W
G, 5-20R

20A, 250V, 2-P, 3-W
G, 6-20R

20A, 125/250V, 3-P, 3-W
N-G, 10-20R

30A, 125V, 2-P, 3-W
G, 5-30R

30A, 250V, 2-P, 3-W
G, 6-30R

30A, 125/250V, 3-P, 4-W
N-G, 10-30R

50A, 125V, 2-P, 3-W
G, 5-50R

50A, 250V, 2-P, 3-W
G, 6-50R

50A, 125/250V, 3-P, 3-W
N-G, 10-50R

Figure 6-16 **NEMA straight-blade receptacles rated 15 to 50 A and 125 to 250 V AC. Abbreviations: P = poles, W = grounding, N-G = nongrounding. Plug patterns are typically mirror images of receptable patterns.**

task of connecting metal conduit and bare wire outside the cable to form a separate ground connection was not only labor-intensive and costly, but was unreliable.

Single-phase, two-pole, three-wire grounding receptacles rated 15 and 20 A at 125 V AC are the most popular receptacles for installation in all new homes and buildings, and they replace the older receptacles and wiring in all updated electric service. However, two-prong plugs are still widely used on line cords for many different 120-V household appliances, from table lamps, toasters, and hair dryers to vacuum cleaners as well as stereos, TV sets, and computer printers. On the other hand, three-prong plugs terminate extension cords and line cords for power tools, desktop computers, and window-mounted air conditioners.

In most homes the number of single-phase 15-A receptacles exceeds the number of 20-A receptacles. Single-phase 30- and 50-A 125/250-V AC receptacles are specified for major appliances such as ranges, ovens, clothes dryers, and large room air conditioners. The plugs on the line cords for those appliances dictate the specific service required.

Nonlocking plugs and receptacles have ratings of 15 to 60 A and 125 to 347 V AC. The single-phase voltage ratings are 125, 250, 277, and 347 V, as well as 125/250 V. The three-phase voltage ratings are 250 V AC, and the three-phase Y ratings are 120/208 V AC.

The straight-blade plug profiles, with the exception of those for three-pole, three-wire, 125- and 250-V, 20-A service, are mirror images of their receptacle profiles. The different blade and prong profiles are intended to prevent accidental insertion of lower-rated appliance plugs in higher-rated outlets.

For more information on straight-blade surge-protective receptacles, see Chap. 12.

Receptacles are manufactured in four general grades: hospital, industrial, commercial, and and residential. The hospital-grade receptacles are durable premium products that have additional safety features. Industrial-grade receptacles are also made to withstand abuse. However, the differences among all of these receptacle grades are generally related to the choice and quality of materials used in their construction, and this is reflected in their prices. Regardless of grade, receptacles should at least be UL listed, CSA certified where applicable, and meet or exceed NEMA and ANSI standards.

DUPLEX STRAIGHT-BLADE RECEPTACLES

The features of a duplex straight-blade 15-A/125-V grounded receptacle are shown in Fig. 6-17*a*. This receptacle has two outlets for receiving two plugs. Each outlet has the 5-15R profile of the 15-A, 125-V, two-pole, three-wire, grounded receptacle shown in Fig 6-16.

Many receptacles, like wall-mounted switches, can be side-wired with screw-type terminals or back-wired by inserting the wire ends in wire wells with internal clamps on the backs of the receptacles. The insulation on the wire ends is cut back to a length indicated by a gauge molded on the back of the receptacle. When the wire ends are inserted into the wire wells, they are gripped by the clamps. While making back-wired connections is fast and easy, connections made to screw terminals are generally considered to be more reliable, particularly if the receptacle is near a refrigerator or other motor-powered equipment. Vibrations transmitted through the floor and walls from this equipment can loosen the wires from the clamps and open the circuit.

Receptacle have straps to mount them to the electrical boxes. The “ears” on the straps brace the switch against the upper and lower edges of the cutout in the wallboard made for the electrical box.

The removal of the connecting tab between the two “hot” brass screw terminals permits each outlet to function independently. Just as on switches, the mounting strap

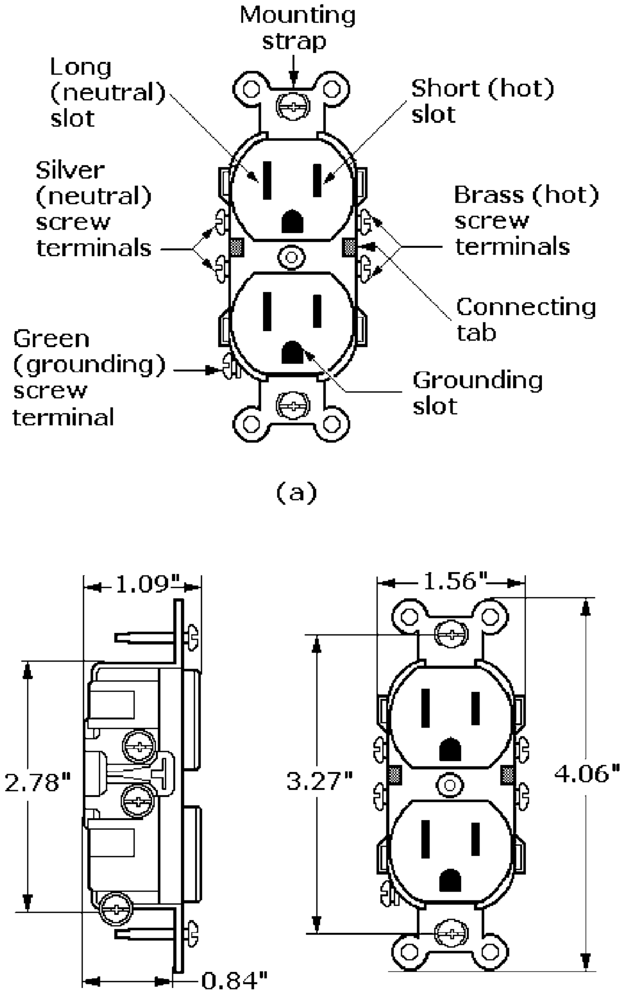


Figure 6-17 **Duplex straight-blade 15-A/125-V AC receptable has both push-in and screw terminals: (*a*) features; (*b*) dimensions.**

for attaching the receptacle to the electrical box has “ears” that can brace the receptacle against the upper and lower edges of the cutout in the wallboard around the box.

Receptacle manufacturers stamp, mold, or print their trademarks and maximum voltage and current ratings on their products, and they can add the UL symbol of Underwriters’ Laboratories, Inc., if that organization has listed their product.

The dimensions of an industrial-grade receptacle are given in Fig. 6-17*b*. These receptacles are likely to have impact-resistant nylon covers and bodies, triple-wipe, nickel-plated brass T-contacts, and nickel-plated brass No. 10-32 terminal screws.

Duplex straight-blade 15-A/125-V AC grounded receptacles are rated for 15 and 20 A, 125 V, and ungrounded versions are rated at 15 A, 125 V. Receptacles rated for more than 20 A are usually available only with a single outlet.

Receptacles marked CU or COPPER are intended for use with solid copper wiring conductors, while those marked CU-CLAD ONLY are approved *only* for use with copper-coated aluminum wiring. Only receptacles marked CO/ALR are approved for use with solid aluminum wiring. NEC 2002 states that receptacles marked AL/CU may no longer be used with aluminum wire.

Ground-Fault Circuit Interrupters

NEC 2002 discusses ground-fault circuit-interrupter (GFCI) circuits in various contexts in 14 different articles, but the most comprehensive coverage is given in Section 210.8, "Ground-Fault Circuit-Interrupter Protection for Personnel." This section states the eight locations where GFCIs must be installed in homes, apartments, or other living spaces. Other articles mandate their installation in hospitals, laboratories, construction sites, auto repair shops, recreational vehicles, and in outdoor receptacles near swimming and spa pools and decorative fountains.

Typical residential circuit breakers without GFCI circuitry trip only when the current surpasses 15 or 20 A, but a current of only 0.1 A passing through a person's body can cause a heart attack. Most electrical shocks received by people in their own homes are caused by a ground fault in a tool or appliance. The human body then becomes a better conductor than the appliance's ground wire.

A "hot" wire with worn or decayed insulation that contacts the metal enclosure of an appliance or power tool can turn the enclosure into a conductor. Similarly, a wet surface on a metal appliance enclosure caused by splashed water or condensation can also turn the enclosure into a conductor. In both cases, ground current will seek an alternate path to the ground wire. If a person touches this surface, especially if he or she is wet, standing in water, or touching a metal sink or plumbing fixture, his or her body will become a conductor that parallels the appliance's ground wire. Although it might conduct a fraction of the ground current, this could have lethal consequences.

Figure 6-18*a* is a simplified schematic diagram for a GFCI circuit that could be in a circuit breaker or a receptacle. This circuit responds when current returning to the outlet from the appliance is less than the input current to the appliance. It compares the current flowing to the load on the incoming "hot" wire (black) with the current leaving the load on the neutral conductor (white), which should normally be equal.

If current leaks inside the load and begins to pass through the user's body to the ground by a parallel path (a "ground fault"), the *sensing coil* inside the GFCI detects the reduction in the return current. An electromagnetic sensing action between the "hot" and neutral wires as they pass through the toroidal sensing coil is illustrated in Fig. 6-18*b*.

The currents in both the incoming "hot" wire and the outgoing neutral wire pass through the coil in opposite directions, but because their fields effectively cancel, the

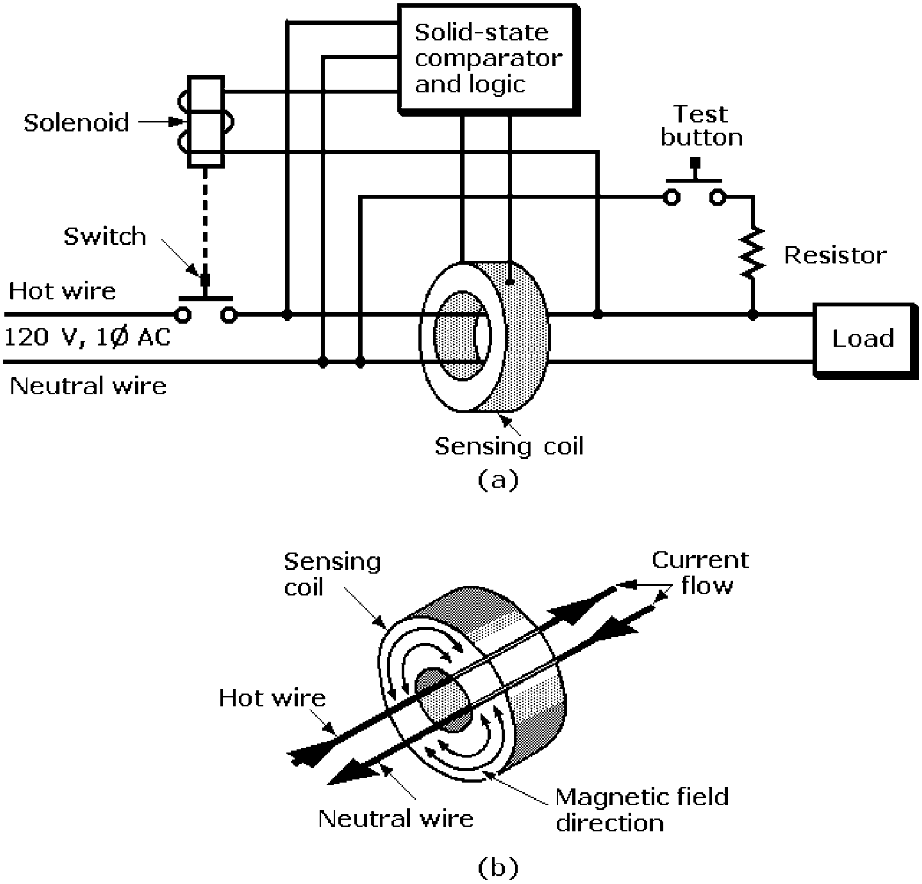


Figure 6-18 Ground-fault circuit interrupter (GFCI): (*a*) schematic; (*b*) electromagnetic interaction between the wires and sensing coil.

net voltage in the coil is negligible. However, if the current in the neutral wire drops, a detectable voltage is induced in the coil. A semiconductor voltage comparator circuit then triggers semiconductor logic which actuates a pull-in solenoid. When the solenoid plunger pulls in, it releases a spring, causing the switch to snap open, interrupting the circuit.

As stated in Chap. 5, there are both advantages and disadvantages to having an entire branch circuit protected by a GFCI circuit breaker. The most common complaint against them is that if they are triggered, the owner/resident must go to the loadcenter, locate the breaker, and reset it to restore the complete branch. This can be inconvenient and time-consuming. Resetting GFCI circuit breakers was discussed in Chap. 5. By contrast, GFCI receptacles offer a more convenient way to comply with NEC requirements.

To comply with UL Standard 943, Class A, all GFCI devices must detect leakage current as small as 5 mA (±1 mA), and interrupt the circuit as fast as 1/40 s (25 ms) to prevent possibly lethal electrical shock to a person.

GFCI RECEPTACLES

The NEC now requires GFCI receptacles or outlets in new and modernized bathrooms, kitchens, garages, and outdoor receptacles. This requirement can be met by GFCI-equipped circuit breakers in the loadcenter upstream of each branch circuit requiring protection or by strategically located GFCI receptacles.

The use of GFCI receptacles in the rooms or locations where GFCI protection is required is the most popular way to comply with the NEC requirements. Of these receptacles, the duplex GFCI receptacle shown in Fig. 6-19*a* is the most popular, but combination switch and GFCI outlets as shown in Fig. 6-19*b* are also available.

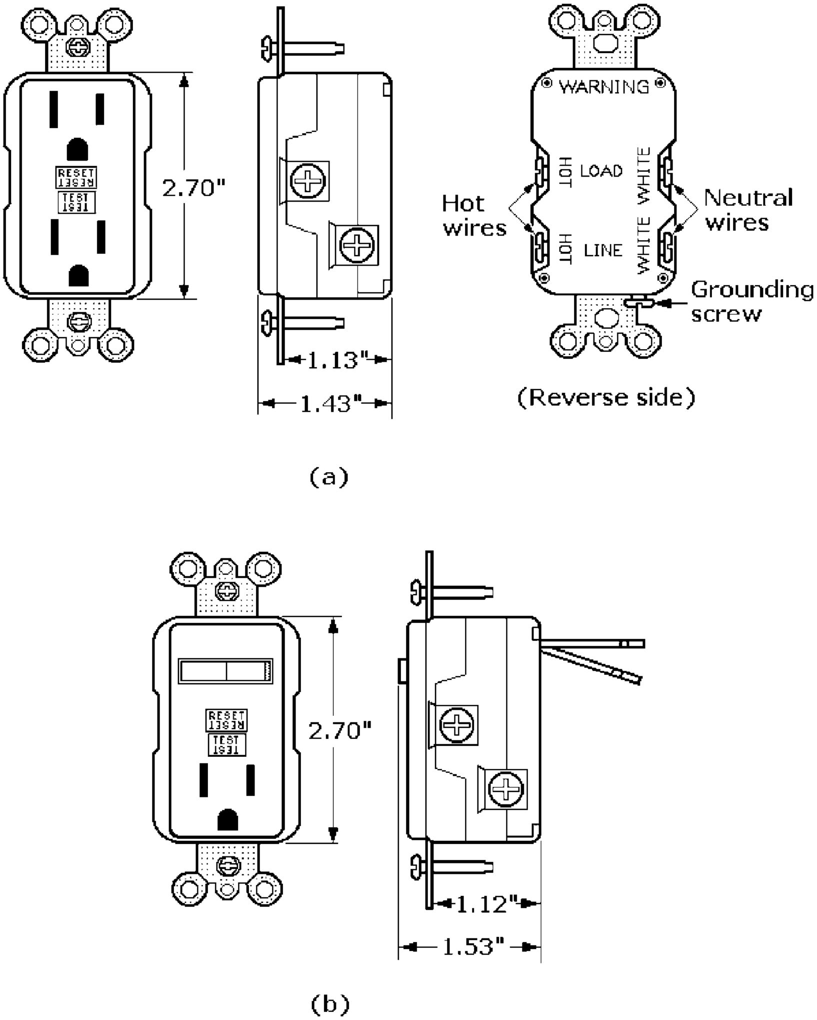


Figure 6-19 GFCI devices: (*a*) duplex straight-blade 15-A, 125-V AC receptacle; (*b*) combination switch and 15-A, 125-V AC GFCI receptacle.

After a GFCI receptacle has opened the circuit, it can be reset manually after the fault condition has been cleared, by pressing the RESET button shown on the GFCI receptacles illustrated in Fig. 6-19. Pressing the button compresses a spring, resetting the GFCI. A TEST button on the GFCI permits it to be tested periodically to be sure it is functioning correctly. By pressing the TEST button a current is sent through a resistor, causing a sensing coil imbalance. This simulates a ground fault that triggers the solenoid and opens the circuit.

GFCI receptacles are rated for both 15 and 20 A. The 20-A versions can be easily identified by the short horizontal “tee” slot intersecting the longer vertical slot. Many electrical codes require that only 20-A GFCI receptacles be placed in kitchens where many different high-current-drawing portable appliances are present. These include toasters, coffee makers, and blenders, typically used near sinks and faucets. They are also recommended for use in bathrooms where high-current-drawing hair dryers are used near sinks, and in laundry rooms with sinks where washing machines and clothes dryers are being used and the floor can be wet.

Both 15- and 20-A GFCI receptacles fit in standard wall boxes. They can be wired to provide GFCI protection for any appliance or load plugged into it, as well as all standard downstream receptacles in the same branch circuit. GFCI receptacles rated for more than 20 A provide ground-fault protection to heavy equipment powered by three- and four-wire circuits grounded with neutral. These devices are wired in conjunction with a switching contactor or relay supplied by the customer. Typical applications include their use in heater packs, high-pressure washers, and industrial mixers.

Portable GFCI modules are available that can be plugged into existing unprotected standard receptacles. The choices include both automatic and manual-reset GFCI right-angle plugs rated 15 A/125 V AC and 20 A/125 V AC. They can be prewired to cables of any length. There are automatic-reset GFCI cord sets available with extension cords from 2 to 35 ft long rated for 15 A/125 V AC or 20 A/240 V AC, and manual-reset versions available with the same ratings but cord lengths up to 25 ft. The GFCI module is located between a short length of cord terminated by a plug on one end and a longer length of cord terminated by a receptacle on the other end. These cord sets can protect individual power tools or appliances plugged into the receptacles.

Temporary portable power distribution centers affording GFCI protection are made as boxes measuring about 20 × 12 × 6 in. fitted with combinations of six or more GFCI-protected straight-blade or locking receptacles rated at 20 and 30 A. These centers provide GFCI protection to power sources for floodlights or power tools at construction sites, trade shows, convention halls, and wherever temporary portable power is required.

Isolated-Ground Receptacles

The NEC-approved common-ground network can provide a ground to protect persons and property, but it can also can be the source of unwanted transient electrical interference (EMI/RFI). This “noise” can scramble the data in a computer connected to the common-ground network and interfere with the operation of equipment containing microcontrollers such as cordless telephones and stereo entertainment systems.

These transient signals gain entrance into the network from their source through a branch connection to the common earth ground shared with the equipment being affected. The signals than travel back up the other ground conductor branch to interfere with the operation of the sensitive equipment.

An isolated-ground receptacle, such as the one shown in Fig. 6-20, can effectively eliminate the noise problems caused by EMI/RFI that has entered a common-ground network. The grounding terminals of the isolated-ground receptacle are electrically insulated from its mounting strap, separating it from the common-ground network.

A separate insulated equipment grounding wire connected to the receptacle's green grounding screw is then run back to the service entrance grounding system without making any interconnections where it is terminated.

The conductor can pass through one or more panelboards without connection to the panelboard grounding terminals before reaching its destination within the same building. This single path is far less likely to pick up electrical noise because it is grounded at a single point rather than to the common building ground network.

Isolated-ground receptacles typically have orange covers and bodies or are identified with orange triangles on their front faces. They are also likely to be covered with orange wallplates to distinguish them from conventional receptacles. Some of these wallplates are also engraved with the legend "Isolated Ground."

Surge-protective receptacles can also include ground isolation characteristics. These receptacles are discussed in Chap. 12.

Isolated receptacles are covered in NEC 2002, Section 250.142, "Use of Grounded Circuit Conductor for Grounding Equipment." This section states that "the use of an isolated equipment grounding conductor does not relieve the [owner/user of the] requirement for grounding the outlet box in which the isolated receptacle is mounted."

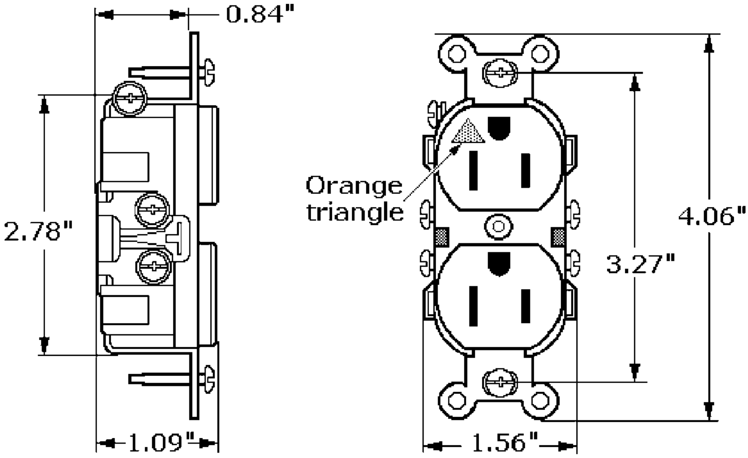


Figure 6-20 Duplex straight-blade 15-A, 125-V AC isolated-ground receptacle is identified by its orange body or an orange triangle on its front face.

Locking Receptacles and Plugs

Locking plugs, receptacles, connectors, inlets, and outlets are designed to perform the same functions as nonlocking plugs and receptacles, but they include features for locking the plug in the receptacle to prevent the plug's accidental disconnection. The unexpected disruption of power to such heavy-duty power tools such as circular saws, grinding machines, or floor polishers resulting from an accidental plug disconnection could cause the operator to lose control of the machine, injuring the operator or damaging property.

Bosses projecting from the ends of the curved locking-plug blades mechanically lock the blades in the receptacle slots when they are inserted and rotated in a clockwise direction. The bosses engage notches at the bottom of the slots in the outlet to lock the plug in position while also making secure electrical contact. The plug then cannot be pulled out of the outlet by accident even if it is under a reasonably high degree of tension. To remove the plug deliberately, it must be rotated counterclockwise back to the insertion position to be withdrawn.

NEMA locking-type plugs and receptacles are classified the same way as NEMA nonlocking plugs and receptacles. Following are the options for locking-type plugs and receptacles:

- Three current ratings, 15, 20, and 30 A
- Seven single-phase AC ratings, from 125 to 600 V and 125/250 V
- Three three-phase AC ratings, 250, 480, and 600 V
- Three three-phase Y ratings, 120/208, 277/480, and 347/600-V-phase Y
- Six wiring classes, from two-pole, two-wire nongrounding to four-pole, five-wire grounding

Table 6-4 summarizes the various ampere and voltage ratings of locking receptacles together with their pole/wire combinations and grounding features.

The body lengths of NEMA locking plugs range from 1.88 (midget) to 2.70 in., with diameters ranging from 1.13 (midget) to 2.22 in. Similarly, body lengths of NEMA locking connectors range from 2.34 (midget) to 3.78 in., with diameters ranging from 1.13 (midget) to 1.97 in. The form factors of these products are similar, and they can be recognized by the number and shapes of their curved blades and slots.

These plugs and receptacles are ruggedly built to withstand the mechanical abuse and environmental extremes encountered in heavy industries. Some of these products have been developed specifically to function in wet and damp environments where they are exposed to extreme temperature excursions, acids, alkalis, grease, oils, and solvents.

In addition, some locking-type plugs and receptacles feature "tongue and groove" construction to seal out water, moisture, and dirt when the plugs are mated with the connectors. Others were developed specifically to withstand dusty and dirty environments, cracking and fading, and temperature extremes. They feature single-piece brass triple-wipe contacts and solid brass plug blades.

TABLE 6-4 INDUSTRIAL-GRADE NEMA LOCKING RECEPTACLES, PLUGS, CONNECTORS, INLETS, AND OUTLETS

AMPERES (A)	VOLTAGE (V)	POLES	WIRES	GROUNDING
15, 20, 30	125	2	3	Yes
15, 20, 30	250	2	3	Yes
15, 20, 30	277	2	3	Yes
15, 20, 30	3Φ 250	3	3	Non
20	347	2	3	Yes
20, 30	480	2	3	Yes
20, 30	600	2	3	Yes
20, 30	125/250	3	3	Non
20, 30	3Φ 250	3	3	Non
20	3Φ 250	3	4	Yes
20, 30	3Φ 480	3	3	Non
20, 30	125/250	3	4	Yes
20	3Φ 480	3	4	Yes
20	3ΦY 120/208	4	4	Non
20	3ΦY 277/480	4	4	Non
20	3ΦY 347/600	4	4	Non
20	3ΦY 120/208	4	5	Yes
20	3Φ 277/480	4	5	Yes
20, 30	3ΦY 347/600	4	5	Yes
30	3Φ 600	3	3	Non
30	3Φ 250	3	4	Yes
30	3Φ 600	3	4	Yes
30	3Φ 120/208	4	4	Non
30	3Φ 120/208	4	5	Non
30	3ΦY 277/480	4	5	Non

Pin-and-Sleeve Devices

A general class of connectors intended specifically for the distribution of electric power in industrial facilities is called *pin-and-sleeve devices*. These devices include four kinds of components: plugs, receptacles, inlets, and connectors. Pin-and-sleeve devices are specified for powering a wide variety of electrical equipment that is exposed to hostile environmental operating conditions: These conditions are encountered in chemical plants and oil refineries, oil drilling platforms, steel mills, coal mines, heavy machine shops, construction sites, shipyards, and container ports.The devices have also been used to power mainframe computers and radio, television, and satellite communications transmitters.

Designed and ruggedly made to maintain reliable mechanical and electrical connections in the presence of high humidity, salt spray, water, oil, dust, and corrosive chemicals, pin-and-sleeve devices are the commercial equivalents of military-specification cylindrical connectors. They can withstand wide temperature excursions, shock and vibration, and a reasonable amount of accidental mechanical abuse.

The name pin-and-sleeve refers to the pin and sleeve contacts in these devices. Brass pins mate with brass self-adjusting contacts. The shells are made from high-quality, tough thermosetting plastics. The receptacle contact carriers of 60- and 100-A units are made of high-heat- and impact-resistant reinforced nylon, and those for 20- and 30-A units are made of high-impact-resistant nylon. There are three-, four-, and five-wire devices in this class of devices.

ILLUSTRATIONS OF TYPICAL PLUGS AND RECEPTACLES

Figure 6-21 is a gallery of outline drawings of an assortment of general-purpose straight-blade, locking, and pin-and-sleeve devices. Devices such as dead-front grounding plugs, inlets, outlets, and single receptacles are most likely to be specified for commercial and industrial rather than residential applications.

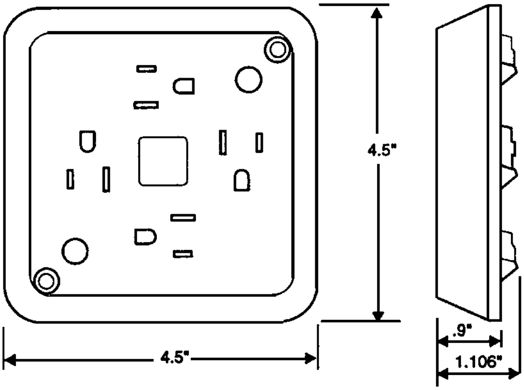
Wire Mesh Cable Grips

Cable grips are flexible, woven wire mesh tools that can be adjusted to conform tightly to the outside diameters of various kinds of cable, rope, and wire bundles, permitting them to be supported or pulled. They can also provide strain release on these objects when it is required. Some cable grips are reusable, and others remain permanently attached to the cylindrical objects they are supporting. The force of the grip on the object is proportional to the tension they are placed under.

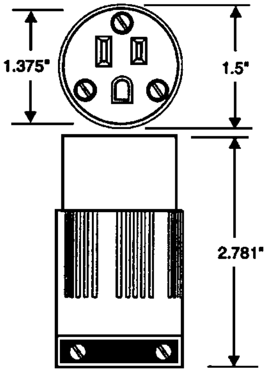
There are three types or wire mesh cable grips: strain relief grips, support grips, and pulling grips.

- *Strain-relief grips* are used in the process of connecting cable or flexible conduit to electrical enclosures and equipment. They prevent pullout caused by tension on the inner conductors and limit the bending angle at the point of entry. These grips distribute strain over the length of the mesh rather than allowing it to be concentrated at a point or transferred to the internal termination. They are woven from galvanized or stainless steel wire and have nylon or aluminum bushings or fittings.
- *Support grips* support the weight of vertical or horizontal lengths of electrical cable, telecommunications cable, or conduit to prevent them from being damaged. They are woven from tinned bronze, stainless, galvanized, or spring steel wire. These grips are supported with different kinds of hangers and bales.

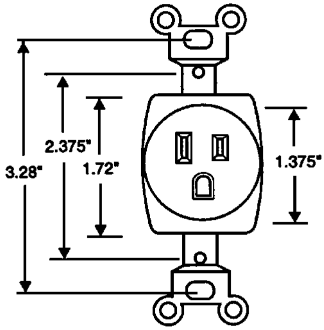
Straight-Blade Devices



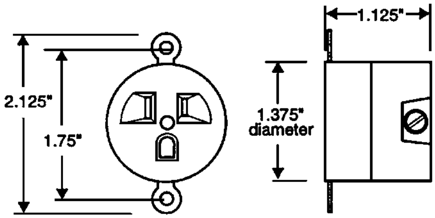
2-pole, 3-wire grounding quad receptacle, 15 A, 120 V



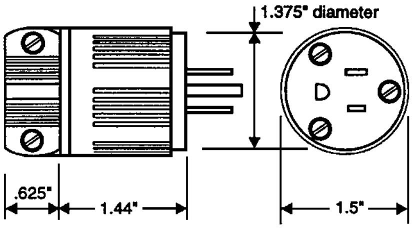
2-pole, 3-wire grounding connectors, 15 A, 125 V



2-pole, 3-wire grounding, side-wired single receptacle, 15 A, 125 V



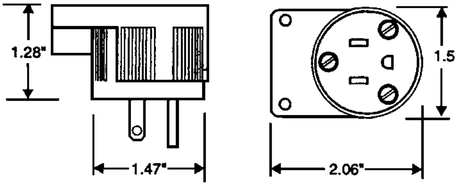
2-pole, 3-wire grounding single receptacle short mounting strap, 15 A, 125 V



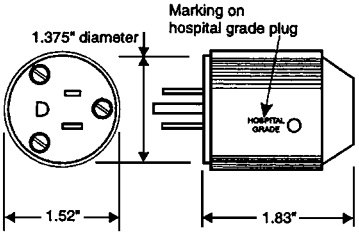
2-pole, 3-wire grounding dead plug, 15 A, 125 V

Figure 6-21 Gallery of outlines and dimensions of straight-blade, locking, and pin-and-sleeve connecting devices.

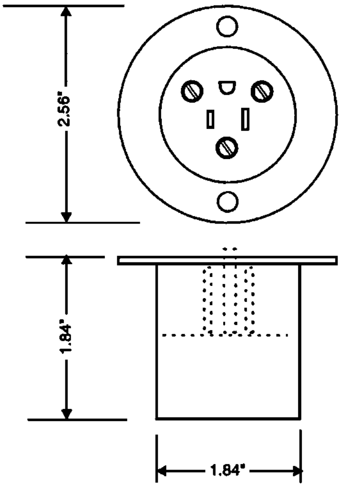
Straight-Blade Devices



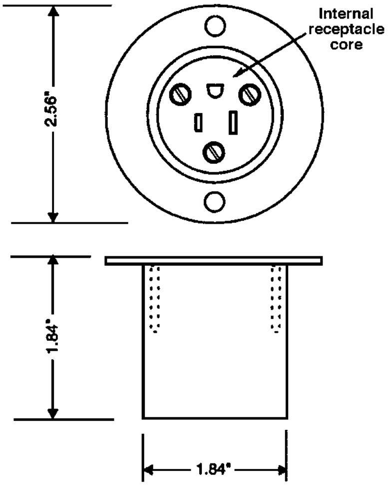
2-pole, 3-wire grounding
dead-front plug, 15 A, 125 V



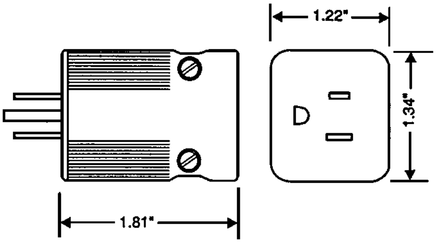
2-pole, 3-wire grounding, dead-
front, hospital-grade plug, 15 A, 125 V



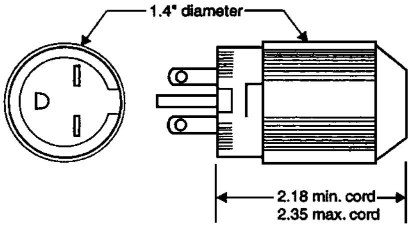
2-pole, 3-wire grounding
flanged inlet, 15 A, 125 V



2-pole, 3-wire grounding
flanged outlet, 15 A, 125 V



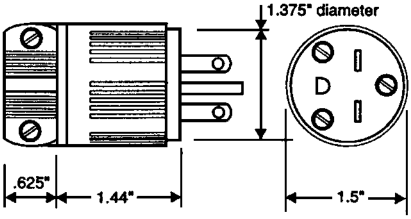
2-pole, 3-wire grounding
dead-front plug, 15 A, 250 V



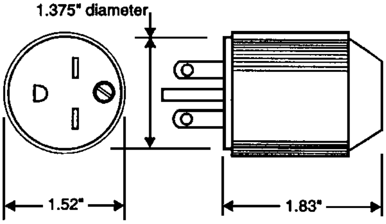
2-pole, 3-wire grounding
dead plug, 15 A, 250 V

Figure 6-21 (*Continued*)

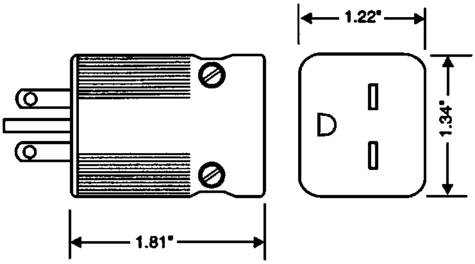
Straight-Blade Devices



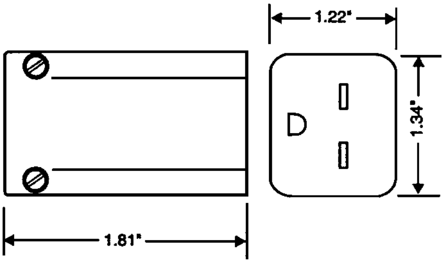
2-pole, 3-wire grounding
dead-front plug, 15 A, 250 V



2-pole, 3-wire grounding
dead-front plug, 15 A, 250 V

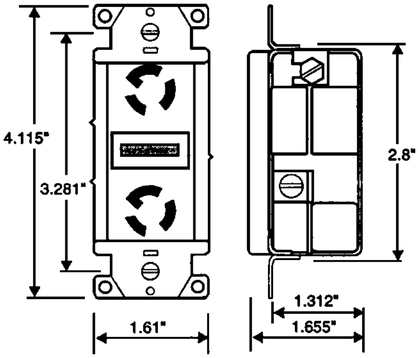


2-pole, 3-wire grounding
dead-front plug, 15 A, 250 V

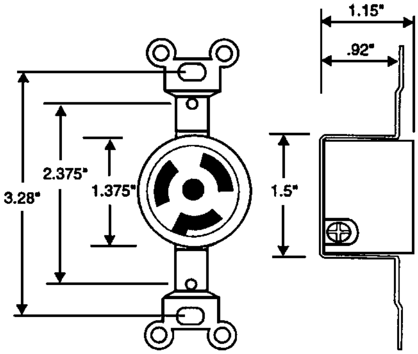


2-pole, 3-wire grounding
dead-front plug, 15 A, 250 V

Locking Devices



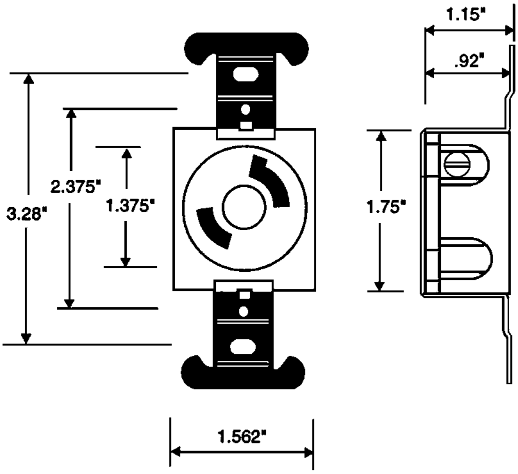
2-pole, 3-wire grounding duplex
surge suppressor, 15 A, 125 V



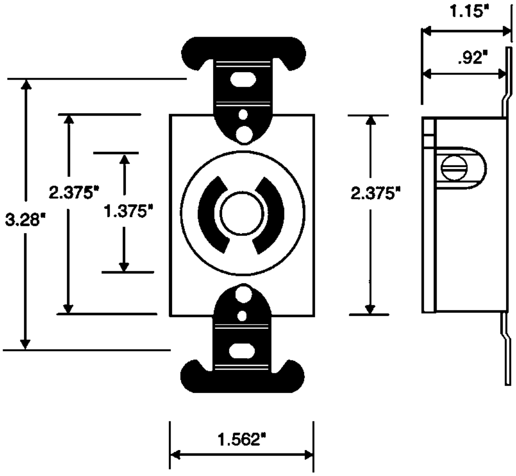
2-pole, 3-wire grounding single
receptacle, 15 A, 250 V

Figure 6-21 (*Continued*)

Locking Devices



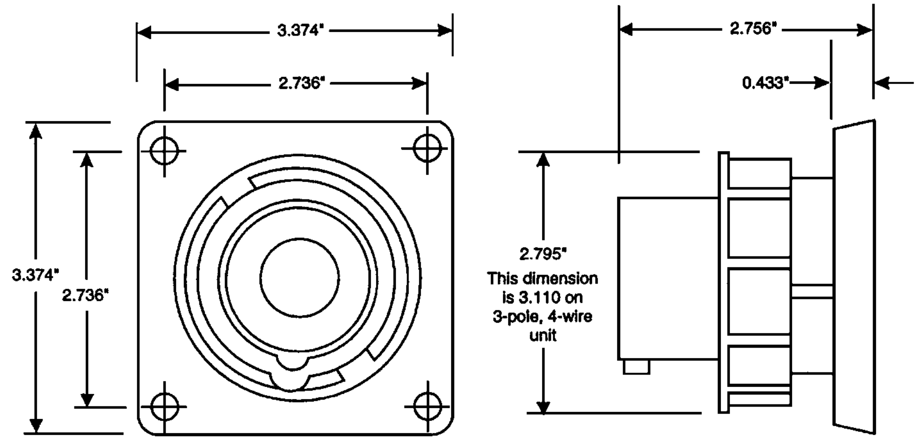
2-pole, 2-wire single receptacle, 15 A, 125 V



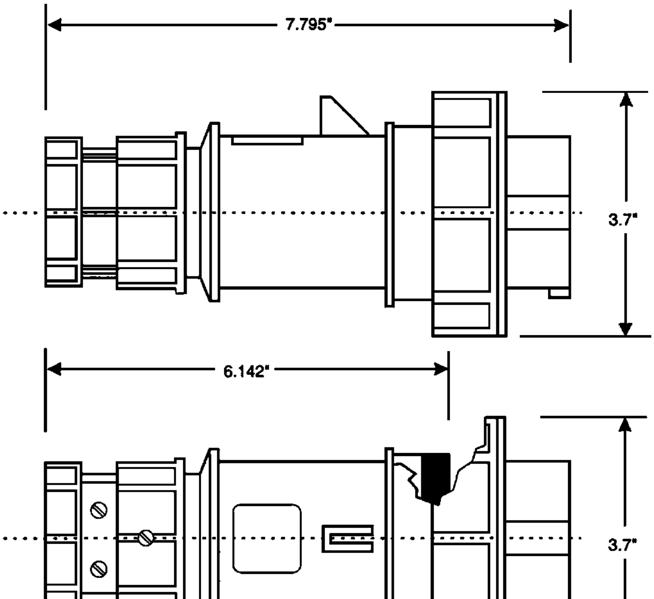
2-pole, 2-wire single receptacle, 15 A, 250 V

Figure 6-21 (*Continued*)

Pin-and-Sleeve Devices



Pin-and-sleeve watertight 20-A, 2-pole, 3-wire and 3-pole, 4-wire inlets have many outline dimensions in common



Pin-and-sleeve watertight 20-A, 2-pole, 3-wire and 3-pole, 4-wire plugs have the same outline dimensions

Figure 6-21 (*Continued*)

- *Pulling grips* are reusable tools that provide a secure grip on bare conductors, insulated wires, cable, and wire or synthetic rope for pulling them through conduit, ducts, or trays to position them between specified termination points. They are woven from galvanized steel wire.

Glossary of Wiring Device Terms

GENERAL TERMS

Corrosion-resistant: Electrical devices made from corrosion-resistant metals or metals that will corrode if left bare but when plated with corrosion-resistant metals will withstand corrosive environments. These devices must pass the ASTM B117-13 (500-hr) Salt Spray (Fog) Test.

Explosion-proof: Electrical devices such as switches or relays whose cases or housings are sealed to confine any internal electrical arcing within that housing. They can also be semiconductor devices that switch power without producing electric arcs. These devices must meet the NFPA-70 requirements for use in situations defined by the NEC as environments presenting fire or explosion hazards.

Hospital-grade: A specification grade for premium-quality electrical devices that meet the “hospital-grade” requirements of Underwriters’ Laboratories Standard UL 498 for performance, durability, and the enhancement of patient safety in hospitals and health-care facilities. They must pass more rigorous tests than industrial or consumer devices.

Plug: An electrical device with male contacts that terminate a line cord and plug into mating slots and holes of an outlet or receptacle.

Receptacle: An electrical device with female contacts usually installed on equipment housings or walls to complete an electrical connection when a plug is inserted.

Switch: An electrical device for making, breaking, or changing the electrical connections in a circuit.

Wallplate (or wall plate): A thin metal or plastic cover plate for enclosing and protecting a permanently wired or empty electrical box. Wallplates are available in a wide variety of sizes with different cutouts to admit actuators or outlets.

Weatherproof: An electrical device constructed of materials with the requisite properties that permit the device to function as designed despite prolonged exposure to adverse weather.

PLUG FEATURES

Angle: A plug made so that an attached line cord exits at 90° to the face of the receptacle or outlet.

Three-prong: A plug with two straight blades and a grounding prong.

RECEPTACLE FEATURES

AL/CU: A code marked on 30-, 50-, or 60-A receptacles indicating that they once could be used with either aluminum (AL) or copper (CU) circuit conductors. NEC 2002 states that receptacles with these marks may no longer be used with aluminum wire.

CO/ALR: A code marked on 15- or 20-A receptacles indicating that they are the *only* ones approved by NEC 2002 for use with solid aluminum wiring.

Duplex: A receptacle containing two outlets in the same housing, each capable of accepting a separate plug.

Four-in-one or "quad": A receptacle in a common housing with four outlets that can accept up to four separate plugs.

GFCI (ground-fault circuit interrupter): A receptacle containing a circuit that rapidly detects potentially fatal leakage currents to ground on the load side of the device. It then interrupts power to the load side of that device to prevent electrical shock. These receptacles must conform to UL Standard 943, Class A requirements, and must be installed in the locations required by the NEC.

Isolated-ground: A receptacle that minimizes or eliminates feedback of electrical noise from adjacent circuits to devices connected to it. Its grounding terminal is connected to a separate ground wire that is electrically isolated from its mounting strap and from the building grounding system until it reaches an approved earth grounding electrode. It is identified by an orange color or an orange triangle imprinted on its face.

Lighted (illuminated): A receptacle with a face that is illuminated by an internal lamp or LED when an energized electrical circuit is plugged into it.

Safety (tamper-proof): A receptacle with mechanical constraints that limit access to its contacts for the safety of children or handicapped adults.

Single: A receptacle that can accept only one plug.

Surge-protected: A receptacle that includes metal-oxide varistors (MOVs) between line and neutral, neutral and ground, and line and ground to protect connected equipment from overvoltages.

PLUG AND RECEPTACLE CONNECTORS

Locking: A plug with curved blades that locks in a mating receptacle when inserted and turned clockwise, but can be removed only after being turned counterclockwise. Locking plugs are used to power heavy-duty portable industrial electrical equipment.

Pin-and-sleeve: A heavy-duty, industrial-grade connector system with round pin- or sleeve-type contacts for connecting high-voltage power to machines and equipment.

Straight-blade, nonlocking: A plug with two straight blades and a prong or three straight blades that mates with a compatible receptacle. The plug can be inserted easily and then removed easily by reversing the insertion motion.

SWITCH FEATURES

AC/DC: A switch marked to show that it is capable of switching either AC or DC.

AC only: A switch marked to show that it should be used *only* for switching AC.

Dimmer, fan control: A switch-and-dimmer combination for controlling ceiling fan speed. Similar in appearance to an incandescent lamp dimmer, it can have similar actuators.

Dimmer, fluorescent: A switch-and-dimmer combination for use with specific ballasts for dimming standard fluorescent lamps. Similar in appearance to an incandescent lamp dimmer, it can have similar actuators.

Dimmer, incandescent: A switch-and-dimmer combination containing a triac for controlling incandescent lamp illumination level by modifying or “chopping” the input AC to reduce current and power to the load. It can have any of various actuators such as a knob, toggle, or slide lever. It should *not* be used to control fluorescent lamps or fan speed.

Double-pole, double-throw (DPDT): A switch that makes or breaks the connection between two conductors to two separate circuits simultaneously.

Double-pole, single-throw (DPST): A switch that makes or breaks the connection of two conductors in a single branch circuit.

Feed-through (or feed-thru): An in-line switch that can be inserted at any place along the length of a flexible line cord or cable to control a load.

Four-way: A switch installed between pairs of three-way switches to control one electrical load from three or more locations. It has no ON/OFF marking.

Horsepower-rated: A switch such as a *manual motor controller* that is marked with a maximum horsepower rating.

Lighted handle: A switch with a lamp or LED light source in its actuator (push-button, toggle, or rocker) that is illuminated when the switch is connected to an energized circuit and the actuator is in the OFF position.

Low-voltage switch: A switch for controlling circuits carrying 50 V AC or less.

Manual motor controller: A switch for controlling small integral horsepower motors that do not have overload protection.

Momentary contact: A switch that makes the circuit only as long as it is depressed in the ON position. When released a spring breaks the contact and returns the switch to the OFF position.

Pilot light: A switch with an incandescent or LED light source in its actuator (pushbutton, toggle, or rocker) that is illuminated when the switch is connected to an energized circuit and the actuator is in the ON position.

Pushbutton: A switch that makes or breaks a circuit when its button is depressed.

Rocker: A switch with a pivoting rocker actuator that makes or breaks the circuit when one side or the other is depressed. Its action is similar to that of a *toggle switch.*

Rotary: A switch with a rotary actuating mechanism that conventionally closes (makes) the circuit when the handle or knob is turned clockwise and breaks it when it is either turned another step clockwise or is reversed counterclockwise.

Single-pole, double-throw (SPDT): A switch that makes or breaks the circuit between a single conductor and a pair of conductors; It is also called a *three-way switch.*

Single-pole, single-throw (SPST): A simple ON/OFF switch that makes or breaks the circuit between two conductors; also called a *single-pole switch.*

Slide: A simple ON/OFF switch that makes or breaks the circuit between two single conductors by sliding its actuator to its alternate position.

Three-way: A switch that, when paired with another three-way switch, can control one electrical load from two locations. It has no ON/OFF marking.

Time delay: A switch capable of turning a load off at the end of a set time period.

Timer: A switch that includes a timer which can be set to turn an electrical load off at preset times.

Toggle: A switch with an actuating lever that makes or breaks the circuit when its actuator is snapped to up or down. Its action is similar to that of a *rocker switch.*

7

BRANCH CIRCUIT DESIGN AND DEVICE WIRING

CONTENTS AT A GLANCE

Overview

NEC Branch Circuit Requirements

Wall-Mounted Wiring Device Diagrams

Wall-Mounted Switch Wiring Diagrams

Wall-Mounted Receptacle Wiring Diagrams

Making Wiring Device Connections

Outdoor Wiring Protection

Driptight and Watertight Enclosures

Conduit for Outdoor Use

Outdoor GFCI Protection

120-V Outdoor Extensions

Low-Voltage Outdoor Wiring

Overview

This chapter focuses on the wiring and devices used in residential and office branch circuits. It starts by reviewing the *National Electrical Code* (*NEC* 2002) branch circuit requirements and includes diagrams for circuit, switch, and receptacle wiring. In addition, it covers such subjects as the use of conduit in branch circuits, ground-fault circuit-interrupter (GFCI) protection, and the wiring of both 120-V AC and low-voltage AC outdoor circuits. The electrical devices discussed and illustrated in this chapter are standard products available in home improvement and hardware stores.

The information in this chapter is accurate to the best of the author's knowledge, but it is intended for educational and reference purposes, not as a guide for the performance of electrical work. The publisher disclaims liability for any personal injury or property damage resulting from the use of or reliance on this text or diagrams for any purpose other than educational. If used for another purpose, the reader should either rely on his or her own independent judgment or seek the advice of a licensed professional electrician.

NEC Branch Circuit Requirements

The National Electrical Code (NEC 2002) provides guidance for electrical contractors and electricians, but it is really intended for use by governmental agencies that have legal jurisdiction over electrical installations and authorized electrical and insurance inspectors. The many mandatory chapters include Chapter 2, "Wiring and Protection," Chapter 3, "Wiring Methods and Materials," and Chapter 4, "Equipment for General Use." These are supplemented by Chapter 5, "Special Occupancies," Chapter 6, "Special Equipment," and Chapter 7, "Special Conditions."

NEC 2002 distinguishes between installations and equipment operating at under 600 V and those operating at over 600 V AC. This chapter covers only installations and equipment operating at under 600 V AC.

It is important to remember that *the code is not inflexible*—specific requirements can be waived when necessary where there is assurance that equivalent objectives can be achieved without compromising safety. Local electrical and building codes as well as local power utilities may define local requirements more definitively than alternatives approved by the NEC that they, based on experience, consider to be too general. However, under no circumstances will they relax any of the NEC provisions. This chapter highlights important information from the first four chapters of NEC 2002, but this coverage is intended as a guide to rather than a substitute for the NEC text. It is limited to the general intent of the mandatory requirements and does not discuss the many exceptions. The reader is strongly advised to read carefully the NEC source articles and become aware of those exceptions.

NEC 2002, Article 210, "Branch Circuits," in Chapter 2, "Wiring and Protection," covers branch circuits except for those that supply only motor loads. The ratings for branch circuits are 15, 20, 30, 40, and 50 A.

- Permanent ground-fault circuit-interrupter (GFCI) protection is to be installed on all 125-V, single-phase, 15- and 20-A receptacles in bathrooms, garages, crawl spaces, and unfinished basements, and at utility sinks and outdoor locations.
- The minimum number of branch circuits in a residence is to be determined from the total computed load and the size or rating of the circuits used.

- The load is to be evenly proportioned among multioutlet branch circuits within the panelboard (main service panel or loadcenter).
- At least two 20-A branch circuits are to be provided for small appliances in kitchens, laundry areas, and bathrooms.
- Ampacity and size requirements for all branch circuit conductors are to be based on the noncontinuous load plus 125 percent of the continuous load. Ampacity ratings of conductors are covered in Article 310.15, Chapter 3, "Wiring Methods and Materials."
- Receptacle ratings must match or exceed the branch circuit ratings.
- Copper branch-circuit conductor gauges must be 15 A, 14 gauge; 20 A, 12 gauge; 30 A, 10 gauge; 40 A, 8 gauge; and 50 A, 6 gauge.
- Receptacle requirements are in addition to any receptacles that are part of a lighting fixture or appliance. Receptacles installed in kitchens, family rooms, dining rooms, bedrooms, etc., are to be spaced so that no point along the floor line in any unbroken space is more than 6 ft from a receptacle.
- *Kitchen receptacles:* Countertops must have at least two small-appliance branch circuits. One is to be on any wall counter space more than 12 in. wide, and none is to be more than 24 in. from any point along the wall. In general, they are to be less than 20 in. above the countertop. Island and peninsula countertop spaces (without adjacent walls) are to have at least one receptacle in each space measuring 12 in. × 24 in. or more. They can be less than 12 in. below the countertop.
- *Bathroom wall receptacles:* At least one is to be installed on the wall adjacent to and within 3 ft of the edge of each basin.
- *Outdoor receptacles:* At least one is to be installed above grade not more than 6.5 ft at the front and back of the residence.
- *Laundry area receptacles:* At least one is to be installed.
- *Basement and garage receptacles:* At least one is to be installed in each basement and garage (attached or detached).
- *Hallway receptacles:* At least one is to be installed in hallways 10 ft long or more.
- *Lighting switch-controlled outlets:* At least one is to be installed in all habitable rooms, bathrooms, hallways, stairways, garages, and outside of ground-level entrances. In general, they should be on each floor and landing level of stairways.

Wall-Mounted Wiring Device Diagrams

There are many ways to install switches, receptacles, luminaires, and appliances along an electrical branch circuit. Therefore, the wiring configurations inside an electrical box can vary widely, even when devices in that box are identical. Recent changes introduced in NEC 2002 are intended to make the requirements for branch circuits more uniform than they have been in the past because of safety considerations, but there are still many valid alternatives for their installation.

There are 13 diagrams in this chapter (Figs. 7-2 to 7-9 and 7-11 to 7-15) showing common practice for wiring switches and receptacles in functional circuits that illustrate the basic principles underlying modern electrical wiring practice. The diagrams assume that the branch circuit power source is rated for 15 A, at 120 V, 60 Hz AC, and all conductors are insulated or bare copper No. 14 AWG wire. Both the switches and receptacles illustrated are rated for 15 A, 125 V AC. However, the same diagrams would apply for 20-A branch circuits with all conductors No. 12 AWG wire and the receptacles and switches rated for 20 A, 125 V AC.

In these diagrams the "hot" or live powered wires with black insulation are shown as heavy black lines, and the neutral wires with white insulation are shown as parallel black lines. Where a white wire serves as a "hot" wire instead of a neutral, both ends of the wire insulation are marked with black stripes. The marking can be done with a suitable permanent black ink marker or by banding with black electrician's tape. All of the grounding wires are shown as single black lines.

Each of the fixture and switch boxes illustrated is considered to be metal with grounding screws, as required by the NEC. The screws permit bare copper grounding wires are then to be fastened securely to the electrically conductive boxes, as shown.

If the switch boxes are nonmetallic and the receptacle or switch terminates the circuit, the grounding wire from the single cable entering the box must be attached to the grounding screw on the device; if two or more cables enter the box, a grounding jumper made from a short length of wire the same size as the other grounding wires can be attached to the grounding screw of the device (pigtailed) and the jumper and other grounding wires are then twisted together and fastened with a wire nut.

In diagrams that include three-way switches, two *traveler* wires run between pairs of traveler screw terminals on the switches. By convention, traveler wires have red insulation and are the third wires in three-wire cable. In the circuit diagrams presented here, red traveler wires are shown as thick shaded lines.

The screws on the right sides of switches and receptacles represent brass screws for connecting "hot" wires, and the screws on the left sides represent silver-colored screws for neutral wires. In diagrams showing a receptacle, grounding jumpers connect the receptacle grounding screw and all grounding wires to the metal box grounding screw, and the jumpers and grounding wires are twisted together and secured by a wire nut.

Wall-Mounted Switch Wiring Diagrams

WALL SWITCHES

The single-pole, wall-mounted toggle switch, as shown in Fig. 7-1*a,* is the most commonly used switch in homes and offices. Although it has been described in Chap. 6, some information is repeated here for convenience in interpreting the wiring diagrams. These switches have the two brass screw terminals on the right side of the switch for the connection of black "hot" wires. It makes no difference which "hot" wire (input or output) goes to which brass screw, but most electricians follow a consistent pattern when wiring them into branch circuits so that input wires can be distinguished from

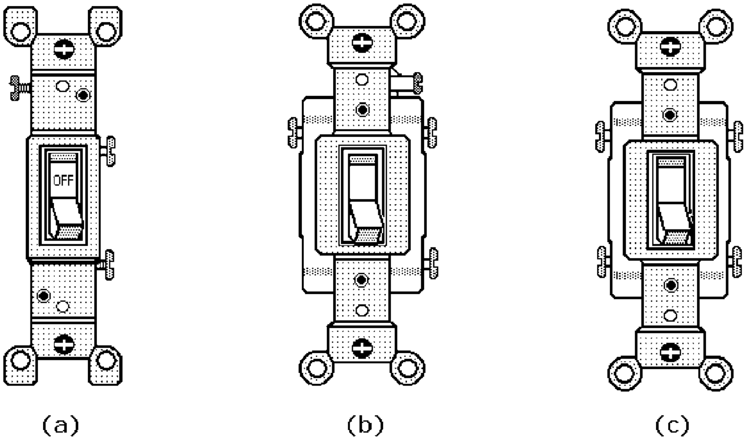


Figure 7-1 Wall switches can be identified by the number and color of their screw terminals: (*a*) A single-pole switch has three screw terminals (one grounding); (*b*) a three-way switch has three screw terminals; and (*c*) a four-way switch has four screw terminals.

output wires. It was explained previously that single-pole toggle switches are the only wall-mounted switches with ON and OFF legends marked on their toggles. If the switch is mounted correctly, ON is visible when the load is powered. Single-pole toggle switches for use in nonmetallic switch boxes have a grounding screw, typically on the left side of the switch.

Neither the three-way switch shown in Fig. 7-1*b* nor the four-way switch shown in Fig. 7-1*c* has the ON/OFF toggle legends because they would have no meaning; the positions of the toggles on the other switches in the three- and four-way circuits determine the ON and OFF positions of any one switch in the circuit.

Each three-way switch has three screw terminals (one painted to identify it as "common") and an internal movable blade. In wiring three-way circuits, as shown later in Figs. 7-7, 7-8, and 7-9, a common traveler wire is connected between one of the brass terminal screws on each switch. A lamp in a three-way circuit is OFF when one switch toggle is *up* and the other one is *down.* By flipping one toggle of the pair so that *both are either up or down,* the circuit is completed and the lamp will turn on.

LAMP CONTROLLED BY A SWITCH

Figure 7-2 illustrates a lamp controlled by a single-pole switch. The black input "hot" wire goes to the upper brass screw, power passes through the switch, and the black output "hot" wire goes from the lower brass screw to the lampholder. The neutral wires bypass the switch and go directly to the lampholder. With the switch between the "hot" wires, the lamp circuit can be made or broken. A switch in the neutral wire could make or break the circuit, but it would not disconnect the lamp from the power source. This

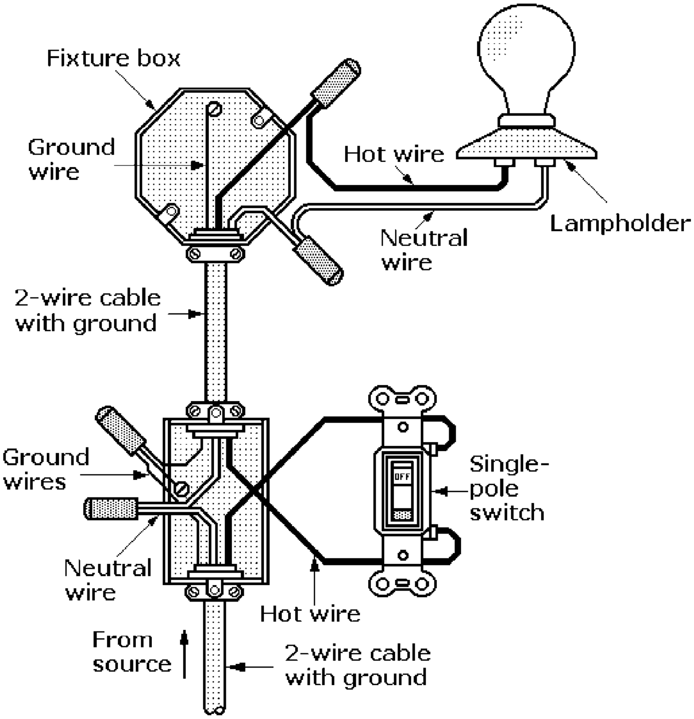


Figure 7-2 Lamp controlled by a switch: The neutral wire bypasses the switch and goes directly to the lampholder.

scheme could expose a person to electrical shock, or a short circuit could occur at the lamp with the switch off.

LAMP CONTROLLED BY A SWITCH LOOP

Figure 7-3 illustrates a *switch loop.* The NEC limits the number of wires allowed in a switch box. To avoid this limit, circuit wires can be run to the lampholder first with a switch loop going to the switch, as shown. The black “hot” input wire and its black-marked extension go to the lower brass screw on the switch. Power passes through the switch and leaves from the upper brass screw on a black wire that goes to the lampholder. The white neutral wire bypasses the switch and goes directly to the lampholder.

LAMPS AT THE ENDS OF CIRCUITS

Figure 7-4*a* illustrates a circuit ending at a lampholder controlled by a single-pole pull-chain switch. The black “hot” and white neutral wires go directly to the lampholder. This wiring scheme is frequently used in unfinished attics and basements.

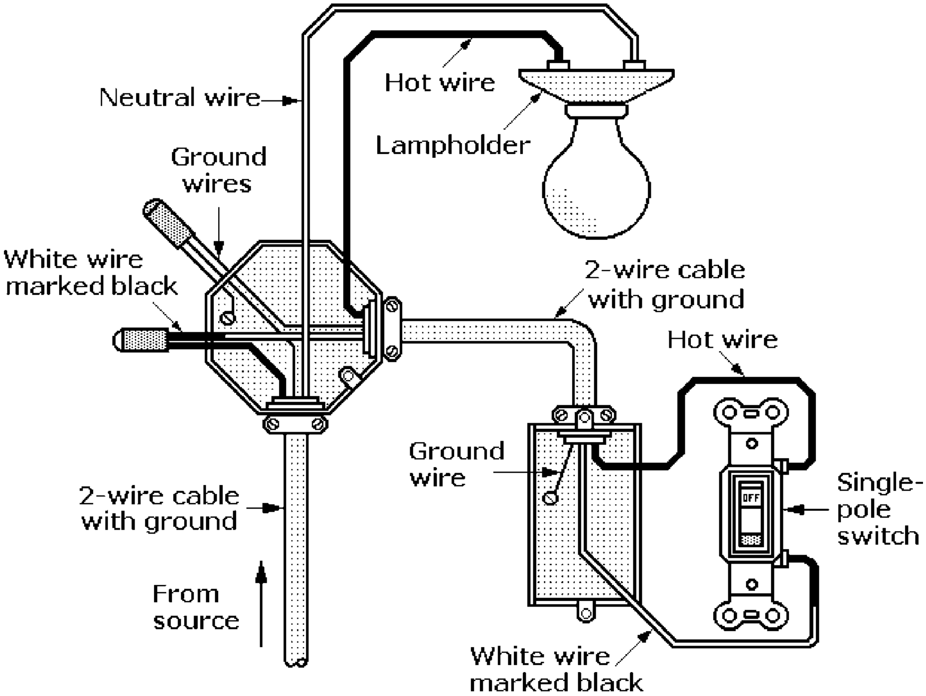


Figure 7-3 **Switch loop: Circuit wires go to a lampholder first, with a loop going to the switch, minimizing the wires in the box.**

Figure 7-4*b* illustrates another example of circuit ending at a lampholder, but this circuit is controlled by a single-pole switch. The "hot" wire connects the black-marked white extension to the lower brass screw of the switch. Power passes through the switch and leaves from the upper brass screw on a black wire to the lampholder. Again, the white neutral wire bypasses the switch and goes directly to the lampholder. This wiring scheme is widely used in finished rooms.

SWITCH IN THE MIDDLE OF A CIRCUIT

Figure 7-5 illustrates a single-pole switch in a middle of a circuit controlling a lamp at the end. The "hot" black wire is attached to the lower brass screw. The power passes through the switch and goes from the upper brass screw on a black wire to the lampholder. Again, the white neutral wire bypasses the switch and goes directly to the lampholder.

LAMP IN THE MIDDLE OF A CIRCUIT

Figure 7-6 illustrates a single-pole switch at the end of a circuit controlling a lamp in the middle of the circuit. This circuit is wired as in the switch loop of Fig. 7-3. The

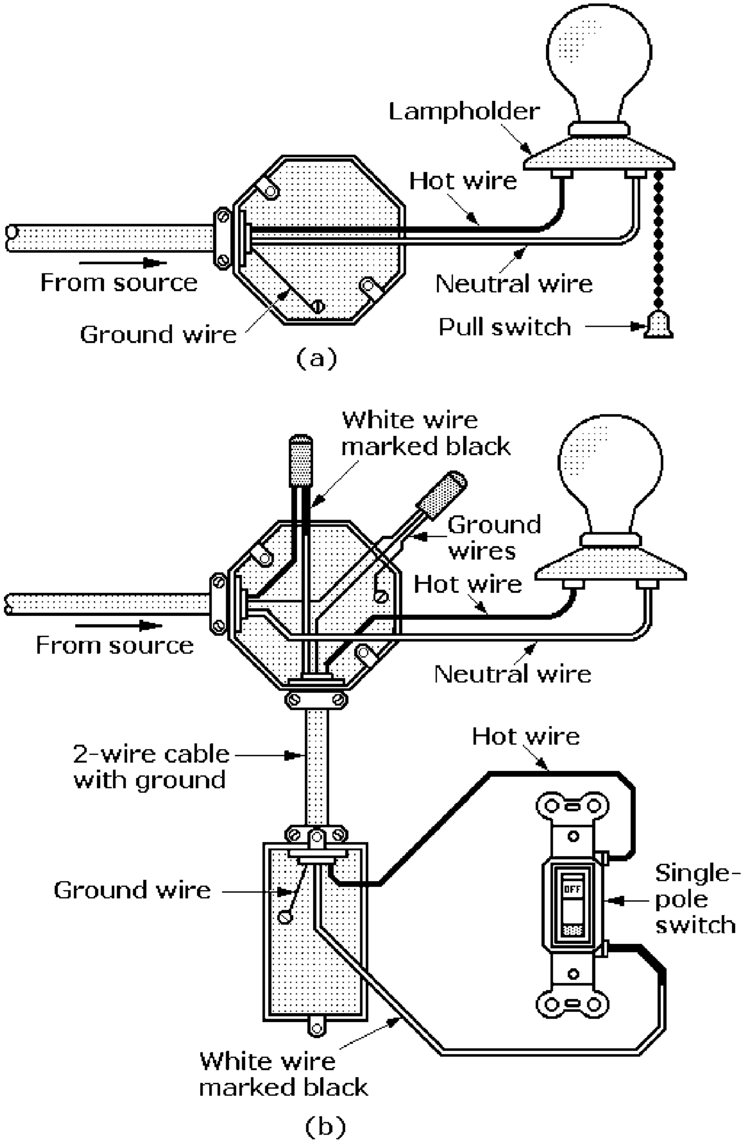


Figure 7-4 **Lamps at the ends of circuits: (*a*) A circuit ends at a lampholder with a pull-chain switch; (*b*) a circuit with a lampholder at the end is controlled by a single-pole switch.**

black “hot” input wire and its black-marked extension go to the lower brass screw on the switch. Power passes through the switch to the upper brass screw and a black output wire that goes to the lampholder. The white neutral wire bypasses the switch and goes directly to the lampholder. In this circuit, two or more cables can enter the octagonal fixture box and the “hot” and neutral wires go to the next outlet.

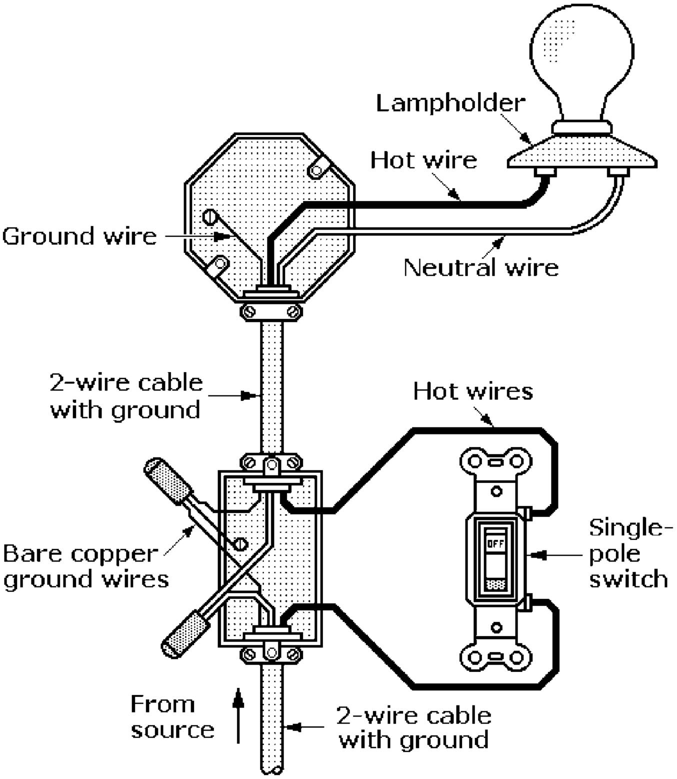


Figure 7-5 Switch in the middle of the circuit.

LAMP IN THE MIDDLE OF A CIRCUIT CONTROLLED BY THREE-WAY SWITCHES

Figure 7-7 illustrates how a pair of three-way switches can control a lamp in the middle of the circuit from two different locations. This circuit allows the lamp to be switched on from either the top or bottom of a stairway, or from either end of a hallway. It can be switched off by the second switch. Each three-way switch has three screw terminals, one painted to identify it as "common" and the other two interchangeable as traveler or return terminals. The three-way switch also contains a movable blade.

The "hot" black wire goes to the common terminal on the lower three-way switch. After power passes through the switch, it leaves by the upper common terminal through a black-marked white wire to the upper common terminal of the upper three-way switch. Again, power passes through that switch to the common terminal to a third black "hot" wire that takes it to the lampholder. The white neutral wire bypasses the lower switch and goes directly to the lampholder. The common red traveler wire connects the two screws not functioning as "common." As stated earlier, a lamp in a three-way circuit will be on only when both switch toggles are in the same positions, either *up* or *down.*

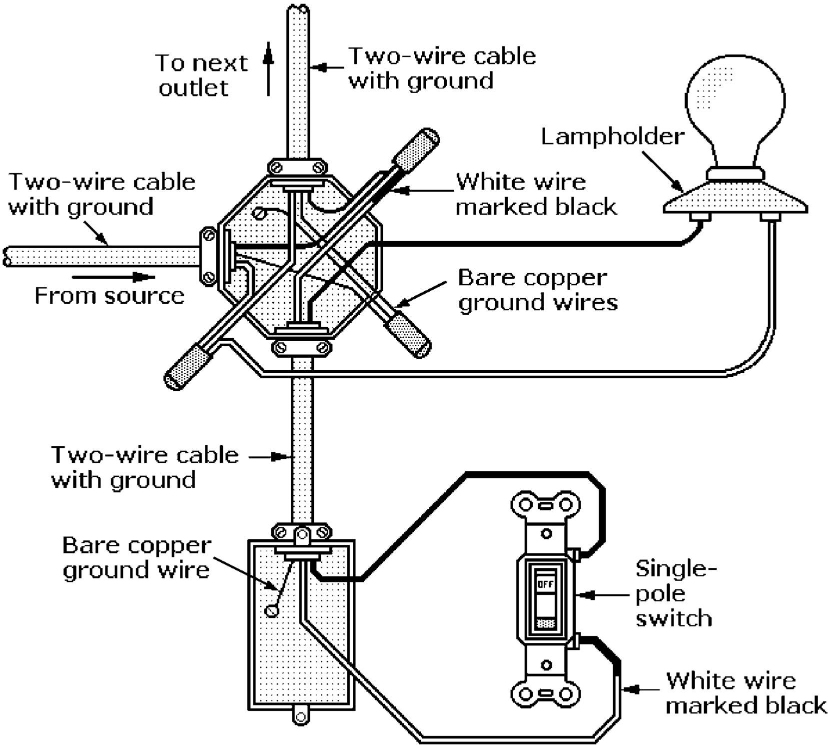


Figure 7-6 Lampholder in the middle of the circuit.

LAMPS AT THE ENDS OF CIRCUITS CONTROLLED BY THREE-WAY SWITCHES

Figure 7-8 illustrates one way a pair of three-way switches can control a lamp at the end of the circuit from two different locations. The black "hot" wire spliced to a black-marked white "hot" wire in the octagonal fixture is attached to the lower "common" screw on the upper three-way switch. The power passes through the switch to a black-marked white "hot" wire that goes to the corresponding terminal on the lower three-way switch. After power passes through the switch, it leaves by the lower common terminal on a black "hot" wire to the lampholder. Again, the neutral wire bypasses both switches, and the red traveler wire connects the third terminals on both three-way switches.

Figure 7-9 illustrates a second scheme for controlling a lamp at the end of the circuit from two locations. The black "hot" wire from the source goes to the common terminal of the lower three-way switch. After power passes through the switch, it goes by a second black "hot" wire to the upper common terminal on the upper three-way switch. After passing through the second switch, it goes by a third black "hot" wire from the lower common terminal to the lampholder. The white neutral wire bypasses both switches and goes directly to the lampholder. As in the previous example, a red traveler wire connects the third terminals on both three-way switches.

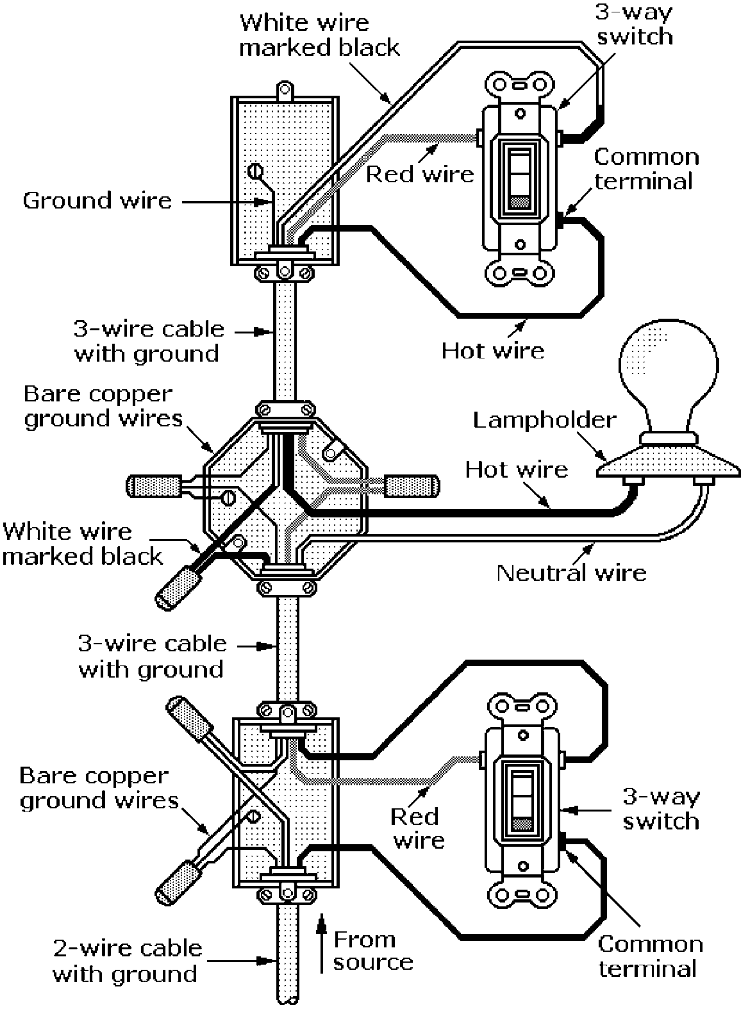


Figure 7-7 Lampholder in the middle of the circuit is controlled by a pair of three-way switches.

Wall-Mounted Receptacle Wiring Diagrams

RECEPTACLES

The most commonly specified duplex receptacles for homes and offices are straight-bladed devices rated for 15 and 20 A, 125 V AC. The NEC 2002 requirement that all 15- and 20-A, 125-V receptacles installed in new construction and updated systems have a slot for a grounding prong was stated in Chap. 6. The three-prong grounded

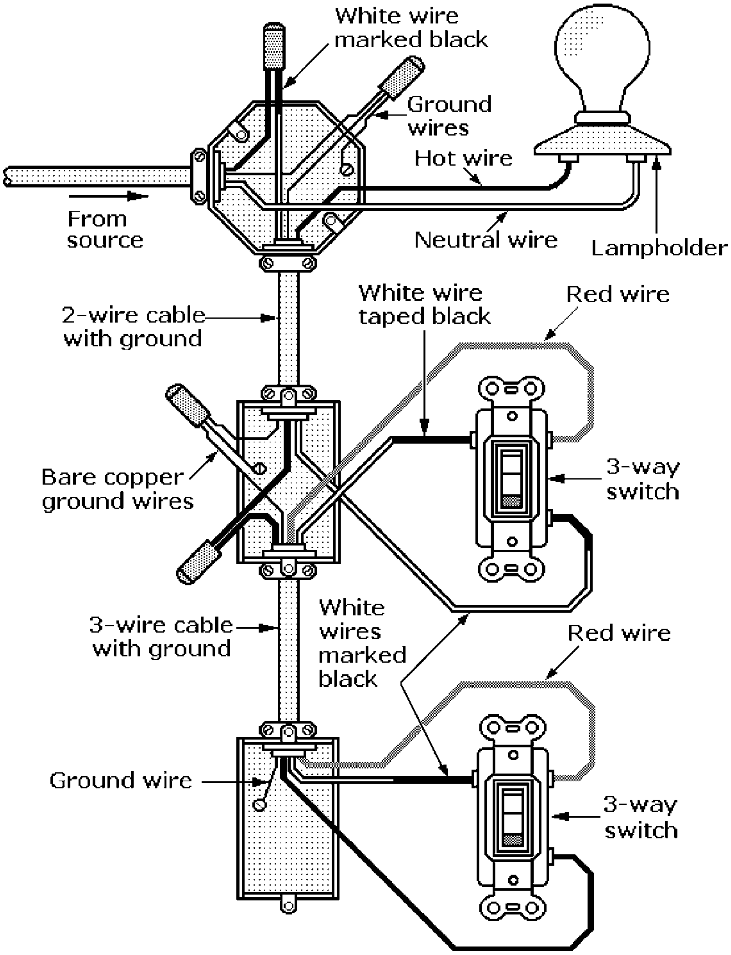


Figure 7-8 **Lampholder at the end of the circuit is wired between a pair of three-way switches.**

plugs that terminate appliance linecords have wide neutral and narrow "hot" straight blades as well as a U-shaped grounding prong that mates with these outlets. They can be inserted in all approved 15- and 20-A, 125-V receptacles.

A straight-blade 15-A, 125-V AC duplex receptacle is illustrated in Fig. 7-10*a,* and the receptacle slot profiles for both 15- and 20-A, 125-V receptacles are illustrated in Fig. 7-10*b.* All two-bladed and three-bladed 125-V plugs can be inserted in either of these receptacles, but the 20-A receptacle has a T-shaped neutral slot indicating its 20-A rating. However, there is an added margin of safety if higher-power-consuming 120-V appliances such as toasters or hair dryers are plugged into 20-A receptacles. The slot patterns of 15- and 20-A, 125-V GFCI receptacles are identical to those shown in Fig. 7-10*b.*

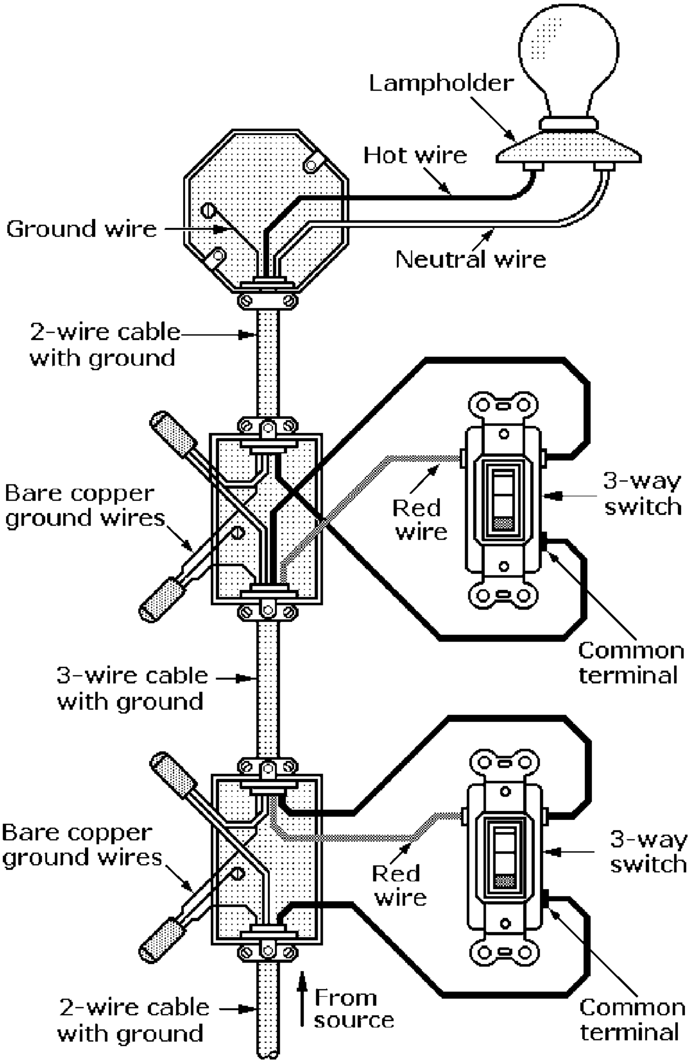


Figure 7-9 Power goes through a pair of three-way switches to a lampholder at the end of the circuit.

RECEPTACLE TERMINALS

Wires can be connected to receptacles with either side screw or clamp-type back-wired terminals. To assist the installer and avoid mistakes, receptacle screw terminals are color-coded. The brass screws on the right side of the receptacle (as shown in Fig. 7-10*a*) are "hot" terminals, the silver-colored screws on the left side are neutral terminals, and the green screw terminal shown in the lower left corner is the grounding terminal.

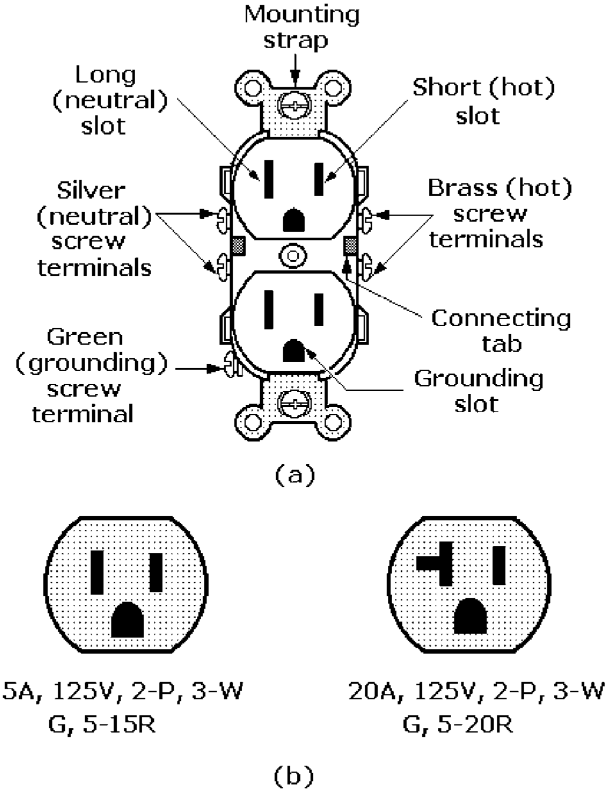


Figure 7-10 Straight-blade 125-V AC receptacles: (*a*) duplex, 15 A; (*b*) slot patterns for 15 and 20 A.

CABLES WITHIN RECEPTACLE BOXES

Receptacles can be wired in many different ways, depending on where the receptacle is located in the circuit and the application. The location of the receptacle can be determined by counting the number of cables entering the box. For example, if one cable enters the box, the receptacle is at the end of the circuit; but if two cables enter, the receptacle is in the middle of the circuit. Receptacle wiring differs if the receptacle is controlled by a switch. In Figs. 7-11 to 7-15 illustrating receptacle wiring, the bare copper ground wires are pigtailed or make direct connections with the grounding screws in all of the metal device or octagonal fixture boxes in the circuit, as was described previously in the discussion of switch circuits. If the boxes are nonmetallic, the same rules for connecting ground wires in switch circuits apply.

RECEPTACLES AT THE ENDS OF CIRCUITS

Figure 7-11 illustrates a duplex receptacle wired at the end of a circuit. The single-pole switch that controls the lamp is wired between the receptacle and the lampholder, and the receptacle is wired so that both the upper and lower outlets are always “hot.” One

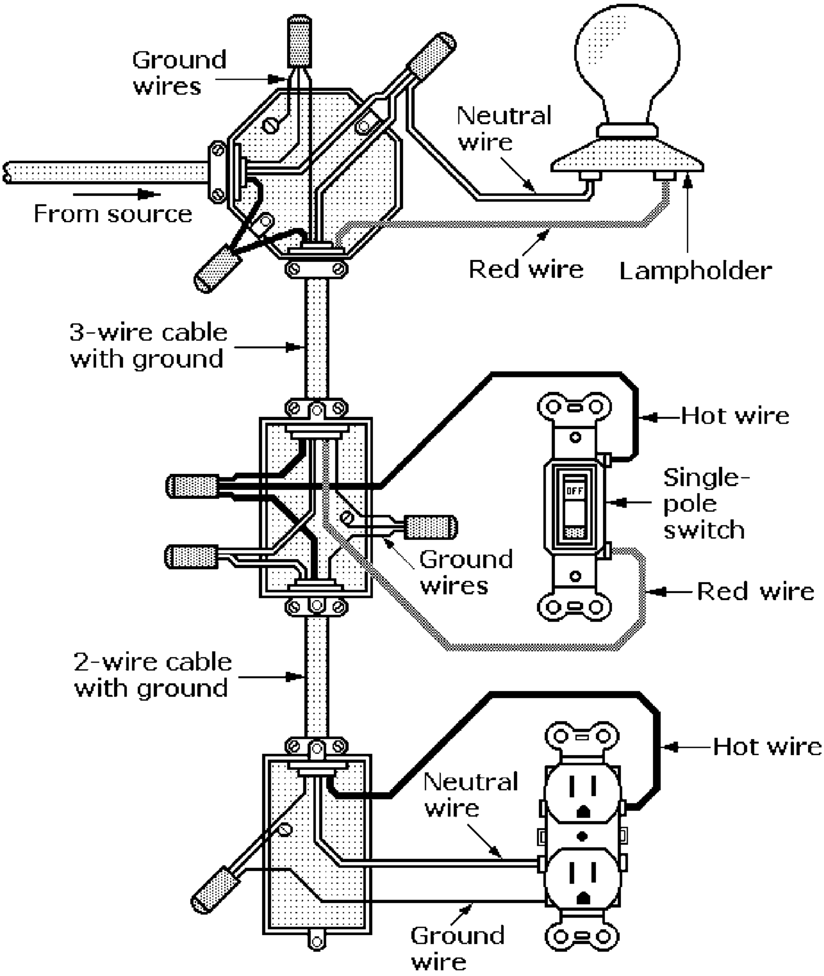


Figure 7-11 **Single-pole switch wired ahead of a duplex receptacle at the end of the circuit controls the lamp. Upper and lower outlets are always "hot."**

two-wire and one three-wire cable enter the octagonal fixture box. The black "hot" wire from the source provides power in parallel to the switch and receptacle, and a red traveler wire conducts power from the switch to the lampholder. The white neutral wire is spliced so that one part goes to the lampholder and the parallel part bypasses the switch to a screw terminal on the left side of the receptacle.

Figure 7-12 illustrates another example of a duplex receptacle wired at the end of a circuit. In this case, however, two receptacles are wired in parallel in the same circuit. Both the upper and lower outlets of each receptacle are always "hot." The black "hot" wire from the source is spliced to conduct power into the brass screw terminals on both receptacles, and the white neutral wire is spliced to provide parallel connections to the silver-colored screw terminals on both receptacles.

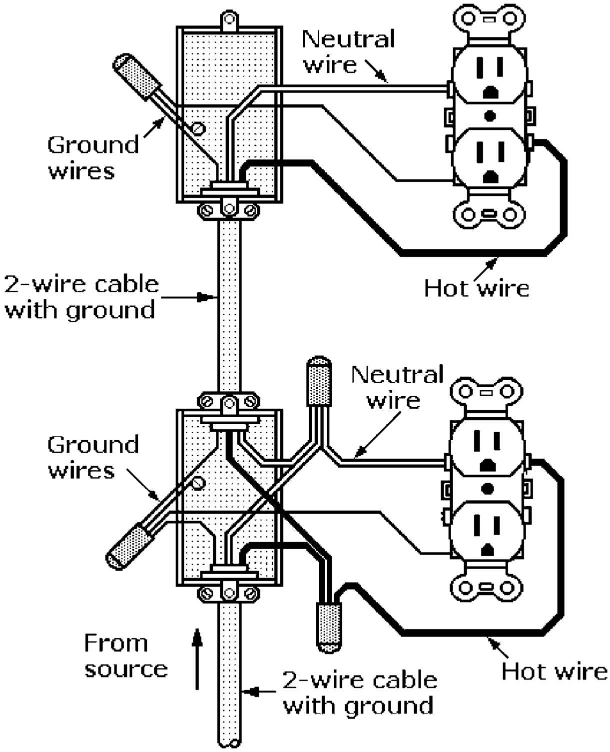


Figure 7-12 Two duplex receptacles at the end of the circuit are wired in parallel. Upper and lower outlets of each receptacles are always "hot."

SWITCH-CONTROLLED RECEPTACLE

Figure 7-13 illustrates how a single-pole switch at the end of a circuit can control a duplex receptacle between it and the power source. The black "hot" wire from the source is spliced to a black-marked white wire that bypasses the receptacle and conducts power to a brass screw terminal on the switch. After passing through the switch, power is conducted by a second black" hot" wire from the second brass screw terminal on the switch to a brass screw terminal on the receptacle. The white neutral wire goes only to the silver-colored screw terminal on the receptacle. When the switch toggle is in the ON position, both the upper and lower outlets of the receptacle are "hot," but when the switch toggle is in the OFF position, there is no power at either outlet of the receptacle.

SPLIT-CIRCUIT RECEPTACLE

Figure 7-14 illustrates a receptacle with the metal tab connecting the upper and lower outlets removed to form two independent outlets. As in Fig. 7-13, a single-pole switch is at the end of the circuit, with the duplex receptacle between it and the power source.

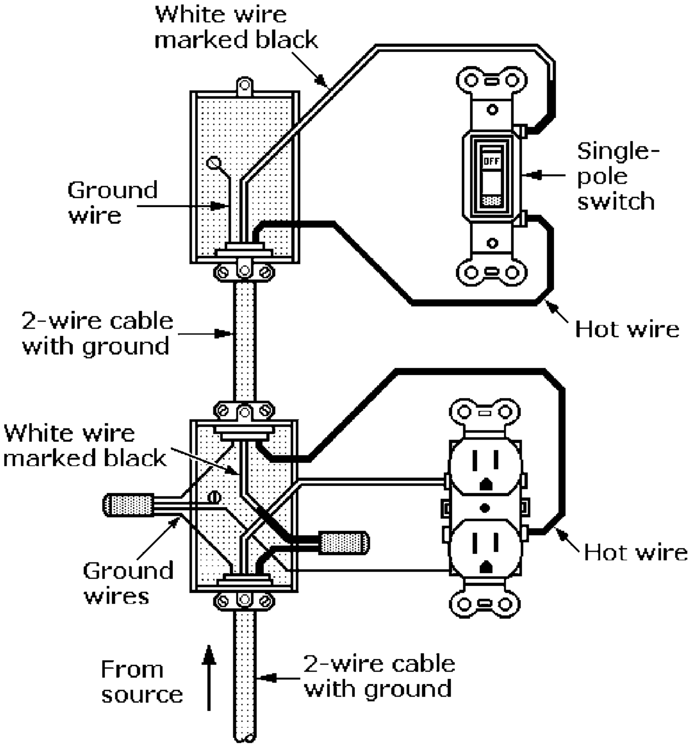


Figure 7-13 Both outlets of a duplex receptacle are controlled by a single-pole switch. Outlets are "hot" only when the switch is on.

The black "hot" wire from the source going to the lower brass screw on the receptacle, spliced to a black-marked white "hot" wire nut, furnishes power in parallel to the lower outlet of the receptacle and the upper brass screw of the switch. Power passes through the switch to the lower brass screw and a second attached black "hot" wire that goes to the upper brass screw on the upper outlet of the receptacle.

The white neutral wire going to the silver-colored screw of the upper outlet provides a return path for both independent outlets. The lower outlet of this duplex receptacle is always "hot," but the upper outlet is controlled by the switch. When the switch toggle is in the ON position, the upper outlet receives power.

GFCI RECEPTACLE

Figure 7-15 illustrates how a duplex GFCI receptacle protects two standard duplex receptacles positioned downstream of it in the same branch circuit. The black "hot" wire from the source conducts power to the lower brass screw on the GFCI receptacle. It passes through the GFCI receptacle. Power passes through the receptacle and leaves through the upper brass screw in a second black "hot" wire that goes to the lower brass screw of the standard (middle) receptacle. After passing through that receptacle, power

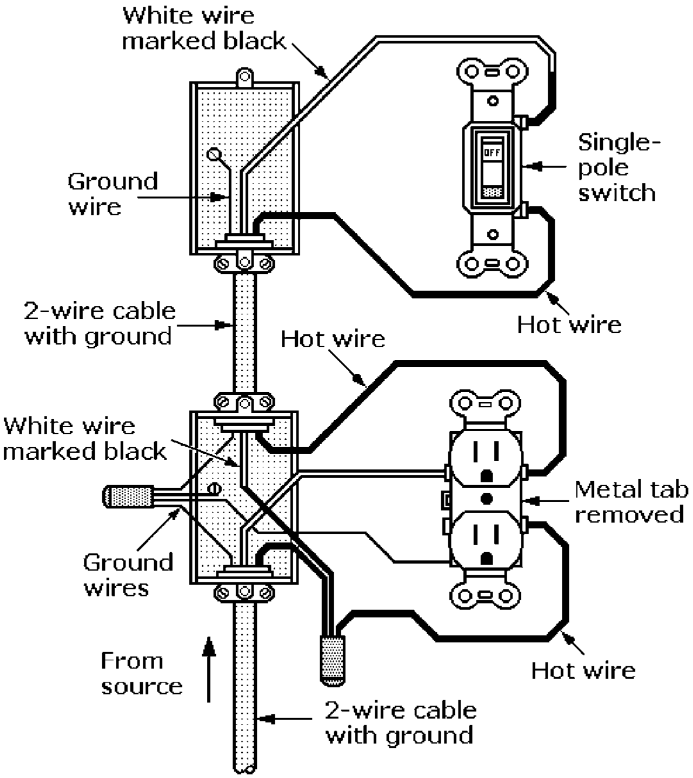


Figure 7-14 **Removal of the metal tab on a duplex receptacle permits independent operation of outlets: The lower outlet is always "hot," and the upper outlet is "hot" only when the switch is on.**

is conducted from the upper brass screw terminal to a third black "hot" wire to the lower brass screw terminal of the end (upper) receptacle. The neutral white wire goes first to the lower silver-colored screw on the left side of the GFCI receptacle and then continues from the upper silver-colored screw terminal, bypassing the middle receptacle, to the upper silver-colored screw terminal on the end receptacle, where it forms the neutral return connection.

Ground-fault protection is afforded to all electrical loads plugged into any of the six outlets on the three receptacles by the GFCI circuitry within the GFCI receptacle.

Making Wiring Device Connections

When making wire connections to switches and receptacles with screw-type terminals, only enough insulation should be stripped from the ends of the insulated wire to permit the bare wires to be wrapped three-quarters of the way around the screw. This

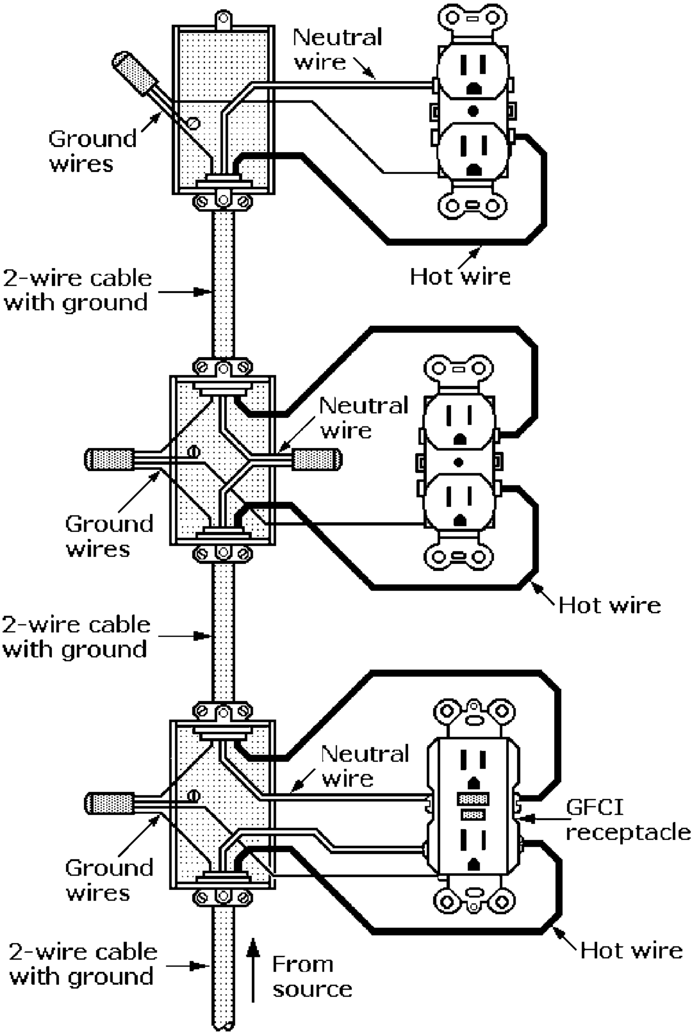


Figure 7-15 Duplex GFCI receptacle protects two downstream receptacles.

applies to all insulated wires, solid or stranded, except those being attached by the clamp-type back-wired terminals. Long-nose pliers are used to make a loop on the bare wire end to hook clockwise around the terminal screw.

When making connections to clamp-type back-wired terminals on switches and receptacles, the length of the insulation removed should be determined precisely by using the gauge molded into the backs of the devices.

In general, white or neutral wires are connected to the silver-colored screw terminals and the black or "hot" wire is connected to the brass screw terminal. The bare grounding wire is attached to the green screw on switches (if they have them) and receptacles by the loop method. Wire nuts should be used to fasten the bare ends of insulated wires with the same colors, or in the case of "hot" wires, black wires and black-banded or marked white wires functioning as "hot" wires.

After all of the wire connections have been made, they should be bundled together so they occupy a minimum amount of space and then pushed carefully into the device box, taking care not to damage the insulation on the wires. The receptacle or switch is then fastened in the device box with the strap on the device and the screws provided. Dimmer switches are installed like other switches except that some have built-in insulated wire leads rather than screw terminals.

Outdoor Wiring Protection

The wiring principles and practice that apply to 120/240-V AC indoor wiring also apply to outdoor wiring. The difference lies in the choice of approved cables, conduits, boxes, and fittings that can withstand the rigors of the outdoor environment or burial in the ground. Outdoor wiring must be protected against or be able to withstand rain, snow, ice, wide temperature excursions, and ultraviolet radiation from the sun. In certain locations wire and cable must withstand airborne dust or sand, corrosive chemical atmospheres, or salt spray.

The extent of the protection for the outside circuitry depends on such factors as accessibility for maintenance, the consequences of circuit failure or outage, and economic considerations. If the wiring is in a sheltered outdoor location such as on a wall protected by a roof overhang or a porch ceiling, the protection can be minimal. In these locations the wiring is unlikely to be exposed to direct rain. By contrast, the protection of electrical wiring and equipment related to swimming pools, garden fountains, and totally exposed year-round lighting must be more comprehensive.

The presence of moisture, salt spray, or corrosive chemical atmospheres can oxidize or rust bare-metal electrical connections or buses. This can cause equipment failure, short circuits, and even fire hazards. In the most extreme situations, electrical wiring and contacts must be completely enclosed in a sturdy sealed box, preferably gasketed against the intrusion of moisture, water, or corrosive gas.

Outdoor fixtures are manufactured in categories termed *driptight* and *watertight.* A *driptight* box or fixture need only be sealed against vertically falling water such as rain. However, its contents could be wet by sprinklers, hoses, or wind-blown rain. Louvered boxes fulfill this requirement. On the other hand, a *watertight* box or fixture must be sealed against water coming at it from all directions. The choice will depend on the intended location of the box or fixture. Outdoor utility electrical equipment such as pole- and pad-mounted transformers, circuit breakers, and voltage regulators, for example, require complete and reliable protection because of the serious consequences of their failure. Electrical equipment installed on ships, oil-drilling platforms, navigational equipment, and traffic signals is typically protected by watertight boxes because failure might result in the loss of lives or extensive property damage. Military electrical and electronic equipment used in all-weather operations is well protected by watertight boxes and cabinets against the stresses of the environment.

Electrical equipment for home and industry that is readily accessible for maintenance can be adequately protected by driptight enclosures. Enameled sheet steel, cast iron, and molded plastic boxes suitable for outdoor use are available commercially, as are suitable fittings. The cost of electrical products suitable for prolonged outdoor exposure is not significantly higher than for comparable indoor fixtures, materials, and appliances.

Driptight and Watertight Enclosures

Driptight enclosures are typically formed from heavy sheet steel that is treated with a rust preventative and a suitable paint finish capable of protecting the underlying metal against rust. These enclosures can be given additional coats of protective paint after the system is installed. The tops of driptight enclosures can be deep-drawn to eliminate exposed edges that would permit the entry of any water, and the sides might have louvers to keep out falling water but permit the circulation of air to prevent internal condensation of water vapor.

Driptight enclosures are suitable for use in sheltered locations protected by roofs or overhangs. Some have covers that can be opened from the outside, and electrical connections to them will typically be made by separate two-piece gasketed and threaded fittings not integral to the enclosure. Metal driptight enclosures with rigid transparent hinged covers are also available.

By contrast, *watertight enclosures* are designed to withstand temporary immersion in water or water streams coming from any direction. The enclosures might be cast from aluminum or bronze or be weldments of heavy-gauge galvanized steel. These boxes will typically have inside threaded holes for making connections with outside threaded conduit. They are normally designed so that they do not need to be opened from the outside. All covers are sealed with gaskets, and waterproof packing will permit exterior levers to operate internal switches without opening a cover.

Conduit for Outdoor Use

In Chap. 6, conduit is discussed in detail and references are made to the appropriate articles of the NEC. Without repeating all of that information, certain generalizations can be made about the use of conduit outdoors, but it is important to note the specifics of where its use is or is not permitted.

- *Electrical metallic tubing* (EMT) is acceptable for outdoor use but is not recommended because its thin steel or aluminum walls are subject to physical damage.
- *Intermediate metal (steel) conduit* (IMC) and *rigid metal (steel or aluminum) conduit* (RMC) are approved in “all atmospheric conditions and occupancies,” including corrosive environments and wet locations.

- *Electrical nonmetallic tubing* (ENT) is permitted in locations subject to severe corrosive gases or chemicals and encasement in poured concrete, but is not permitted for direct earth burial. No references are made to its use outdoors.
- *Rigid nonmetallic conduit* (RNC) is approved for exposed locations where it is not subject to physical damage.
- *Nonmetallic underground conduit* (NUCC) is permitted for direct burial underground and encasement or embedding in concrete, but it is not permitted in exposed locations.
- *Liquidtight flexible conduit* (LFMC) is permitted for use in exposed or concealed locations including outdoor locations and direct burial where listed and marked.

The most common nonmetallic material for extruding conduit is polyvinyl chloride (PVC) Schedule 40. While it is practically impervious to moisture and will not corrode, it requires a separate grounding wire.

As stated in Chap. 5, IMC and RMC conduit must be buried at least 18 in. below ground level in residential locations, but if it is under slabs, as specified in NEC 2002, Table 300.5, it can be as shallow as 4 in. It does not need a ground wire unless it is used to conduct power cable to a swimming pool or other in-ground bath or fountain.

Outdoor GFCI Protection

NEC 2002 requires that any new outside receptacle be protected with a ground-fault circuit-interrupter (GFCI) circuit. These are available in watertight outlet boxes suitable for powering outdoor appliances such as electric lawnmowers, power tools, lawn blowers, and hedge trimmers.

120-V AC Outdoor Extensions

A 120-V AC branch circuit can be extended outside a building following the same practice used to extend a branch circuit indoors. Indoor service terminates in an approved outdoor junction box. Underground cable must be protected by rigid conduit as it passes from the junction box to the depth underground required for running it unprotected horizontally to an outdoor fixture.

Nonmetallic (NM) cable in conduit can be used to extend the branch circuit to an approved junction box outdoors. It can be spliced within the junction box to underground feeder (UF) cable, which can then be used to make the connection to an outdoor luminaire or appliance within a watertight box.

An example of an outdoor branch wiring extension is shown in Fig. 7-16. An NM cable extension of a branch circuit in an attic is brought down within EMT conduit through a watertight connection to a driptight junction box. This box can be used here because it is sheltered by the overhang of a roof. A splice from NM to UF direct-burial cable is made within the driptight junction box.

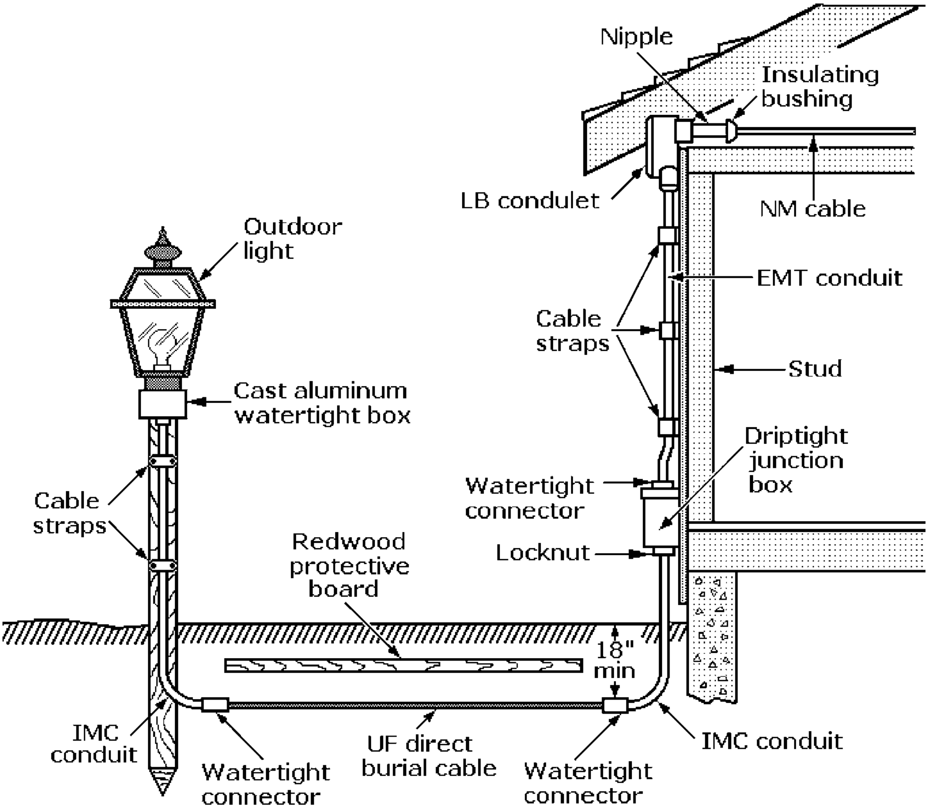


Figure 7-16 **Outdoor 120-V AC lamp is powered by a UF cable extension of an NM cable from an attic branch circuit.**

The UF cable is protected by a curved section of IMC conduit from the junction box to the approved depth underground. It then it passes through a second watertight connection and runs unprotected to a third watertight connection that terminates a curved length of IMC conduit buried near the lamp post. The cable is then run through the conduit to a watertight box on top of the post. The cable connection to the outdoor lampholder mounted on the watertight box is made within the box.

Low-Voltage Outdoor Wiring

There are certain advantages in the use of low-voltage wiring outdoors. It can power individual floodlamps, pump motors for garden fountains, and strings of luminaires for decorative reasons. Outdoor low-voltage lighting can make it safer for persons to walk outside at night on their own property. It will help people see any obstructions or threats on the walkways. The low-voltage lighting system discussed here is an example of how strings of light can be powered economically in yards or gardens. Its advantages and disadvantages can be compared with the use of 120-V systems outdoors.

All of the components needed to install a complete residential low-voltage lighting system are now readily available in kit form from home improvement and building supply stores. Figure 7-16 illustrates a low-voltage lighting system. This lighting can be installed by electrical contractors during new home construction, or it can be successfully installed by homeowners with little or no experience in electrical wiring—if the directions are carefully followed and the necessary safety precautions are taken.

The pricing on low-voltage lighting kits is generally related to the number and type of luminaires. All kits include a 120-V AC to 12-V AC transformer/timer. The built-in timer permits the lights to be switched on and off according to a precise program. These kits include a set number of low-profile, low-voltage luminaires and lengths of two-wire connecting cable sufficient for reasonable spacing between the number of luminaires included in the kit.

The prime advantage of an outdoor low-voltage lighting system is its ability to illuminate a larger area with more lamps at lower cost than a 120-V AC system. Moreover, it eliminates the shock hazard that would be present if a 120-V AC cable were accidentally severed. Also, 12-V AC circuits consume less power than 120-V AC outdoor circuits and are easier and less expensive to install and maintain.

GFCI receptacles have virtually eliminated the shock hazards from faults in all 120-V AC outdoor wiring and lighting systems. Nevertheless, GFCI receptacles should also be used with low-voltage lighting systems because a fault in the 120- to 12-V AC transformer/timer could expose a person to electric shock from the 120 V AC.

Figure 7-17 illustrates the installation of two lights of a typical low-voltage lighting system. It is recommended that the transformer/timer be located in a protected space such as a garage or basement to keep it out of the weather. If it must be installed outdoors, it should be located under a roof extension or porch and protected by a rain cover to minimize its exposure to snow and rain. A more complete discussion of the available styles of low-voltage luminaires is given in Chap. 8.

POSITIONING AND BURYING LOW-VOLTAGE CABLE

After the lighting cable is laid out from the transformer location to each position where the low-voltage luminaires will be located, adequate slack should be allowed for stresses caused by frost, rain, or ground settling. The luminaires are then clamped to the cable with insulation displacement connectors (IDCs), and a trench is cut into the ground along the entire path of the cable to a depth of 6 to 8 in.

The cable is then buried to prevent it from becoming a tripping hazard and protect it from abrasion caused by pedestrian traffic or severing by a lawn mower or other lawn tool. The luminaires are then positioned in the ground in the planned locations, and the cable is connected to the terminals on the transformer. Finally, the transformer is plugged into a GFCI receptacle located indoors or in a suitably protected location.

Any exposed cable left above ground should be protected from abrasion by short lengths of metal or nonmetallic conduit. The task of passing the cable under sidewalks or paved walkways can be simplified by first digging a shallow trench on both sides

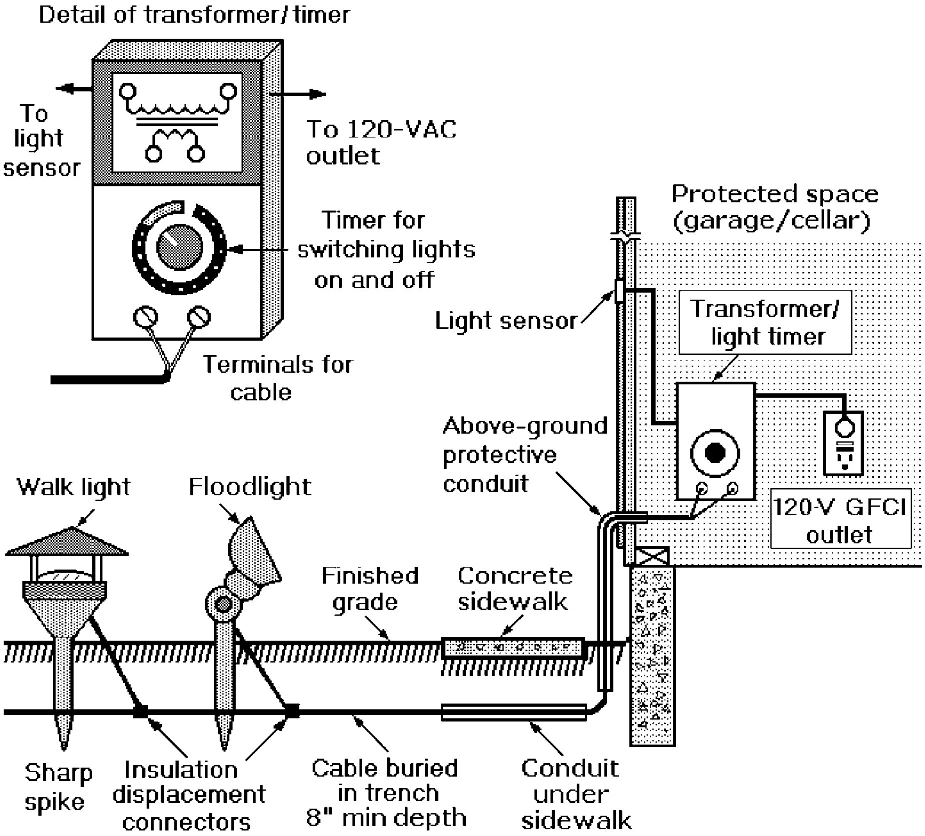


Figure 7-17 Low-voltage outdoor lighting circuit is powered from a transformer/timer that converts 120 V AC to 12 V AC.

of the pavement to be crossed. Then a plugged length of rigid metal conduit can be driven through the ground underneath the pavement. When the plug is removed, the cable can be snaked through the conduit, and the conduit can be left in position to protect the cable.

Some electrical contractors and electricians have questioned the reliability and effectiveness of low-voltage outdoor lighting systems, especially in places where there are severe winters and deep frost layers form in the ground.

8

LIGHTING, LAMPS, AND LUMINAIRES

CONTENTS AT A GLANCE

Overview

Light Spectrum Color Temperature

Incandescent Lamps

Tungsten-Halogen Lamps

Specialized Lamps

Fluorescent Lamps

Fluorescent Luminaires and Ballasts

High-Intensity Discharge (HID) Lamps

Characteristics of Typical Lamps

Residential Lighting Design

Types of Lighting

Luminaires and Lighting Systems

Calculations for Room Lighting

Residential Room Lighting

Outdoor Lighting

Glossary of Lighting Terms

Overview

Electric lighting has brought about a significant improvement in the standard of living for millions of people all over the world. The availability of bright, instantly available illumination has made it possible for people to read, write, and do intricate work more effectively during the nightime hours, without concern for the fire hazards of open flames in fireplaces or from lamps fueled by coal gas, whale oil, or kerosene. It also made homes more secure and streets safer to travel after dark.

The first electric power stations were built in cities in the United States and England to extend the benefits of electric lighting to the general public. More than 100 years later, more electricity is still consumed for lighting than for any other purpose.

Incandescent lamps have long been the dominant light sources, but that dominance is being challenged by halogen and fluorescent lamps. The halogen lamps offer more intense and natural-appearing light, while the newer fluorescent lamps consume less power for equivalent illumination, have far longer lives, and also provide cooler, more natural light. This chapter describes, illustrates, and explains the most popular light sources as well as the high-intensity discharge (HID) lamps. An extensive table gives the leading features of popular examples of all of these lamps.

Other topics discussed in this chapter include the different types and styles of light fixtures (now called luminaires), and the principles of home lighting design for each room. Suggestions for obtaining the most cost-effective illumination are given, and various methods are described for calculating recommended illumination levels for each room. Useful formulas for making those determinations are included.

Other topics in the chapter are the installation of lighting in and around swimming pools and fountains, general 120-V outdoor lighting, and low-voltage lighting for lawns and gardens. A glossary of illumination terms at the end of the chapter defines many words and phrases associated with electric lighting for ready reference.

Light Spectrum Color Temperature

All light bulbs, generally called *lamps*, produce a *thermal spectrum* of light with a specific *color temperature.* This spectrum is a broad, featureless mixture of colors that peaks at a wavelength determined by the temperature or equivalent temperature of the light source. The spectrum of incandescent and tungsten-halogen lamps is determined by filament temperature, but that in fluorescent lamps and some high-intensity discharge lamps is the result of secondary emission from the phosphor coatings.

Because the color temperature of light emitted by lamps is much cooler than that emitted by the sun (5800°C), the light appears redder than sunlight, and very little blue light is present. Although it might not seem logical, the visual "coolness" and blue content of the light increases with its Kelvin (absolute) temperature. The typical color temperatures of incandescent lamps are 2800 K, those of tungsten-halogen lamps are

3000 K, and for cool white fluorescent lamps, they are 4100 K. However, color temperature is an even higher 5000 K from fluorescent lamps manufactured specifically to simulate daylight.

Incandescent Lamps

Incandescent lamps are available in hundreds of different bulb shapes with a wide range of light output, energy consumption, and life ratings. Energy consumption can range from a fraction of a watt for a flashlight lamp to more than 10,000 W for a floodlight.

The number and types of available incandescent lamps are astonishing. Typical manufacturers' catalogs list hundreds of different bulb styles with a wide range of wattage and voltage ratings, estimated useful lives, output in lumens, and other special qualities. However, average hardware stores, home improvement centers, and supermarkets narrow the number and type of lamps they carry down to the relatively few of those that are most familiar and most likely to be purchased by consumers.

The smallest incandescent lamps are made for flashlights, holiday lighting strings, and instruments, while the largest bulbs, with diameters exceeding 20 in., are spotlights and street lights. Mid-sized incandescent lamps, typically rated from 40 to 200 W, are those most widely used in home and office lighting.

All incandescent lamps are made in essentially the same way, and today these processes are automated. Figure 8-1 shows the construction of a typical incandescent lamp. The filament leads are encased in glass and mounted on a glass stem assembly

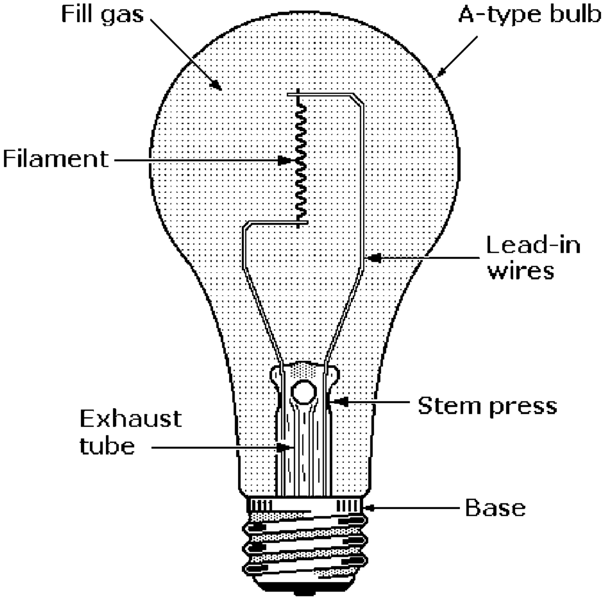


Figure 8-1 Incandescent filament lamp construction.

with a glass exhaust tube. The blown glass bulb, which has been coated inside or "frosted," is then sealed to the stem in a machine. Gas flames directed at the mating edges of the glass parts melt them to form a complete envelope.

A vacuum pump exhausts the air from the bulb and inert gas is released into it. Then the glass stem is "pinched off" by a flame to seal the bulb. The filament leads extending from the lamp are trimmed, and the bulb is inserted into an aluminum or brass base containing a bonding cement. Finally, one lead is soldered to the insulated contact at the bottom of the base and the other is soldered to the rim of the base to complete the lamp.

Screw-in- or Edison-type bases made of aluminum or brass are widely used on incandescent lamps rated for 30 to 200 W. In addition to supporting the lamp, the base makes electrical contact with the wired socket of the lampholder as soon as it is securely screwed into the socket.

Incandescent lamps emit visible light when enough current passes through the filament to heat it to incandescence. When the lamp is first turned on, the filament presents a low ohmic resistance, but that resistance increases rapidly as the filament heats up. All incandescent lamp filaments are made of tungsten, and they are capable of producing from 11 to 33 lumens per watt (lm/W).

The inert gas fill released into the bulb puts enough pressure on the filament to retard tungsten evaporation, permitting it to be operated at higher temperatures than could be achieved in a vacuum, while extending lamp life. Moreover, high filament temperatures permit gas-filled incandescent lamps to emit whiter light than those without a gas fill.

The larger the surface of the filament wire in relation to its volume or mass, the greater will be its ability to dissipate heat. However, if this ratio is too large, the benefits of gas fill will be nullified. The surface-to-volume ratio is large in filaments with current ratings of less than ⅓ A. The filament wire diameters in those lamps are so fine that gas fill actually becomes a disadvantage. For this reason most type B incandescent lamps rated for less than 40 W do not contain gas.

Gas-filled lamps rated 40 W and higher are type C. The gas fill in most type C incandescent lamps is a mixture of nitrogen and argon. The proportion of nitrogen can range from 2 to 100 percent, but even 2 percent prevents the electrical arcing across the filament lead-in wires that occurs if the argon fill is 100 percent.

Examples of incandescent lamp gas fill proportions are:

- *Projection lamps*—100 percent nitrogen
- *High-voltage lamps*—50 percent argon and 50 percent nitrogen
- *High-wattage standard-voltage and street lamps*—98 percent argon and 2 percent nitrogen

Krypton and hydrogen are used as gas fill in some specialized incandescent lamps.

Illumination from typical incandescent lamps generally gives neutral-colored surfaces a yellowish-white appearance, but it enhances red, orange, and yellow surfaces while dulling blue surfaces. This characteristic makes complexions appear ruddy.

Because there is a high degree of standardization in incandescent lamp manufacture, their manufacturers give their products gimmicky names to attract consumer attention and help to build brand-name loyalty. Unfortunately, these names do nothing to enlighten the consumer. For example, lamps are variously called Soft Pink, Dawn Pink, or Softone Pastels, but their color spectrums are essentially the same as are Energy Saver Soft White, Energy Choice, and Energy Saving.

INCANDESCENT LAMP BULB SHAPES

Most incandescent lamp bulb shapes were developed in the early days of electric lighting, and a wide variety of those lamps are still made in those shapes. Those shapes have also been adopted for tungsten-halogen, infrared, fluorescent, and high-intensity discharge (HID) lamps. In the intervening years specialized lamp shapes were developed for automobile headlights, traffic signals, and other applications, but many of them have now been replaced by special HID and LED-array lamps.

Lamp manufacturers agreed on an alphanumeric code to designate lamp shapes. Some typical general-purpose lamp shapes are illustrated in Fig. 8-2, but many of them are no longer exclusive to incandescent lamps. The letter designations and brief descriptions of them are:

- A—*arbitrary,* the classical bulb shape
- B—*miniature elliptical*
- BR—*miniature reflector*
- C—*miniature decorative*
- ER—*narrower bulb reflector*
- F—*flame,* a contoured flame-shape

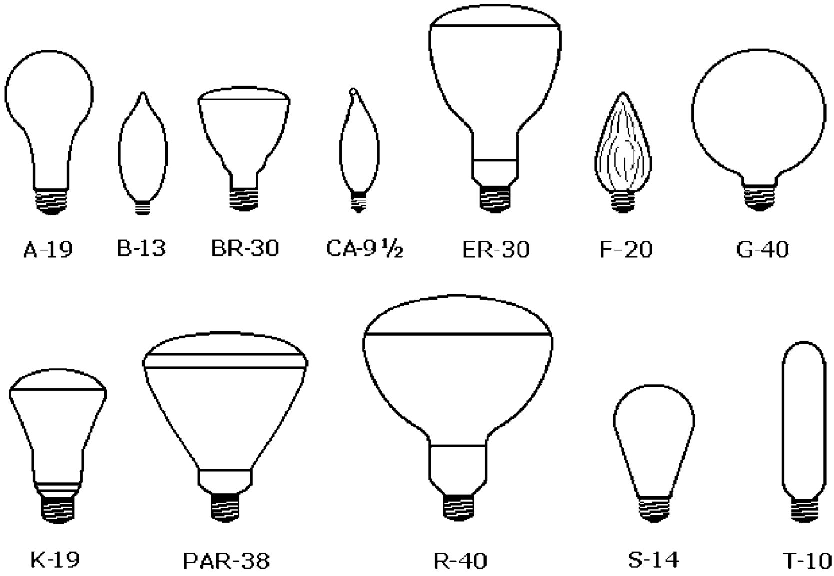


Figure 8-2 Incandescent lamp bulb shapes: Alphanumerical codes identify the shapes and major diameters in eighths of an inch.

- G—*globe,* a round or globe shape
- GT—*bulb* with a cylindrical end cap
- K—*bulb* with a spherical end cap
- P—*pear-shaped,* with a short neck
- PAR—*parabolic aluminized reflector,* a rounded conical shape with a nearly flattened lens and a long neck, suggesting a small TV tube
- PS—*pear-shaped,* straight-sided, similar to A but with a longer neck
- R—*reflector,* a bulb with bulged conical sides and a rounded end lens
- S—*straight-sided,* a conical bulb shape or miniature globe
- T—*tubular,* an elongated tubular bulb with a rounded end

The numbers in the bulb designation indicate the maximum diameter of the bulb in eighths of an inch. For example, an A-21 bulb has a maximum diameter of 21 eighths of an inch or 2⅝ in.

INCANDESCENT LAMP FINISH AND COLOR

Various methods are used to diffuse the light from incandescent lamp filaments. Some bulbs are frosted on the inside by etching them with acid, and others are coated on the inside with white silica, a technique that offers better light diffusion. While the acid frosting inside the bulb absorbs no measurable amount of emitted light, the silica coating absorbs about 2 percent. These etching and coating processes leave the outer surfaces of the bulb smooth, so they can be easily cleaned. Diffusing bulbs are preferred for most general-purpose lighting, but clear or transparent lamps with fully exposed filaments are still used in optical systems and light projectors.

Other interior finishes for general-purpose incandescent lamps are translucent white and opaque silvered bowls. The translucent white coating inside the bulb bowl reduces both direct and reflected glare from open luminaires. A lamp with an opaque silvered bowl is highly reflective. Because the silvered coating is inside, it is not degraded by dust or abrasion, permitting it to last for the life of the lamp. Silver-bowl lamps are used in indirect-lighting luminaires, but they can also act as dome reflectors in direct-lighting luminaires.

Colored light can be obtained from incandescent lamps by applying pigmented coatings to the bulbs that subtractively absorb all of the emission wavelengths except those desired. These coating can be applied to either the inner or outer surfaces of a clear bulb. Other bulbs are coated by fusing a ceramic coating to their outer surfaces. There are lamps with red, blue, green, yellow, orange, ivory, flame tint, and white coatings.

Three-way lamps that emit light with a pink tone are made by applying a pinkish silica coating inside the bulb. These bulbs are used in home luminaires, where delicately tinted warm light is desired. Outer coatings are applied for both indoor and outdoor lamps, but most exterior bulb coatings are subject to wear or they can be degraded by exposure. If they are used outdoors, the bulbs should be protected by weatherproof enclosures with clear lenses and gasketed covers.

Lamps can be colored by blowing the bulbs from glass colored by chemical additives. These bulbs are available in daylight blue, blue, amber, green, and ruby colors. The light from these lamps is purer and more intense than that from surface-colored bulbs, making them suitable for theatrical and photographic studio lighting.

Among colored glass bulbs, daylight blue is the most popular. These lamps suppress the emission of red and yellow light from the filaments, so their emission approximates daylight. Colored glass bulbs cost more than coated bulbs, but are less efficient because they absorb about 35 percent of the emitted light.

INCANDESCENT LAMP BASES

A selection of lamp bases is illustrated in Fig. 8-3. The most familiar incandescent lamp bases shown are the threaded brass and aluminum bases named after Thomas Edison, the inventor. Medium screw-in Edison-type bases with diameters of 1 in. across the threads are found on most general-purpose incandescent lamps rated for 300 W or less. Mogul screw-in-type bases with 1½-in.-diameter bases are used on higher-wattage lamps for street and industrial high-bay lighting.

Intermediate threaded $\frac{13}{32}$-in.-diameter bases are found on incandescent lamps for decorative luminaires such as candle sconces, and miniature screw-in-type $\frac{3}{8}$-in.-diameter bases are on lamps for holiday light strings, games, and flashlights.

Bayonet bases with unthreaded metal shells and two diametrically opposed studs are used on low-voltage incandescent lamps. To insert the lamp in its socket, it must be pushed down against spring pressure with the studs inserted in the L-shaped keyway. When the studs reach the keyway bottom, the lamp is twisted to lock it in place.

The bi-post or two-pin base is used on high-wattage incandescent lamps. The leads embedded in the glass base of the bulb are inserted into and soldered to hollow pins. Other lamp bases have prongs, screw terminals, contact lugs, or single cup-type contacts.

INCANDESCENT LAMP FILAMENTS

The tungsten filament of an incandescent lamp is a resistor whose temperature is raised to incandescence within the bulb by the passage of electric current. The mechanical

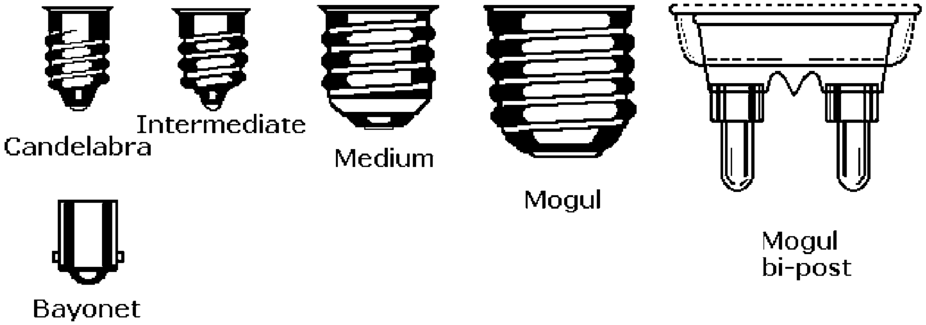


Figure 8-3 Examples of incandescent lamp bases.

characteristics of the filament determine its electrical properties and those of the lamp. The wattage rating of filament lamps is determined by applying Ohm's law:

$$W = V \times A$$

where V = volts and A = current in amperes. The value of A is determined by dividing the applied voltage V by the resistance of the filament in ohms when it reaches incandescence.

Tungsten filaments are also used in tungsten-halogen and fluorescent lamps and various electron tubes. Tungsten is a heavy, hard, ductile, and strong metal with a melting point of 3410°C (6170°F), the highest of any known metal. Filament wire can be as fine as 10 to 15 μm (0.0004 to 0.0006 in.) in diameter in standard lamps, but in special lamps it can be as fine as 5 μm (0.0002 in.).

Tungsten filaments in incandescent lamps have the following characteristics:

- Operating temperature is directly proportional to filament wire diameter and inversely proportional to tungsten evaporation.
- The higher the filament temperature, the greater is the emission in the visible part of the light spectrum, and the more closely its emission approximates sunlight.
- Incandescent lamps are only about 10 to 12 percent efficient. The remaining 90 percent of the input energy is dissipated as heat in the near-infrared (770- to 3000-nm) region, trailing off into the far-infrared region.
- Low-voltage lamps with thicker filament diameters are more efficient than higher-voltage lamps with the same wattage rating.
- Lamps with higher wattage ratings are more efficient than those with lower wattage ratings operating at the same voltage.

In practical terms, a 150-W general-purpose lamp produces over 30 percent more light than three 50-W lamps when all are powered by 120 V.

Incandescent lamps can have many different forms of straight and coiled filaments. Lamp manufacturers classify these forms with an alphanumeric code. Some examples of various tungsten filament shapes are shown in Fig. 8-4. The designations of those shown begin with the letter C (for coiled) or CC (for coiled coils). Most standard incandescent lamps in the 50- to 1000-W range have coiled filaments. They are more effective than straight filaments in gas-filled bulbs because they reduce filament heat losses from conduction and convection through the gas.

It was also found that individual turns in the coil tend to sustain the heat in adjacent coils, and that coiled filaments are mechanically stronger than straight filaments. The effective length of a filament can be increased in a given space by coiling the wire before forming the larger coils. These denser filaments permit higher-wattage lamps in smaller bulb sizes.

The relatively small diameters of bulb necks make it difficult to insert horizontal filament assemblies in a bulb. This was overcome by with vertical filaments such as C-8 and CC-8 of Fig. 8-4 (an example of this filament is shown in Fig. 8-1). In addition to simplifying lamp manufacture, vertical filaments provide higher light emission

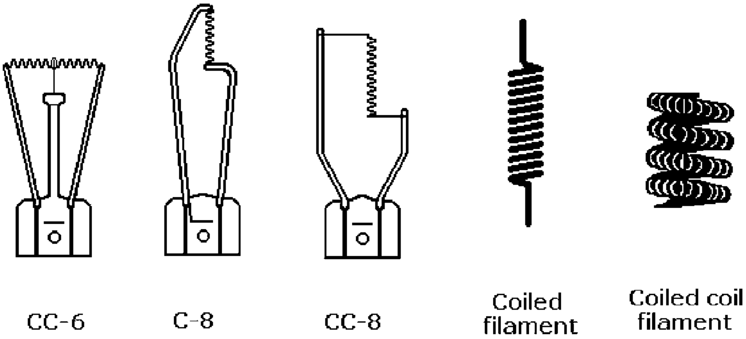


Figure 8-4 Examples of incandescent lamp filament forms.

because gas convection currents raise the filament temperature and less light is absorbed by the lamp base. Moreover, the black stains from evaporated tungsten deposition inside the bulb are smaller and more localized with vertical filaments. By contrast, wide tungsten-smear rings occur in bulbs with horizontal filaments.

More elaborate filament and support structures are found in projection lamps, spotlights, and floodlights. They are intended to achieve more accurate control of light emission from smaller sources. Although coiled filaments predominate, lamps with straight and flat filaments are still being made. The letter S in the filament code stands for a straight or uncoiled filament, and the letter R indicates a flat or ribbon-shaped filament.

INCANDESCENT LAMP LABELING

The U.S. Energy Policy Act of 1992 mandated that all lamp cartons include three rating values for each bulb: *light output,* measured in lumens, *energy used,* measured in watts, and life, measured in average hours of lamp life. In general, light output in lumens is directly proportional to energy consumption in watts, while life is inversely proportional to energy consumption. Wattage and voltage ratings or just wattage ratings are imprinted on the ends of the bulbs.

Tungsten-Halogen Lamps

A halogen or *tungsten-halogen lamp* is a high-pressure incandescent lamp containing a halogen gas such as iodine or bromine which allows the filament to be operated at a higher temperature than an incandescent lamp, increasing its efficacy. Halogen lamps emit brighter, more intense white light than incandescent lamps, but they are smaller than incandescent lamps with comparable wattage rating. However, the characteristics of the two lamp sizes are similar. Because of the higher color temperatures of halogen lamps (3000 K versus 2800 K), they use quartz rather than glass bulbs. The high-temperature chemical reaction involving tungsten and the halogen gas recycles evaporated particles of tungsten back onto the filament surface. These lamps are used in high-intensity desk and reading lamps, vehicle headlights, spotlights, and flashlights.

Care is needed in handling and using 120-V AC halogen lamps because the high bulb temperatures of an illuminated lamp can cause severe skin burns. Fingerprints on the cold quartz surface of a halogen bulb leave an oily residue that shortens lamp life by causing heat to be distributed unevenly over the surface of the bulb when the lamp is illuminated. Most desk and reading lamps have protective glass lenses over the bulbs to prevent accidental burns when they are illuminated and to prevent fingers from touching them when they are cold.

Halogen lamp light makes neutral surfaces appear yellowish-white. It enhances red, orange, and yellow colors, makes complexions appear ruddy, and dulls blue colors. There are lamp shapes used exclusively for halogen lamps because of their high-temperature characteristics. These include T double-ended, single-ended, and bi-pin quartz bulbs, and projector and reflector (PAR) bulbs

Specialized Lamps

TUBULAR (T) BULB LAMPS

Tubular-envelope incandescent lamps are intended for illuminating store display cases and bathroom mirror luminaires where a long, linear light pattern is desired. These lamps can be paired with external reflectors to concentrate the light pattern. Some T lamps have internal reflecting surfaces covering about half of the inner surface of the bulb to focus light into long, thin fan beams. The common T bulb sizes, T-6½, T-8, and T-10, are available with ratings of 25 and 40 W, and T-10 lamps have ratings of 60 W.

PROJECTOR AND REFLECTOR (PAR) BULB SHAPES

Projector and reflector lamps are made as incandescent, tungsten-halogen, mercury, and metal halide high-intensity discharge (HID) lamps. They all include compact filaments that are accurately positioned with respect to the base for more efficient light beam formation. Their internal parabolic reflectors are formed by sputtering aluminum on the inner curved surfaces of the bulb. The combination of internal reflector and contour of the front lens focuses the output light in a unidirectional conical beam.

PAR lamps are generally designated as *flood* and *spot,* but manufacturers have expanded those classifications to include *narrow flood, wide flood,* and *narrow spot* to define their light patterns more precisely. Unfortunately, these terms are not standardized. Flood PAR beam angles are typically 40°, narrow floods are 30°, and wide floods are 50°. Spot PAR beam angles are typically 12°, and narrow spots are 9°.

PAR-38 incandescent lamps are available, but PAR-38SPL and five other PAR lamps, PAR-14, PAR-16, PAR-20, PAR-30, and PAR-30LN, are available only as tungsten-halogen lamps. As with other lamps, the PAR part number indicates its lens diameter in eighths of an inch. For example, a PAR-30 bulb lens diameter is 30 eighths of an inch or 3¾ in. All PAR bulbs of the same size and technology, whether classed as flood or spot, have the same lumen output. PAR lamp packages give the beam spread or width in approximate degrees under the designation "beam."

REFLECTOR (R) BULBS

Incandescent, mercury, and metal halide lamps are available in *reflector (R) bulbs.* Incandescent R lamps are made for general-purpose indoor track and recessed flood lighting. The R-14 bulbs are rated for 25 and 40 W, the R-16s are rated for 40 W, the R-20s for 50 W, and the R-40s for 65, 250, 300, 375, and 500 W. In addition, the R-52 lamps are rated for 750 and 1000 W. The beam widths of 500-W R-40s are 115°, but for R-52s they are 70°. These lamps can distribute light in both wide and narrow beams, and they are rugged enough to be approved for installation as factory lighting because they can withstand airborne dust, smoke, or fumes.

The *elliptical reflector* (ER) bulb is a variation of the R bulb for incandescent lamps. This bulb shape produces a focal point directly in front of the lamp, reducing light absorption in some types of luminaires. ER bulbs are particularly effective for increasing the efficiency of baffled downlights.

INFRARED (IR) LAMPS

Infrared (IR) lamps are incandescent lamps with filaments that operate at lower temperatures than incandescent lamps. IR radiation is the part of the electromagnetic spectrum from about 770 nm to 1 mm. Energy in this range is not visible to the human eye, but it can be sensed as heat on skin.

IR lamps look like conventional incandescent lamps, but when in operation their filament voltage is so low that the filament appears more red than white. The visible light output from an IR lamp is only about 7 or 8 lm/W. This compares with the 15 lm/W for a 60-W incandescent lamp. IR lamps are used primarily for therapeutic and other localized heating applications. Because of their lower filament temperatures, they have far longer lives than conventional incandescent lamps, perhaps as long as 5000 hrs. Because of their thicker filament wire, they are less susceptible to damage by shock and vibration than conventional incandescent lamps.

Fluorescent Lamps

Fluorescent lamps are high-efficiency lamps that produce visible light as a result of an interaction of the ultraviolet (UV) energy they produce with the phosphor coating on the insides of their glass envelopes. The lamp envelope contains traces of an inert gas and a drop of mercury. When the lamp is turned on, the mercury is vaporized, and this vapor and the inert gas are ionized by electron flow between electrodes at each end of the lamp to produce UV emission.

The UV energy excites phosphor powders that have been applied as thin layers on the inside of a glass envelope, a tube or bulb. The phosphors transform the UV emission into visible light whose color temperature and characteristics depend on the composition of the phosphors in the layers. Fluorescent bulbs or tubes can operate with either “hot” or “cold” electrodes called cathodes. A cutaway view of a hot-cathode, preheat-starting fluorescent tube is shown in Fig. 8-5.

After a vacuum is pumped in the tube and before it is sealed, a drop of liquid mercury is inserted and the inert gas, usually argon, is admitted. When the lamp is turned on, the voltage between the electrodes is high enough to vaporize the mercury and ionize the mercury-gas mixture. The UV emission from the gas discharge is almost entirely due to the mercury vapor.

After gas ionization occurs, a much lower voltage can sustain illumination. This voltage is typically less than 100 V for tubes rated for 30 W or less and 100 to 175 V for those rated more than 30 W. When the lamp is turned off, the mercury-gas mixture deionizes and becomes nonconductive.

The phosphor coatings inside the tube are mixed to tailor the properties of the emitted light for specific coloration and lighting effects. Among the possibilities are cool white, deluxe cool white, warm white, deluxe warm white, white, and daylight. Energy-saving lamps have an argon–krypton gas mixture, and others have combinations of argon and neon or argon, neon, and xenon. Commercial fluorescent lamps are available in the following categories, which depend on their ballast circuits:

- Hot-cathode, preheat-starting
- Hot-cathode, rapid-starting
- Hot-cathode, instant-starting
- Subminiature
- Cold cathode
- Compact

STANDARD FLUORESCENT LAMPS

Fluorescent lamps can produce 50 to 100 lm/W, making them 4 to 6 times more efficient than incandescent lamps. In general, a quality fluorescent lamp can produce 3 to 4 times the light output of an incandescent lamp with an equivalent wattage rating. For

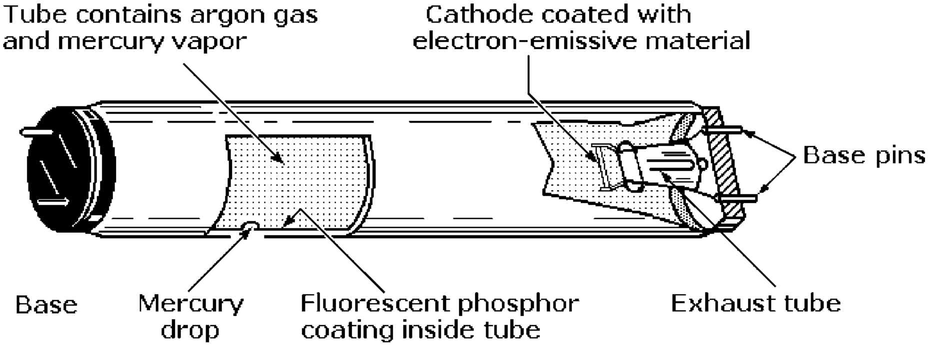


Figure 8-5 Cutaway view showing the construction of a hot-cathode, preheat-starting fluorescent tube.

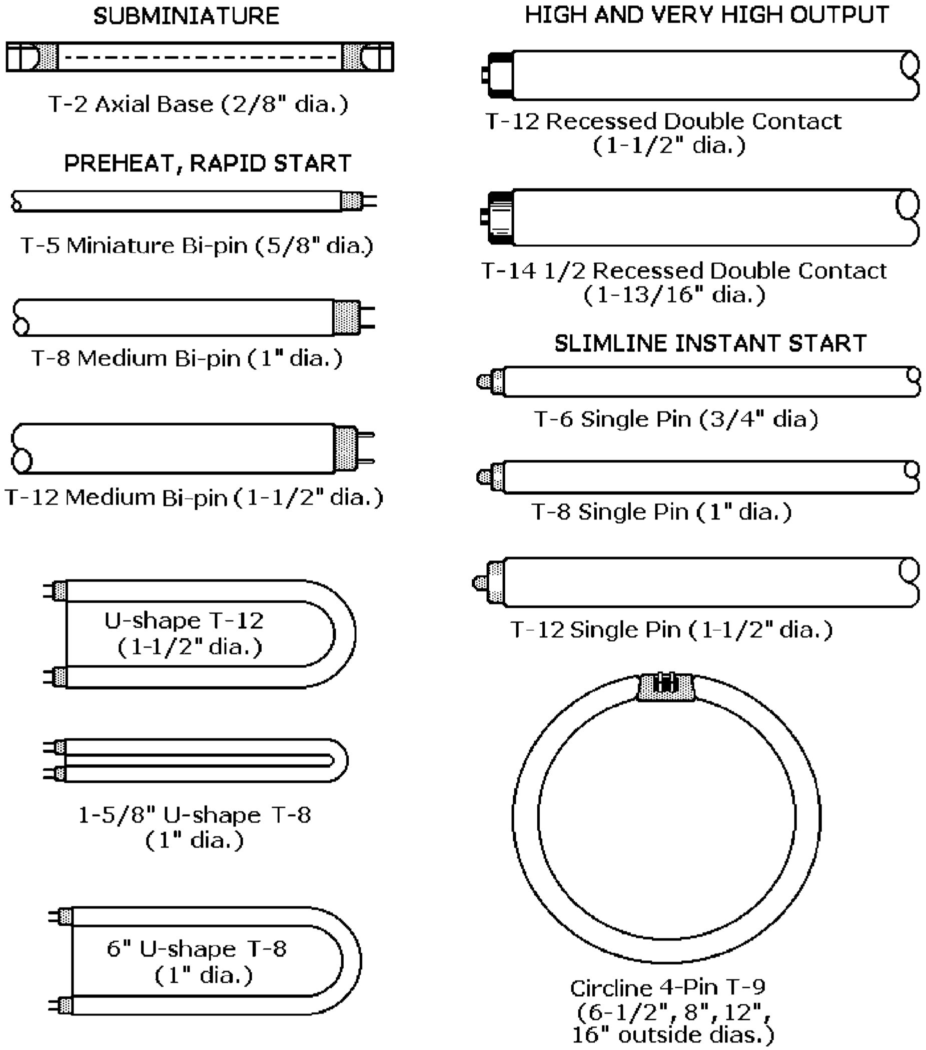


Figure 8-6 Standard fluorescent lamp bulb and base shapes.

example, a 15-W fluorescent lamp can produce as much light as a 60-W incandescent lamp. About 90 percent of its energy is converted into light, with the remaining dissipated as heat (near-infrared) radiation. The fluorescent spectral distribution curve closely conforms to the visible light spectrum of 380 nm (violet light) to more than 770 nm (red light). All fluorescent tubes and bulbs run cooler than incandescent lamps because of their higher efficiency. The shapes and styles of fluorescent lamps are illustrated in Fig. 8-6.

- *Tubular bulb* lamp sizes are identified by a code consisting of the letter T (designating that the bulb is “tubular” in shape) followed by a number that expresses the diameter of the tube in eighths of an inch. Their diameters vary from ¼ in. for the T-2 to 1½ in. for the T-12. Fluorescent tube lengths range from 6 to 96 in., measured between the ends of their bases. For example, the overall length of the rapid-start T-12, 48-in. lamp is actually 47¾ in. Subminiature T-2 fluorescent lamps have axial bases on the ends of the tubes. Preheat and rapid-start lamps require four electrical contacts, so they have two-pin bases at each end. Standard T-5 lamps have miniature bi-pin bases, while both T-8 and T-12 lamps have medium bi-pin bases.

- *Circular bulb* fluorescent lamps are available in four outside diameters: 6½, 8, 12, and 16 in. There are also U-shaped fluorescent tubes with T-8 and T-12 bulbs. The widths of U-shaped tubes are measured between their ends, and their overall lengths are measured from the faces of the bases over the outsides of the glass bends.
- *U-shaped fluorescent* lamps have bi-pin bases at the tube ends, while circular lamps have four-pin bases positioned in the gap between the opposing ends of their circular tubes. High- and very-high-output lamps have recessed double-contact (RDC) bases. By contrast, Slimline instant-start lamps require only two electrical contacts, so they have single-pin bases at each tube end.

FLUORESCENT LAMP CHARACTERISTICS

Standard fluorescent lamps are available with four different starting methods.

- *Preheat fluorescent lamps* are hot-cathode fluorescent lamps with two-pin bases. They require starters that pass current through their filament cathodes to heat them. Emission from the cathodes occurs only after they have been preheated. There is a time delay at turn-on before these fluorescent lamps reach full brightness, but this drawback is offset by savings in the cost of ballasts and longer lamp life. The switch and starter connected across the lamp can be either automatic or manual.
- *Instant-start* (IS) *fluorescent lamps* require specially designed instant-start ballasts that deliver voltages high enough to start fluorescent lamps as soon as the power is applied, so no cathode preheating is required. These voltages decrease to normal operating voltages after the lamps have started. IS ballasts use from 1.5 to 32 W less per lamp than rapid-start (RS) ballasts. Because IS fluorescent lamps do not require preheating, the bases on each end of the lamp require only a single pin. IS ballasts were developed to eliminate separate mechanical starter devices. Slimline fluorescent lamps operate only on instant-start ballasts. Some IS ballasts can start a lamp within 50 ms.
- *Rapid-start* (RS) *fluorescent lamps* are the most popular fluorescent lamps. RS ballasts apply low voltage to the cathodes prior to lamp ignition to accelerate the starting interval, and then provide continuous cathode heating as long as the lamp is energized to maintain light output at efficient levels. A built-in electrode heating coil in the ballast permits the lamp to reach full brightness almost as quickly as an IS fluorescent lamp. RS lamps eliminate the need for separate starter switches, and their ballasts can be either electromagnetic, electronic, or hybrid. Full-range fluorescent lamp dimming is possible only with RS lamps.
- *Standard preheat rapid-start* (RS) *fluorescent lamps* can be operated from either preheat or RS ballast circuits.

BALLAST CIRCUITS FOR FLUORESCENT LAMPS

A *ballast* is an electrical component that starts and controls the operation of fluorescent and high-intensity discharge (HID) lamps once they have started. There are three types of lighting ballasts:

- *Magnetic:* Now technically obsolete, these low-frequency ballasts use a core and coil transformer to perform the functions required to start and operate the lamp.
- *Hybrid:* These are essentially low-frequency magnetic ballasts with a few electronic components that switch off the voltage to the lamp coil once the lamp has started.
- *Electronic:* These ballasts contain an electronic circuit that operate lamps at frequencies of 20 kHz or higher. They are now replacing both magnetic and hybrid ballasts.

Electronic ballasts made it possible to eliminate the bulky core and coil of magnetic ballasts and replace them with small magnetic devices and solid-state electronic circuits capable of operating fluorescent and HID lamps in the higher 20- to 35-kHz frequency range by converting 60-Hz line frequency. They gained popularity during the 1990s.

High-frequency electronic ballasts operate fluorescent lamps 30 to 40 percent more efficiently than magnetic ballasts for equivalent light output. This results in a 10 to 25 percent energy saving. This energy saving can result in payback of their higher initial cost in less than a year. Electronic ballasts dissipate less power as heat, thereby lowering the burden on air-conditioning systems. They also have higher power factors than magnetic ballasts. These ballasts eliminate most of the hum and flicker of magnetic ballasts, making them virtually silent. People working in small, quiet offices frequently complain about the objectionable humming noise made by magnetic ballasts.

Perhaps the best feature of electronic ballasts is that they work better than magnetic ballasts when dimmed. Dimming with magnetic ballasts has long been a problem. When dimming requirements fall below the 50 percent illumination level, dropouts, flickers, and shorter lamp life are frequent unwanted results. By contrast, typical electronic ballasts eliminate these problems and can provide full-range dimming from 100 percent down to 10 percent that is steady and flicker-free without annoying dropout. Some electronic ballasts are said to be able to dim to 1 percent of output and provide for more than 100,000 switching cycles, making them desirable for rooms with occupancy sensors.

Other electronic ballasts can provide either two levels (100 or 50 percent) or three levels (100, 60, or 30 percent) of light by using wall switches. There are also electronic ballasts for HID lamps with different ballast circuits, but only a few products are available. Moreover, they provide only minor improvements in the effectiveness of HID lamps.

COMPACT FLUORESCENT LAMPS

Compact fluorescent lamps (CFLs) are intended to replace standard incandescent lamps where longer life, lower power consumption, and lower heat dissipation justify their higher cost. They are available in many different shapes, but are generally about the same size as conventional incandescent lamps. Some of the more common CFL bulb shapes are illustrated in Fig. 8-7. They are the spiral, also called a swirl or twist,

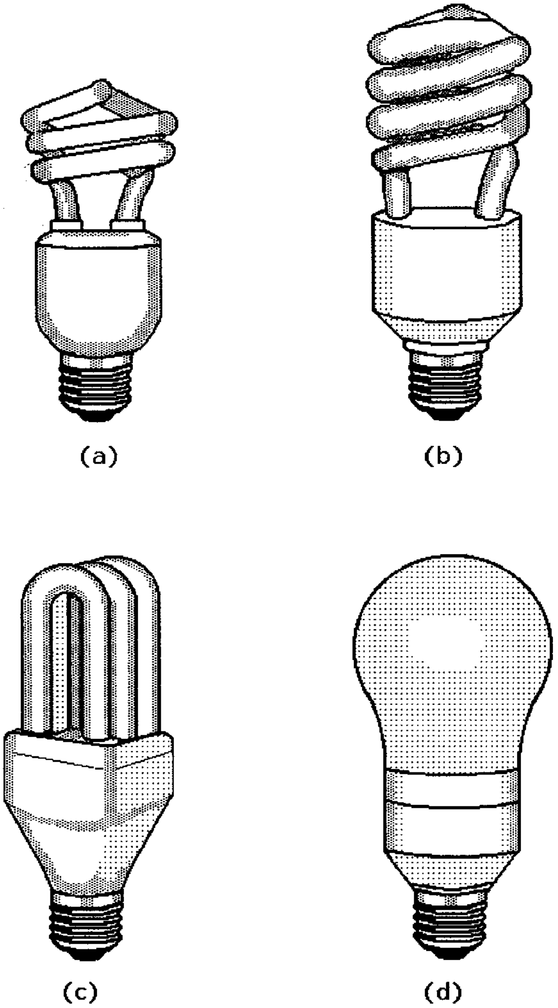


Figure 8-7 Compact fluorescent lamps (CFLs): (*a*) 13-W spiral; (*b*) three-way 8-, 14-, and 28-W spiral; (*c*) 15-W biax; (*d*) 15-W bulb.

a spiral three-way, an inverted U-shape called bi-ax, and a bulb shape that approximates a conventional A-type bulb shape.

The number of turns on a spiral CFL bulb relates directly to its lumen output, and the number of U-shaped elements (two to four) on a bi-ax lamp relates directly to its lumen output. There are also circular, cylindrical, globe, three-way, chandelier, and candelabra CFLs. Most of these lamps have medium screw-type bases.

The 13-W spiral lamp shown in Fig. 8-7*a* is said to be the equivalent of a 60-W incandescent lamp, and the three output values of the three-way spiral lamp shown in Fig. 8-7*b* are said to be equivalent to those of a three-way incandescent lamp—8 W to 30 W, 14 W to 70 W, and 28 W to 100 W. The 15-W bi-ax lamp shown in Fig. 8-7*c* and the 15-W bulb shown Fig. 8-7*d* are both said to be equivalent to a 75-W incandescent lamp.

CFLs with Edison medium-size screw-type bases are intended to replace incandescent lamps in table lamp and luminaire sockets. Most consume from 14 to 27 W and offer lumen output that is comparable to that from incandescent lamps, which consume 4 to 5 times as much energy. Some specialty CFLs have wattage ratings as low as 3 and 5 W. Regardless of bulb shape, all CFLs operate the same way as standard fluorescent lamps, and they all require ballasts that add to their weight and cost.

Promoted as energy-savings alternatives to incandescent lamps, CFLs offer a range of illumination characteristics. Another important feature of CFLs is their long life, typically 10 times that of the nearest equivalent incandescent lamps. They have continuous rated lives of 6000 to 10,000 hrs (10,000 hrs is longer than 1 year). These compare with 750- to 1000-hr ratings for typical incandescent lamps.

The characteristics of CFLs match those of conventional fluorescent tubes and also depend on the phosphor coating inside each lamp. They also convert about 90 percent of their energy into light, with the remaining 10 percent dissipated as heat (infrared) radiation. Consequently, they also run cooler than incandescent lamps. Some CFLs have bases that can be separated from their ballasts when the lamp part burns out. This permits the ballasts, which have lives up to 50,000 hrs, to be reused with replacement lamps.

CFLs with electronic ballasts are less top-heavy than those with magnetic ballasts, making them more suitable for use in table and floor lamps. However, some CFLs have magnetic ballasts as separate units that plug directly into wall outlets and permit the CFL to be lighter, shorter, and more stable. These CFLs can fit table lamps with shorter shade-supporting harps that cannot accept the taller integral-ballast CFLs.

CFL manufacturers also list the light output of their products in lumens, energy used in watts, and life in hours on lamp packages. However, the different shapes of CFLs result in different illumination characteristics, and these have led some to question the accuracy of manufacturers' claims of lumen equivalency. Typical claims are that 15-W CFLs are equivalent to 60-W incandescent lamps rated for about 850 lm, 20-W CFLs are equivalent to 75-W incandescent lamps rated for about 1200 lm, and 25-W CFLs are equivalent to 100-W incandescent lamps rated for about 1600 lm.

However, for many people CFL illumination appears weaker than that from the comparable incandescent lamps because of the differences in their light sources. Light from a CFL is more diffuse than that from an incandescent lamp, because it is distributed throughout the tube. By contrast, the hot-filament light source of an incandescent lamp is essentially a point source able to project light farther than a CFL. Thus CFLs are not satisfactory replacements for incandescent lamps in all applications.

The principal benefits of CFLs are energy conservation and heat-load reduction in a room. As a result, the cost of lighting and perhaps air conditioning can be reduced. CFLs with integral ballasts cost between $10 and $20 retail, compared with the approximately 90-cent retail price for a typical incandescent bulb. CFLs are most cost-effective and efficient when they illuminate rooms or spaces where lights remain on for long periods of time, so if CFLs are switched on and off frequently or stay on for only a few minutes, such as in closets, payback or cost justification will be slower. Moreover, frequent on/off switching of CFLs can decrease their lives. Because CFLs have long lives, they are ideal for hard-to-reach sockets in rooms with high ceilings. Some CFLs are dimmable with incandescent lamp dimmers.

As illustrated in Fig. 8-7*b,* three-way CFLs with three wattage and lumen levels comparable to three-way incandescent lamps are also available. Users are cautioned, however, that three-way CFLs should be used only in three-way sockets. CFLs are designed to operate within a specific temperature range. Temperatures below this range reduce the light output. The CFL's temperature range is printed on most lamp packages. CFLs are generally intended for indoor use, but those made for outdoor use should be mounted in enclosures that protect them against the adverse effects of colder temperatures.

The high frequencies from electronically ballasted CFLs cause them to emit high-frequency infrared emissions that interfere with infrared remote controls. CFLs with electronic ballasts operate at frequencies between 25 and 50 kHz and produce a 50- to 100-kHz flicker. While this is too fast for the human eye to perceive, it modulates a narrow band of infrared energy that can jam the binary-coded infrared signals for remote switching of cable boxes, TV sets, VCRs, and stereos, because they also switch in this 50- to 100-kHz range. However, these spurious IR signals do not interfere with the receiver circuits in most TV sets and stereos, because both include circuitry that isolates them from all but valid code signals. This possible interference problem is best solved by keeping all CFLs away from these entertainment products and the line of sight between them and the remote controls used to switch them.

All fluorescent tubes including CFLs contain mercury, but there is only a microscopic amount in CFLs. There are no regulations on the disposal of CFLs (as there are for full-size standard fluorescent tubes), but for safe disposal the bulbs should not be broken.

FLUORESCENT LAMP EMISSION COLORS

As explained earlier, emission color is that quality of visual sensation which is associated with the distribution of light within the visible spectrum. The colors emitted from fluorescent lamps relate directly to the *correlated color temperatures* achieved from the phosphor inner coatings. The 4100 to 5000 K correlated color temperatures of cool and daylight-simulation fluorescent lamps are higher than the actual color temperature range of 2800 to 3000 K for incandescent and tungsten-halogen lamps.

Fluorescent correlated color temperatures are classed as warm (3000 to 3500 K), midrange (3500 to 3900 K), cool (4100 to 4150 K), and daylight-simulation (5000 K). These definitions are not standardized, but they suggest the most likely applications for the lamps.

- *Cool white* gives neutral surfaces a white appearance and is suitable for homes, offices, and stores because it simulates and blends well with natural daylight. It is the most popular fluorescent color because it brightens orange, blue, and yellow, and darkens red. Complexions appear pink in this light. This color has the highest efficacy.
- *Deluxe cool white* also gives neutral surfaces a white appearance. It is generally suitable for the same applications as cool white because it also simulates natural daylight. It enhances most colors and provides the best overall color rendition. Complexions appear most natural in this light. This color offers medium efficacy.
- *Warm white* gives neutral surfaces a yellowish-white appearance. Used where color rendition is not critical, it simulates yellowish incandescent light. It brightens orange, yellow, and tan surfaces, but dulls those that are red, green, and blue. In this light complexions appear sallow. This color offers high efficacy.
- *Deluxe warm white* also gives neutral surfaces a yellowish-white appearance and simulates yellowish incandescent light. It enhances red, orange, yellow, and green

surfaces but dulls blue surfaces. In this light complexions have a ruddy tone. This color offers medium efficacy.

- *Daylight* most closely resembles cool white. It gives neutral surfaces a bluish-white appearance and in work areas it strengthens blue and green surfaces and tones down red and orange surfaces. This light gives complexions a gray tone. This color offers medium high efficacy.
- *White* is a compromise between cool white and warm white. It gives neutral surfaces a pale yellowish-white appearance. White is selected for general lighting in homes, schools, offices, and stores where the effect of the light on people, furnishings, or merchandise is not critical. It strengthens orange and yellow but dulls red, green, and blue. This light gives complexions a pale tone. It offers high efficacy.

Fluorescent Luminaires and Ballasts

Standard fluorescent lamps require dedicated luminaires with compatible ballasts to operate them because they cannot be inserted into 120-V AC sockets. Figure 8-8 is an exploded view of a typical two-tube fluorescent luminaire. The base pan of the luminaire is formed from light sheet metal, usually painted white to blend in with the ceiling on which it is mounted. The four tube sockets are fastened to the corners of the base pan. A sheet-metal coverplate protects the wiring and ballast.

After the base pan is bolted or screwed to the ceiling or an appropriate overhead support, the wiring connections are made. The metal cover protecting the ballast and wiring is then clamped in position. After installing the tubes and testing the fixture, the translucent plastic diffuser is positioned over the lamps and snapped into the base pan.

High-Intensity Discharge (HID) Lamps

A general class of lamps called high-intensity discharge (HID) includes mercury-vapor, metal halide, and high-pressure sodium lamps. All electric discharge lamps include cylindrical transparent or translucent arc tubes that enclose the mercury, various gases, and metal salts and confine the electric discharge. The arc tubes are enclosed in a glass bulb which performs three functions:

- Excludes air to prevent oxidation of metal
- Stabilizes operating temperature of the lamp
- Reduces ultraviolet radiation emitted by the excitation of the vapors

HID lamps are packaged in a wide range of bulb styles, including BT, E, ET, PAR, R, and T. There are also specialized double-ended and single-ended styles. The bases include a range of screw-type, bayonet, and ceramic styles. Some HID lamps are designed for base-up, base-down, or horizontal operating positions, while others can be operated in any position. Like fluorescent lamps, all HID lamps require ballasts.

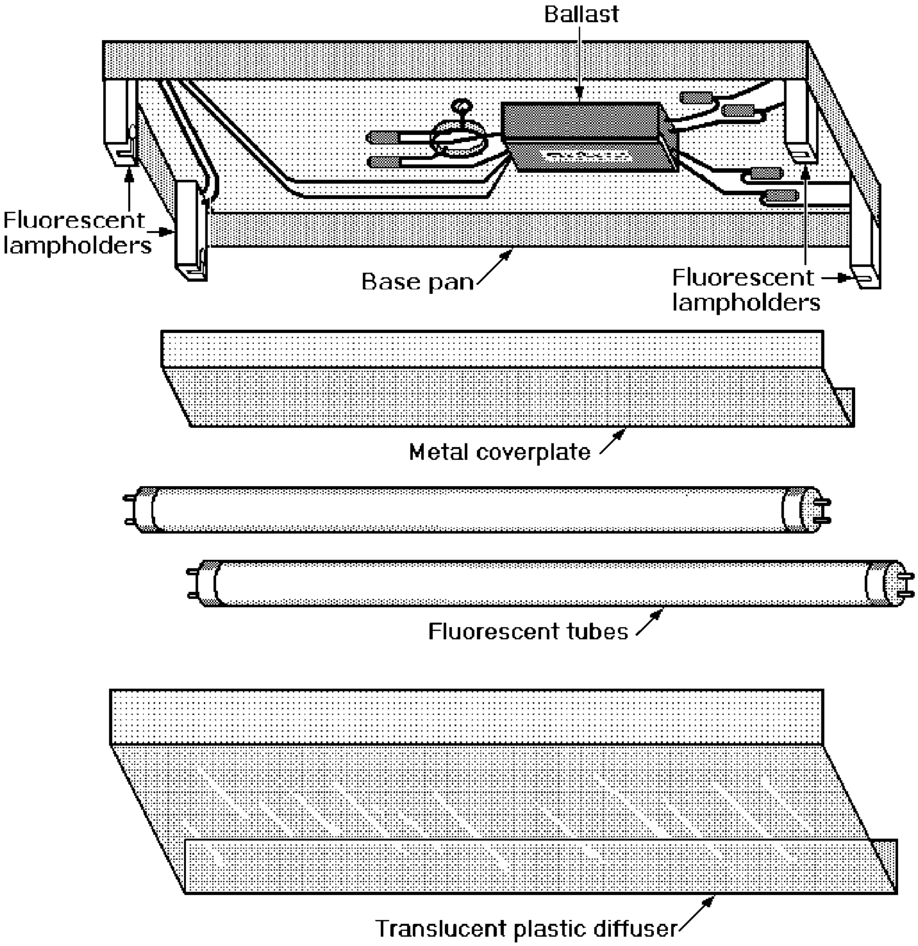


Figure 8-8 Exploded view of the parts of a two-tube fluorescent luminaire.

These lamps operate at high pressures and very high temperatures. They can be ruptured by mishandling, misapplication, or ballast failure. An arc-tube rupture can burst and shatter the outer glass bulb, resulting in an explosion that scatters glass fragments at temperatures as high as 1832°F (1000°C). To reduce the risk of personal injury, property damage, or fire, the lamp must be enclosed in a rigid housing with a combination lens and diffuser that can contain these hot fragments. HID lamps give full light output over a wide range of ambient temperatures. This makes them suitable for street, stadium, and parking lot lighting as well as building floodlighting and interior high-bay illumination.

MERCURY-VAPOR (MV) LAMPS

Mercury-vapor (MV) lamps produce most of their light from the excitation of mercury atoms. A small amount of liquid mercury, which is vaporized, and argon gas fill is sealed within a quartz arc tube mounted inside the MV lamp's outer glass envelope. The construction of an MV lamp with a phosphor-coated bulb is shown in Fig. 8-9. After arc-tube warmup, it emits both ultraviolet (UV) and visible blue-white light that enhances yellow, green, and blue surfaces but dulls red and orange surfaces. MV lamps have correlated color temperatures (CCTs) of 3000 to 7000 K. The color rendering indexes (CRIs) of standard MV lamps range from 15 to 25, while those with phosphor-coated bulbs are 40 to 55. The efficacies are from 30 to 65 lm/W. MV lamps are used in both indoor and outdoor lighting where good efficiency and long life are required, but color rendering is only moderate. Complexions look greenish or very pale in this light. However, by phosphor-coating the bulb for color correction as is done with fluorescent lamps, an MV lamp's output color can be made to appear more natural. Correction adds a warmer purplish tone that enhances red, yellow, and blue surfaces while dulling green surfaces. Corrected MV light is similar to cool-white fluorescent light in giving complexions a ruddy tone. Correction also boosts light output and improves the lamp's efficacy. MV lamps have longer lives than other HID lamps (up to 24,000 hrs), but cost less. They are available with wattage ratings of 40 to 1000 W.

METAL-HALIDE (MH) LAMPS

Metal-halide (MH) lamps produce light by radiation from an excited mixture of mercury vapor in their arc tubes and the products of the dissociation of halides. The construction

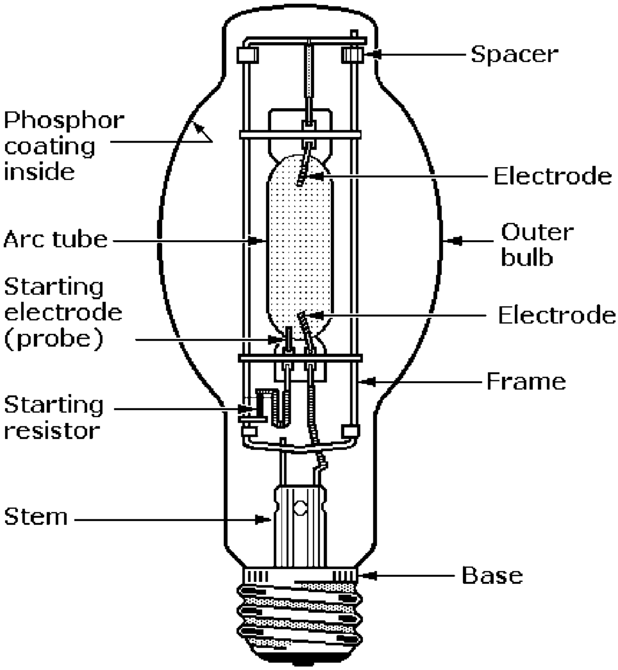


Figure 8-9 Mercury-vapor (MV) lamp construction.

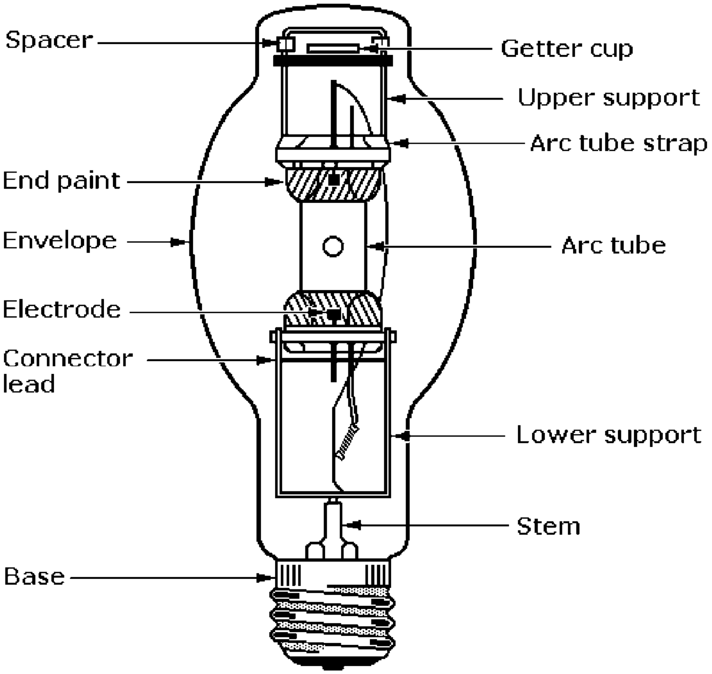


Figure 8-10 Metal-halide (MH) lamp construction.

of an MH lamp, which is similar to that of a mercury-vapor lamp, is shown in Fig. 8-10. In addition to an argon gas fill, the quartz arc tube contains halide (iodide) additives to increase the lamp's luminous efficiency and provide a more pleasing color balance than can be obtained from mercury vapor in an argon gas fill. Common additives are halides of sodium, thallium, and indium.

MH lamps have correlated color temperatures (CCTs) of 2300 to 5400 K and color rendering indexes (CRIs) of 60 to 93. These CRIs are better than those of other HID lamps because the different additives produce more visible wavelengths, resulting in a more complete spectrum. Efficacies of MH lamps are 75 to 125 lm/W. Phosphor coating is not needed on MH lamp glass envelopes because their emitted light color is comparable to fluorescent cool white. Uncorrected MH light enhances yellow, green, and blue surfaces but dulls red surfaces. However, phosphor coating can add orange-red light to improve complexion tone. MH lamps emit less UV radiation than MV lamps, are 50 to 75 percent more efficient than fluorescent lamps, and have wattage ratings from 40 to 1000 W.

HIGH-PRESSURE SODIUM (HPS) LAMPS

High-pressure sodium (HPS) lamps produce light by the excitation of sodium vapor under high pressure. The construction of an HPS lamp is shown in Fig. 8-11. It is constructed and operates in a way similar to mercury-vapor and metal-halide lamps. The internal arc tube is made from translucent ceramic polycrystalline alumina (aluminum oxide) rather than glass. The arc tube contains a small amounts of metallic sodium and

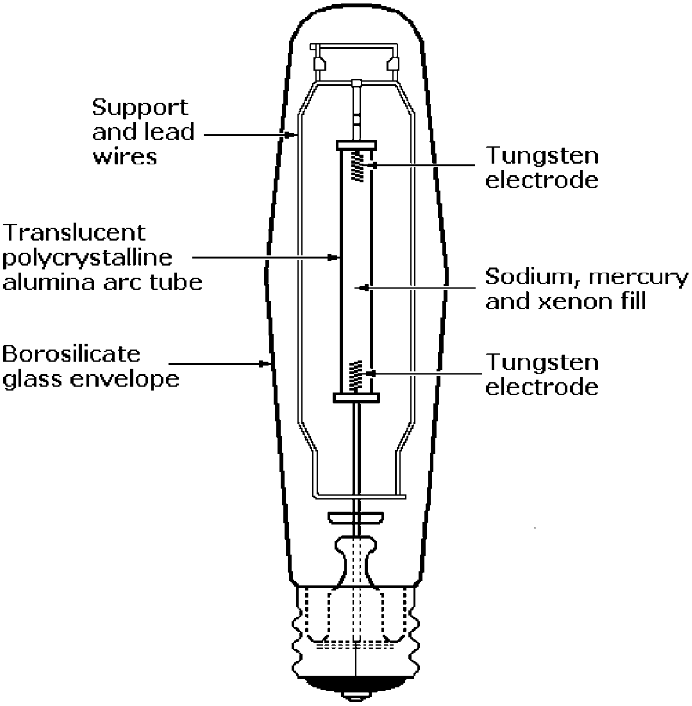


Figure 8-11 High-pressure sodium (HPS) lamp construction.

mercury sealed with a xenon gas fill. The arc tubes cannot be made from glass or quartz because those materials lose their strength at the high operating temperatures of HPS lamps (about 1300°C), and they would be attacked chemically by the sodium. (Some HPS lamps use a neon–argon mix in place of xenon.)

The correlated color temperatures and efficacies of HPS lamps depend on their color rendering index values. Standard lamps with CRIs of 22 have CCTs of about 2000 K, and those with nonstandard CRIs of 60 to 80 have CCTs from 2200 to 2700 K. Standard lamps have efficacies up to 150 lm/W, but for those with high CRI values, they are as low as 25 lm/W. HPS lamps produce an orange-white light that appears yellowish in tone on neutral surfaces. This light enhances yellow, green, and orange surfaces while dulling red and blue surfaces. It also imparts a yellowish tone to complexions. HPS lamps, the most efficient of the HID lamps, are about twice as efficient as fluorescent lamps. They have wattage ratings from 35 to 1000 W. On the other hand, low-pressure sodium (LPS) lamps have wattage ratings of only 18 to 180 W.

Characteristics of Typical Lamps

Table 8-1 lists the leading characteristics of a wide selection of typical lamps, including incandescent, PAR, R, and ER, tungsten-halogen, fluorescent, mercury, metal-halide, and high-pressure sodium.

TABLE 8-1 CHARACTERISTICS OF TYPICAL LAMPS

STANDARD INCANDESCENT LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	COLOR TEMP. (K)	INITIAL LUMENS
A-19	40	1000		490
A-19 (clear)	60	870		870
A-19	60	1000	2790	865
A-19	75	750	2840	1180
A-19	100	750	2900	1740
A-19	100	1125		1600
A-21	100	750	2880	1690
A-21 (3-way)	30	2500		305
	70	1500		995
	100	1500		1300
A-21	150	750	2960	2880
A-23	150	2500		2350
PS-25	150	750	2900	2660
PS-25 (3-way)	50	1500		580
	100	1200		1640
	150	1200		2220
A-23	200	750	2980	3910
A-23	200	2500		3400
PS-25	300	750	3010	6360
PS-30	300	2500		5200
PS-35	500	1000	3050	10,600

PAR, R, AND ER LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	INITIAL LUMENS
R-20 Spot/Flood	45	2000	440
R-20 Spot/Flood	50	2000	410
R-30 Spot/Flood	65	2000	755
R-30 Spot/Flood	75	2000	850
R-30 Spot/Flood	150	2000	1825
R-30 Spot/Flood	300	2000	3600
R-40 Spot/Flood	120	2000	1600
PAR-38 Spot/Flood	100	2000	1250

TABLE 8-1 CHARACTERISTICS OF TYPICAL LAMPS (*CONTINUED*)

PAR, R, AND ER LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	INITIAL LUMENS
PAR-38 Spot/Flood	150	2000	1730
ER-30	50	2000	525
ER-30	75	2000	850
ER-30	90	5000	950
ER-40	120	2000	1475

TUNGSTEN-HALOGEN (QUARTZ-IODINE) LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	COLOR TEMP. (K)	INITIAL LUMENS
PAR-38	50	2000		590
PAR-38	90	2500		1260
PAR-38	250	6000		3500
T-4	100	1000		1800
T-4	150	1500	3000	2900
T-4	250	2000	2950	5000

STANDARD FLUORESCENT LAMPS

BULB DESCRIPTION	WATTS	LENGTH/ SIZE (in.)	LAMP LIFE (hr)	COLOR TEMP. (K)	INITIAL LUMENS
F40T12CW/RS	40	20,000	4300	3150	48
F40T12WW/RS	40	20,000	3100	3170	48
F40T12CWX/RS	40	20,000	4100	2200	48
F40T12WW/RS	40	20,000	3000	2170	48
F40T12D/RS	40	20,000	6500	2600	48
F40T12W/RS	40	20,000	3600	3180	48
F96T12CW	75	12,000	4300	6300	96
F96T12WW	75	12,000	3100	6335	96
F9612CWX	75	12,000	4100	4465	96
F9612WWX	75	12,000	3000	4365	96

MERCURY-VAPOR (MV) LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	INITIAL LUMENS
H45AY-40/50 DX	50	16,000	1680
H43AY-75/DX	75	24,000	3000
H38BP-100/DX	100	24,000+	2865

TABLE 8-1 CHARACTERISTICS OF TYPICAL LAMPS (*CONTINUED*)

MERCURY-VAPOR (MV) LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	INITIAL LUMENS
H38JA-100/WDX	100	24,000+	4000
H38MP-100/DX	100	24,000	4275
H39BN-175/DX	175	24,000	5800
H39KC-175/DX	175	24,000+	8600
H37KC-250/DX	250	24,000+	12,775

METAL-HALIDE (MH) LAMPS

BULB DESCRIPTION	WATTS	LAMP LIFE (hr)	COLOR TEMP. (K)	INITIAL LUMENS
M57PF-175	175	7500	3600	14,000
M58PH-250	250	10,000		20,500
M59PK-400	400	1500	3800	34,000

HIGH-PRESSURE SODIUM (HPS) LAMPS

BULB DESCRIPTION	WATTS	COLOR TEMP. (K)	INITIAL LUMENS
S68MTR-50	50	24,000	3800
S54MC-100	100	24,000	8800
S55MD-150	150	24,000	15,000

Residential Lighting Design

Good lighting design provides a suitable “brightness pattern” for each room based on the recommended average footcandles of incident light on the floor of the room to be illuminated. The principal factors to be considered for satisfactory room lighting are the following.

- *Room dimensions:* ceiling height and floor area
- *Architectural or structural features* that can affect lighting
- *Reflectance, diffusion, and absorption of light* by ceilings, walls, floor, and furnishings
- *Proper selection of luminaires* by evaluating their light distribution, efficiency, decorative value, elimination of glare, and economy
- *Height and spacing of luminaires* within rooms based on room function

Luminaires, receptacles, and switches should be distributed among many branch circuits in homes or offices to provide alternative light sources if one branch is disabled by a short circuit or overvoltage. Enough light should be available from alternative sources in the same or adjacent rooms to permit the occupant or occupants to correct any obvious faults in the disabled branch circuit and still reach the loadcenter safely to restore power.

Lighting design includes the estimation of lighting loads as well as the power requirements of all major appliances and building services. Because of the variables in these estimates, the lighting loads should be slightly overestimated to provide excess capacity for safety reasons. As a rule of thumb, it is recommended that no branch circuit be loaded for more than 80 percent of its capacity. The total ampacity in volt-amperes for 15-A lighting circuits is 15 A × 120 V AC = 1800 VA. Thus, if the 80 percent rule is followed, the maximum initial connected load should not exceed 1440 VA.

Luminaires should be selected that provide the highest comfort level and performance appropriate for the room being lighted. This information is conveyed to builders and electrical contractors by drawings, schedules, notes, and specifications.

Figure 8-12 is a scale drawing of a lighting plan for a home. It shows the location of permanent ceiling luminaires (indicated by the cross-in-circle symbols), and their wiring to switches as indicated by curved dotted lines. This floor plan also shows the approximate locations of receptacles and other electrical devices, and gives branch-circuit ratings.

The locations of lighting fixture symbols on floor plans, keyed with a luminaire schedule or written specifications, gives the electrical contractor enough information to bid successfully on the electrical work. In addition to the contract documents that also guide the contractor, luminaire manufacturers typically provide specific instructions on the shipping cartons for installing their products.

A *luminaire schedule* is an important specifications document that identifies the graphic symbols used to designate the positions of each permanently installed luminaire specified. It also identifies the manufacturer and gives the catalog number, operating voltage, and mounting method: surface-mounted, recessed, or wall-mounted.

An architect or electrical contractor might prepare separate detail drawings of unusual or custom-made luminaires designed specifically for a home or office. These drawings will save time in the estimation process and make it easier and less time-consuming for the electrician in the field to install the luminaire the way it is intended.

Permanently installed luminaires such as ceiling domes, wall sconces, and track and recessed lighting can provide enough general illumination for normal movement about the room and the performance of routine tasks. The presence or absence of natural lighting from windows or skylight must be factored into the design. However, the illumination level from either ceiling luminaires or natural light is usually insufficient for activities such as reading or writing. This light can be supplemented by table, floor, and desk lamps.

Lighting design is not a completely scientific process because it involves human perception, tastes, and moods. Satisfactory lighting for children and youth might not be acceptable for seniors because of differences in their visual acuity. In addition, the colors and textures of floors, walls, and ceilings affect the selection of appropriate luminaires.

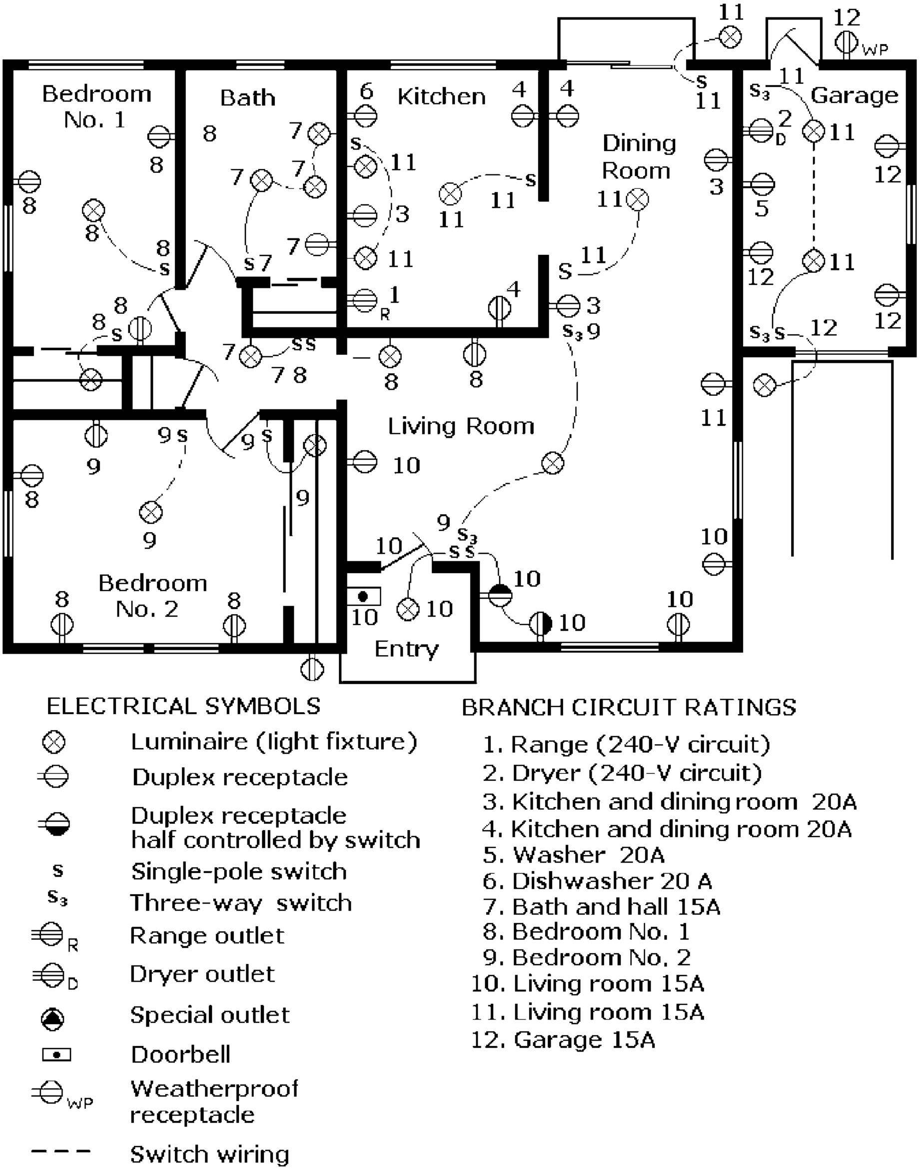


Figure 8-12 Luminaires are identified by the cross-in-circle symbol on a wiring diagram for a two-bedroom home.

Types of Lighting

Ambient lighting is natural lighting provided by windows supplemented by ceiling- or wall-mounted luminaires at various times. However, it is supplied artificially by lamps and luminaires at night. Floor and table lamps, considered to be *task lights,* usually cannot be the prime sources for ambient lighting at night because of their limitations and the fact that they leave parts of the room in darkness. The amount of ambient light required in a room depends on the activities that take place in that room and the color of its walls. Dark walls absorb more light than white or off-white walls, increasing the lumens required. Kitchens and bathrooms need bright, uniform ambient lighting, but more subdued ambient lighting is acceptable in bedrooms and hallways.

Task lighting from floor, table, and desk lamps supplements ambient lighting by providing secondary light to rooms for occupants performing some activity calling for high visual acuity, such as reading, sewing, preparing food, shaving, or applying makeup. Task lights are positioned to illuminate kitchen and bathroom counters and sinks, desks, and workbenches. The sources can be incandescent, halogen, or fluorescent lamps.

Kitchens require direct light on countertops where food is being prepared. This can be achieved with lamps mounted under kitchen cabinets, recessed ceiling lamps, or ceiling-mounted track lights focused on counters. Supplemental light on range tops can give shadow-free illumination on food being prepared. Kitchen task lighting should have color tones that make food appear as natural as it would in daylight.

Good lighting around bathroom mirrors eliminates facial shadows on persons shaving or applying makeup. These task lights should also be carefully selected to enhance skin tones. In bedrooms, living rooms, and home offices, task lighting from table or floor lamps and wall-mounted luminaires should provide enough light to eliminate eyestrain while reading, writing, studying, or doing intricate hobby work such as sewing or embroidery.

Accent lighting enhances decorative or architectural features by selectively illuminating such features as fireplaces, paintings, sculpture, plants, or aquariums. Wall-washers, uplights, sconces, and recessed and track lights are examples of luminaires intended to illuminate walls or soften the stark appearance of furniture.

Luminaires and Lighting Systems

The International Commission on Illumination (CIE) has classified luminaires for general industrial, commercial, and residential lighting according to the percentage of light that is distributed above and below the horizontal, as follows:

Direct	0 to 10% upward, 90 to 100% downward
Semidirect	10 to 40% upward, 60 to 90% downward
General diffuse	40 to 60% upward, 40 to 60% downward
Semi-indirect	60 to 90% upward, 10 to 40% downward
Indirect	90 to 100% upward, 0 to 10% downward

Light is distributed by transmission, reflection, and diffusion. For example, it can be transmitted directly from either clear or frosted lamps, or it can be reflected by lamps containing aluminized parabolic and spherical surfaces. In addition, light from any lamp can be reflected by metal reflectors that are part of the luminaire. These reflectors can be formed into parabolic or spherical shapes by stamping or drawing, or into cylindrical or flat shapes by rolling or bending.

External metal reflectors can be made from polished aluminum or chromium-plated brass or steel. They can also be made from any sturdy metal finished with aluminum paint or white enamel capable of withstanding the heat emitted by the lamps.

Many different kinds of lamps have internal etched, frosted, or phosphor-coated surfaces that diffuse light to eliminate annoying glare. In addition, frosted lenses, domes, or panes of glass or plastic built into luminaires can supplement this lamp diffusion. Lamp shades made from fabric or plastic also enhance diffusion. Translucent shades in various colors can enhance room decor, while opaque shades conceal the lamp while focusing the light downward and upward in conical beams.

The number of different styles of commercial luminaires is astonishing. They can distribute light in any of the five general patterns ranging from direct to indirect. Some common luminaires styles are the following.

- *Ceiling domes* are permanently mounted flush with the ceiling for general direct illumination. They typically have one or two 100- or 150-W incandescent lamps or fluorescent or halide lamps that provide the equivalent light output. The translucent glass domes can be removed for relamping and cleaning. Ceiling domes are typically installed in bedrooms, hallways, dens, and laundry rooms. The wattage of the lamps within is restricted by the need to dissipate the heat from the lamp or lamps because the domes are mounted flush with the ceiling and have no air circulation vents.
- *Close-to-ceiling domes* are similar to ceiling domes and also provide semidirect lighting, but they are mounted 6 to 12 in. below the ceiling and allow air to circulate around the lamp or lamps for cooling. They can accept higher-wattage lamps to provide more light than ceiling domes because they are better able to dissipate heat.
- *Wall sconces* are mounted on walls for general diffuse and semi-indirect ambient or accent lighting. They can have various shapes such as half-domes of metal or translucent glass that are removable for cleaning and relamping. These luminaires can direct light upward or downward, but some also radiate diffused light in all directions. With proper lampholders, they can accept incandescent or halogen bulbs up to 200 W, because their open ends permit the heat from lamps to dissipate.
- *Uplights* and *wall-washers* illuminate the ceilings. Some wall-washers are mounted on the ceiling to direct light downward, accenting artwork or features such as fireplaces.
- *Eyeballs* are small round luminaires that are recessed in the ceiling. They are so named because they look like eyes with eyelids. They can be focused on any object in the room by adjusting the "lids," so they are widely used for accent lighting.
- *Recessed lights* provide direct ambient or task light. They are mounted flush with the ceiling in holes cut into the gypsum ceiling board. Round recessed downlights are also called *cans* or *high-hats.* Larger square or rectangular downlights, called *troffers,* usually contain incandescent or halogen reflector lamps. Units with prewired junction boxes and adjustable hangers such as the one shown in Fig. 8-13 are installed during new construction. These luminaires can accept R or PAR incandescent or halogen bulbs rated for 75 to 90 W. Others versions with expandable clamps can be inserted in holes cut in finished ceilings. After the assembly is inserted in the ceiling

cutout, the clamps expand to grip the back surfaces of the ceiling board and clamp them in position. Recessed lights are widely installed in pairs, threes, quads, or more in kitchens, living rooms, family rooms, and dining rooms.

- *Track lights* have multiple incandescent, halide, or fluorescent lamps enclosed in canisters mounted on swivel joints so that they can be positioned to direct the light in different locations. The canisters are mounted on a length of track containing internal conductor rails that can be attached to a wall or ceiling. Each canister can be positioned independently along the track and swiveled to focus it up or down on selected objects within the room. Some can be rotated through nearly 360°, but they are restrained by their mounting brackets from full rotation. After focusing, the canisters can be locked in position. Track lighting can provide ambient, task, or accent lighting. It can be installed during new construction, but kits are available for attaching it later to finished ceilings. Low-voltage track lights are available, but they require transformers. These can be part of the assembly or located remotely.
- *Pendants* are a general class of permanently mounted luminaires that are suspended from the ceiling by chain, pipe, or cable. They can have opaque metal or metal and translucent glass parabolic reflectors or globes. Their lamps can be incandescent, halogen, or fluorescent, and their illumination is usually direct or semidirect.

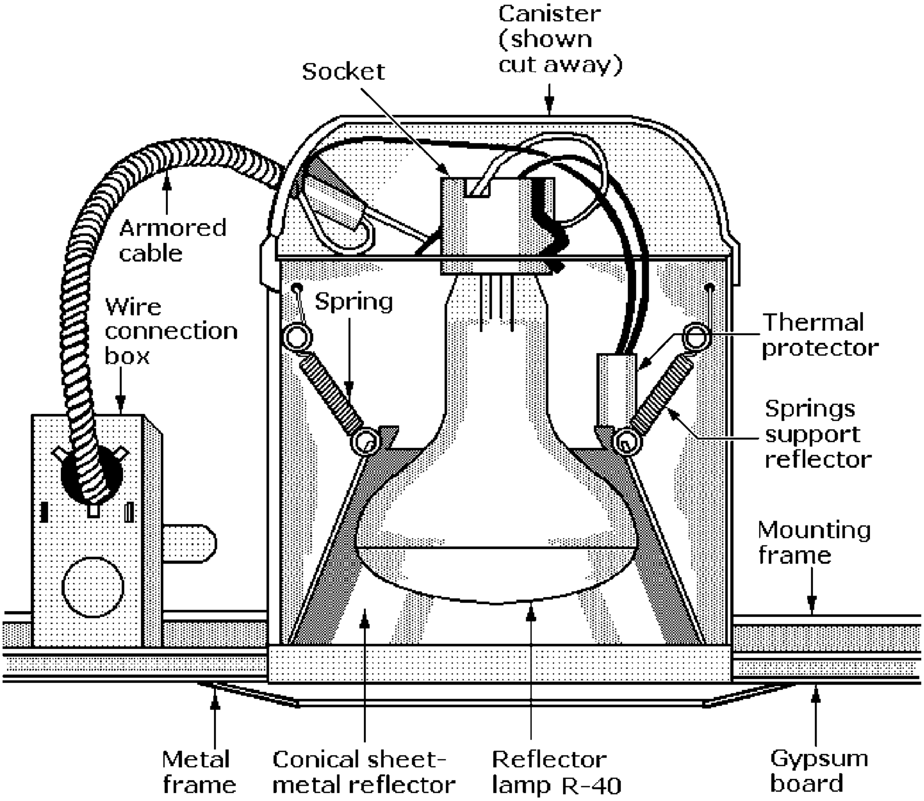


Figure 8-13 Cutaway view of a recessed luminaire installed in a ceiling.

- *Chandeliers* are a subclass of pendant luminaires designed to be esthetically pleasing as well as light sources. Frequently intended as focal points in room decoration, they are usually installed in dining rooms over dining tables or in entryways near the front door. They are particularly effective in two-story or cathedral-style entryways. Chandeliers typically include crystal or polished brass elements and are multilamped, with flame-shaped miniature incandescent lamps to mimic classical candelabra. These lamps are typically rated for 30 to 40 W, and can be tinted or clear so the filaments can be seen so they impart a warm flamelike glow. Their overall light output is the sum of the lumen values of the individual lamps, which form a generally diffuse light pattern.
- *Floor-standing lamps* have lamps mounted on poles 4 to 5 ft high but otherwise have the same attributes as table lamps, including portability. They can provide uplighting in dark corners of rooms or they can provide downlighting for reading or performing other precise tasks where there is no suitable furniture for supporting a table lamp.
- *Torchieres* are a subset of floor-standing luminaires designed primarily for uplighting. Some have translucent or opaque parabolic reflectors positioned for indirect or semi-indirect uplighting. Torchieres depend on the reflective surfaces of the ceiling to distribute illumination, and typically contain one or two incandescent or halogen lamps rated for as much as 200 W.
- *Table lamps* are movable cord-connected luminaires that are placed on tables or desks primarily to provide task downlighting in living rooms, family rooms, and bedrooms. Many are lamped with three-way incandescent lamps rated for 50, 100, or 150 W or their CFLs. Decorative table lamps are made in a wide variety of styles with choices of metal, ceramic, or novelty. Lamp shades are available in a wide variety of materials and range of colors from translucent to opaque, permitting them to be color-coordinated with any desired room decor.

ARCHITECTURAL LUMINAIRES

Architectural luminaires are custom-designed and -built fixtures that offer features not available in commercial luminaires. They can be built to fit specific locations or perform desired functions as well as provide unusual visual effects. These luminaires can be made from wood, metal, or plastic decorative elements and they can include standard lamp sockets, lampholders, wiring, switches, and miscellaneous fittings.

Examples of these are wall-, drapery-, and shelf-lighting valences, luminous ceilings, and units that are mounted under cabinets to increase illumination over kitchen or bathroom counters. The simplest, a soffit, can be made from a fluorescent fixture base pan with lampholders and ballast, shielded by a custom-made panel to match the decor.

- *Soffits* are architectural luminaires that direct light downward. They wash walls and provide general lighting in rooms with low ceilings. Soffits can be used for direct lighting over a counter or a table in a work area. Recessed soffits can be installed between joists that run parallel to a wall.

- *Valences* are architectural luminaires that direct light both upward and downward to provide general lighting and wall-washing. The top of a valance can be aligned with the tops of windows and doors.
- *Coves* are architectural luminaires that direct light upward. They are recommended for rooms with high or vaulted ceilings and above kitchen cabinets. The top of a cove should be at least 18 in. from the ceiling and its base at least 6 ft 8 in. from the floor. In kitchens where clearance space between the tops of cabinets and the ceiling is 12 in. or more, coves can be mounted on top of the cabinets.
- *Baffles* and *diffusers* are commercially available elements that can shield bare lamps without blocking all of their light. They should shield lamps from the view of persons standing or sitting in normal positions or standing on landings overlooking the room. Baffles are parallel blades available in different sizes, finishes, heights, and spacing.
- *Louvers* or *egg crates* with typical cell sizes of ½ × ½ × ½ in. deep can be cut to fit from 2-ft × 4-ft sheets. Acrylic and metal louvers are better than those made from polystyrene because the latter yellow with age. Louver finishes are white, silver, and gold.
- An array of fluorescent fixture base pans with lampholders and ballasts for either T8 (1-in.-diameter) or T12 (1½-in.-diameter) fluorescent tubes can be fastened to the permanent ceiling in rows or columns to form all or part of a drop ceiling. A matrix of supporting framework can be suspended 1 ft or so below the ceiling. Translucent plastic diffuser panels can be set in the frames under the lighting fixtures, and commercial ceiling panels can be set in the remaining frames. Separate switches for each row of lamps can provide high and low light settings.
- Shields or skirts can be made for custom-built luminaires from finished lumber, plywood, or metal. They should be wide enough to mask any bare lamps from the view of persons sitting or standing in the room, as described for baffles or diffusers. They can be can be fastened directly to ceilings, walls, or the undersides of cabinets with adequate provision for air circulation around the lamps, and they should not interfere when relamping. The shield interiors can be finished with reflective white paint, and their exteriors can be stained, painted, or covered with fabric to match the decor.

SELECTION OF LAMPS, LUMINAIRES, AND CONTROLS

The following advice, based on the experience of professional lighting designers, is offered as practical guidance in planning lighting schemes.

- Specify electronic fluorescent lamp ballasts instead of lower-cost magnetic ballasts because they virtually eliminate the flicker and hum of magnetic ballasts, are lighter in weight, and improve the efficiency of the fluorescent lamps, thus conserving energy.
- Consider compact fluorescent lamps (CFLs) with screw-type bases as substitutes for incandescent lamps. They fit many simple ceiling-mounted luminaires and table lamps and are more economical to operate than incandescent lamps. Take advantage

of their low heat emission and energy-saving characteristics in hallways, bedrooms, and living rooms, and in rooms with low ceilings. They are also suitable for porch, post-top, and small-yard lighting when low light output is acceptable. Their merits and shortcoming were discussed previously under "Fluorescent Lamps."

- Purchase luminaires with opaque or translucent parts that completely mask bare lamps from the view of persons standing or normally seated in the room, to prevent them from seeing the annoying glare from the lamps.
- Purchase IC-rated recessed luminaires approved for installation in insulated ceiling or roof cavities. Luminaires with this rating are designed so that no fire hazard will result if the insulation surrounds the luminaire canister. Luminaires manufactured to restrict air leakage through the tops of the canister are labeled *performance tested.*
- Consider luminaires containing linear, long twin-tube, or circular fluorescent lamps for kitchens, playrooms, home offices, and utility rooms.
- Position linear incandescent or fluorescent lamps vertically in bathrooms on both sides of the mirror and above light-colored counters to provide shadow-free illumination of the face. They can be in separate luminaires or built into mirrors or medicine cabinets.
- Use track lighting where flexibility or accent lighting is important. If the canisters do not have built-in reflectors, use halogen reflector lamps. Position the track heads so their lamps cannot be seen by persons standing or seated normally in the room.
- Install wall-mounted luminaires more than 6 ft 8 in. from the floor or be sure that they do not extend more than 4 in. from the wall, to prevent people from accidentally bumping into them.
- Install junction boxes for wall sconces at least 5 ft 9 in. above the floor, to prevent people from accidentally bumping into them.
- Halogen PAR flood lamps are the most efficient lamps for lighting large indoor or outdoor areas. Combination PAR lampholders and motion detectors are available for use outdoors for nighttime security. The motion detectors switch on one or more PAR floodlights when motion is sensed. Photocells within these luminaires deactivate them at dawn and activate them at dusk.
- Consider metal-halide (MH) lamps rather than other high-intensity discharge (HID) lamps for lighting large areas over extended periods. High-pressure sodium (HPS) lamps emit objectionable red-orange light; mercury vapor (MV) lamps are less efficient than MH lamps, and their emission color is only slightly better than that of HPS lamps. All HID lamps require compatible ballasts and need a warmup time of a few minutes before their illumination reaches full intensity.
- Low-voltage landscape, walkway, and driveway lighting poses fewer shock hazard problems than 120-V AC systems, but solar-powered lighting, if practical for the location to be illuminated, eliminates the need for wiring them to a power source.
- Floodlights mounted high on buildings or poles and focused at shallow angles provide the widest light distribution. Avoid aiming floodlights at nearby neighbors' windows or yards, because it can annoy them and others working or playing in their yards.
- Luminaires with an Underwriters' Laboratories (UL) *wet location* listing can withstand prolonged exposure to the weather, but those with *damp location* listings should be sheltered in locations such as covered porches to protect them from rain and snow.

- Install wall switches that will be used by children or handicapped people in wheelchairs less than 4 ft above the floor for convenient access. (In this location they will not interfere with the edges of gypsum wallboard edges and seams.)
- Place switches at room entrances on the wall closest to the door knob so that they can be found easily in a dark room just as the door is opened. Install three- or four-way switches in rooms with two or more entrances, particularly if they are widely separated.
- Install door-actuated switches for turning on lamps in clothes closets. These spring-loaded switches should be mounted on the inside face of the jamb. Opening the door turns the light on and closing it turns the light off.
- Install a switch with an illuminated toggle or LED indicator to control ceiling or wall lamps that cannot be seen from the switch location. They will indicate that the light has been left on. These switches can control a porch light from indoors and basement lights from the landing at the top of an enclosed stairway. There should be a separate switch for each basement light.
- Install occupancy sensors for shutting off the lights in rooms that are infrequently occupied, and timers for controlling bathroom heat lamps that are intended for short-duration operation. However, timers are not appropriate for shower rooms or other rooms where people could be stranded in the dark if the lights turn off.

ILLUMINATION DATA FOR HOME LIGHTING

There are many methods for calculating the illumination requirements for rooms in homes, offices, and commercial, industrial, and public buildings. In using the simplified *lumens per square foot method* described here, it is important to remember that the color of the walls and ceilings of rooms will have a profound influence on determining a suitable lighting plan. In this method it is assumed that the ceilings and walls of all rooms are papered or painted in white or off-white to provide the highest reflectance.

The Illuminating Engineering Society of North America (IESNA) has established a range of illumination levels for various tasks or activities and the size and characteristics of the room in which they will be carried out. The variables include:

- The nature of the task/activity and its dependence on high illumination
- The age of the person(s) performing the task/activity
- The wall/ceiling reflectances of the room
- Requirements for timely completion of the task/activity
- Requirements for precision or accuracy in the task activity

Illumination levels for dining, conversation, listening to music, and watching TV need not be as high as for general reading. On the other hand, activities such as reading for long periods, sewing, or doing detailed hobby or artwork call for more intense illumination.

Illuminance categories for various activities are assigned a letter from A to I: A represents the lowest value for general lighting in noncritical areas, and I represents the illuminance requirements for specialized and difficult tasks. Prepared tables give the illuminance categories for selected activities and the corresponding range of illuminances that are recommended for each category. Another table gives illuminance values for general lighting throughout a room (categories A to C) and task illuminance (categories D to I). These values are in lux units but can be converted to footcandles by dividing by 10.

For residences, general lighting is in category B, dining room and hallway lighting is in category C, while lighting for bathrooms, noncritical kitchen tasks, and normal reading is in category D. Category E is assigned to lighting calling for high levels of illuminance.

Table 8-2 gives the recommended illuminance values for residential rooms in homes in lumens per square foot (lm/ft^2) and footcandles. The recommended values are based on the assumption that table lamps, floor lamps, and other movable light sources will be contributing to the lumens provided by permanent luminaires. However, the recommended footcandle values are fixed and will apply regardless of the kinds of luminaires used. If walls are paneled with dark wood or papered or painted in dark blue or green, the value of lumens per square ft in this table should be increased by at least 25 percent.

Calculations for Room Lighting

Residential lighting circuits must conform to the NEC, local and state, and even local electric utility codes. Complete coverage of luminance calculations and the publication of the necessary reference tables is beyond the scope of this handbook. For this information the reader should consult publications from the Illuminating Engineering Society of North America (IESNA) or the *Electrical Engineer's Portable Handbook* and the *Standard Handbook for Electrical Engineers,* both published by McGraw-Hill.

TABLE 8-2 LIGHTING REQUIREMENTS FOR HOMES

ROOM	lm/ft^2	fc
Living room	80	70
Family room	80	70
Dining room	45	70
Kitchen	80	70
Bathroom	65	50
Bedroom	70	30
Hallway	45	30
Laundry	70	50
Workshop	70	70

There are both long- and short-form methods for calculating illuminance. The coverage of this subject in this book is limited to a simplified method for determining the number and kind of luminaires needed for various rooms in a residence, but general formulas are given for more rigorous methods.

With a plan view of a home such as the one shown in Fig. 8-12 drawn to scale, general illumination planning can be done without making actual measurements. If the floor plan is drawn to a standard architectural scale such as ¼ in. = 1 ft, a scale rule can be used to obtain room measurements directly from the drawing. For example, if a rectangular living room is found to measure 14 × 19 ft, multiplying these numbers together gives a floor area of 266 ft^2. From Table 8-2 a value of 80 lm/ft^2 is recommended value for living rooms. Multiplying the value of lm/ft^2 by the floor area gives the total requirement in lumens: 80 × 266 = 21,280 lm. By referring to luminaire specifications in manufacturers' catalogs, one or more luminaires can be selected that will give a close approximation of that lumen output.

ZONAL CAVITY (LUMEN) METHOD

The number of luminaires required to light a space to the desired illumination level in footcandles rather than lumens can be calculated with a knowledge of the characteristics of the room and light sources. The formula for calculating illumination by the *zonal cavity (lumen) method* is presented here to illustrate another method for calculating illumination. (*Note:* The inclusion of all the data tables necessary for making practical use of this equation is beyond the scope of this handbook.)

$$\frac{\text{Area}}{\text{Luminaire}} = \frac{N \times \text{lumens/lamp} \times \text{CU} \times \text{LLF}}{E}$$

where N = number of lamps, CU = coefficient of utilization, LLF = light loss factor, and E = footcandles required.

- *Footcandle* recommendations are found in tables and typically vary from 5 to 20, depending wall and ceiling surface colors and the brightness of the surroundings.
- *Coefficient of utilization* (CU) is a factor for determining the actual lumens from a luminaire that reach the work surface. It accounts for losses in lumens due to conditions within the room and depends on the luminaire selected, room size, and surface reflectance. CUs are included in manufacturers' product catalogs.
- *Light loss factor* (LLF) is a fraction representing the amount of light that will be lost over time due to dust, dirt, and normal lamp depreciation. An average factor of 0.9 is valid for most indoor locations. It is also dependent on ambient temperature.

The preceding formula can be rewritten to find the number of luminaires or to determine the footcandle level:

$$\text{Number of luminaires} = \frac{\text{footcandles required} \times \text{room area}}{N \times \text{lumens/lamp} \times \text{CU} \times \text{LLF}}$$

$$\text{Footcandles} = \frac{N \times \text{lumens/lamp} \times \text{CU} \times \text{LLF}}{\text{area/luminaire}}$$

For general ambient lighting in a room, values range from 30 to 70 footcandles (fc), but for performance of typical visual tasks including reading newspapers and magazines the value could be as high as 200 fc. Values greater than 200 fc are recommended for sewing, reading for prolonged periods, and doing intricate hobby craftwork.

Residential Room Lighting

Architects of development houses usually select the locations for switches, receptacles, and luminaires at a quality and price level determined by the builder. However, purchasers of architect-designed, custom-built homes usually have an opportunity to decide on the selection of luminaires and exert some influence over price, quality, and locations that suit their preferences.

In either case, the homeowner must provide the task and accent luminaires needed to supplement the lumens from the permanent ambient luminaires to arrive at the recommended illumination levels. Dimmer switches give the homeowner additional control over the illumination, permitting it to be varied according to the desired mood for the room—bright for parties and festive occasions and subdued for relaxation.

FAMILY ROOM LIGHTING

The family room is the recreation and entertainment center in modern homes. Lighting plans for these rooms closely resemble those for living rooms. Lighting will include permanent lighting fixtures supplemented by task and accent luminaires. Accent lighting can highlight such features as pictures and bookcases. According to Table 8-2, family rooms should have 70 fc of illumination.

Family rooms typically include a sofa, various upholstered chairs, and perhaps a table with chairs for reading, playing games, studying, or doing homework. Three-way table and floor lamps providing 800 to 1700 lm with incandescent or fluorescent lamps can supply the necessary task lighting. Dimmer-equipped recessed or track lighting permits the illumination level to be adjusted for glare-free TV or computer-screen viewing.

DINING ROOM LIGHTING

Dining rooms or spaces typically have a chandelier mounted directly above the likely position of the dining table. It is likely to be the centerpiece of the room as well as the principal source of ambient illlumination. According to Table 8-2, ambient lighting should be 70 fc. A wall-mounted dimmer will permit the light from the chandelier to be controlled to set the mood of the room. Most dining rooms have supplementary lighting at the buffet or sideboard that can be provided by sconces or table lamps.

KITCHEN LIGHTING

The IESNA recognizes the need for two levels of task lighting in a kitchen: category D for general lighting and category E for such critical tasks as reading labels and recipes, and slicing and dicing food. According to Table 8-2, 80 lm/ft^2 is recommended for kitchens. In modern kitchen lighting design, a central dome luminaire is supplemented by recessed lights. Under-cabinet luminaires are widely used to increase countertop illumination.

BATHROOM LIGHTING

Bathrooms need bright general lighting that can be supplied by permanent wall or ceiling-mounted luminaires with incandescent or fluorescent lamps mounted above or around the mirror. According to Table 8-2, ambient bathroom lighting should be 70 fc. For effective illumination in large bathrooms, it is common to have a row of recessed lights in the ceiling. Fan-light combinations are also used above bathtubs and showers to remove steam and water vapor rapidly. Some bathrooms are fitted with infrared heat lamps to assist in after-bath drying and to supplement room heating during cold weather. These lamps can be controlled by a timing switch that shuts them off after a set period.

BEDROOM LIGHTING

Modern bedrooms typically have ceiling dome lights for general-purpose lighting and separate task luminaires for bedside tables or bed headboards. According to Table 8-2, ambient bedroom lighting should be about 30 fc. An overhead light in a walk-in closet controlled by a doorframe switch avoids fumbling for a light switch in the dark. Light for reading in bedrooms is typically provided by adjustable reading lamps with incandescent or halogen bulbs on bedside tables on both sides of queen- and king-size beds.

Bedrooms with twin beds are likely to have a dual-lamp luminaire with separate switches on a night table between the beds. Bedrooms often have a floor lamp or torchieres to provide subtle accent lighting effects. They could provide enough light for reading if placed next to chairs located in the bedroom. A table lamp can usually provide adequate lighting for a large mirror on a bedroom bureau.

NEC 2002 includes requirements for the installation of closet lighting to prevent fires because of the close proximity of hot lamps to combustible clothing, blankets, or storage boxes in a confined space. The following statements are made about clothes closet lighting installations:

- "On the wall above the closet door, provided the clearance between the fixture and a storage area where combustible material may be stored within the closet is not less than 18 in."
- "On the ceiling over the area which is unobstructed to the floor, maintaining an 18 in. clearance horizontally between the fixture and a storage area where combustible material may be stored within the closet."
- "Pendants shall not be installed in clothes closets."

LAUNDRY ROOM LIGHTING

Laundry rooms are separate rooms or spaces on the first floors of homes where a washing machine, clothes dryer, utility sink, and perhaps an ironing board are located. The recommended ambient lighting for these rooms is 50 fc, primarily from ceiling or wall-mounted luminaires, to minimize the shock hazard presented by the close proximity of a sink and plumbing and metal appliance cabinets if a ground fault should occur.

BASEMENT LIGHTING

The basements of most new homes are unfinished, so their lighting requirements are usually met with porcelain lampholders fastened to overhead joists or finished ceilings. Lampholders installed on ceilings above stair landing are controlled by three-way switches, while those located strategically around the basement are actuated by pull-chain switches. They are generally placed at enough locations to assure a minimal level of illumination throughout the entire basement.

Specific locations for lampholders are over the main circuit breaker or loadcenter, furnace, and hot-water heater to provide enough light for routine maintenance or parts replacement. Other recommended locations are over the utility sink and a possible site for a workbench. GFCI wall receptacles for powering tools or other service equipment must be fastened to studs. The lampholders will be in a 15-A branch circuit, but the receptacles might be in a 20-A circuit. Exposed NM cable for the lamps and receptacles must be stapled to the joists. The easy accessibility to these cables and lampholders simplifies the task of adding luminaires or receptacles if the basement is ever finished.

LIGHT DIMMER APPLICATIONS

As discussed in Chap. 6, there are three kinds of dimmers: incandescent lamp, fluorescent lamp, and fan speed controls. Incandescent dimmers should not be used to dim standard fluorescent tubes or low-voltage lighting or to control ceiling fan speed, because their “chopped” current output can damage them. Also, receptacles should not be controlled by incandescent dimmers because fans, vacuum cleaners, power tools, and other inductive loads that might be plugged into them could be damaged. However, some compact fluorescent bulbs with integral electronic ballasts marketed as incandescent lamp replacements can be safely controlled by incandescent dimmers if the manufacturer states this on the lamp cartons.

High-quality dimmers have built-in radio frequency interference (RFI) filters to suppress any radio frequencies they might emit. A filter including a choke coil and capacitor network can eliminate most RFI caused by a dimmer. Dimmers rated to 600 W have bar coil filters, while those in the 800- to 2000-W range contain more effective toroidal filters. Precautions taken to minimize or eliminate the effects of RFI from dimmers include keeping audio and microphone cables away from dimmer wiring, the use of low-impedance microphone cables and shielded audio cables, and the proper grounding of all equipment.

SINGLE-POLE AND THREE-WAY DIMMERS

Single-pole incandescent dimmers can replace single-pole switches and still provide on/off switching as well as lighting control from one location. Three-way dimmers can be used in a three-way circuit for lighting control from two locations. Only one three-way dimmer is needed with one three-way switch, but dimming is possible from only one location.

DIGITAL LIGHT CONTROLS

Digital lighting control is a new development that is an improvement over existing lighting controls for a wide range of applications. Digital dimmers provide soft-on, fade-off switching as a result of their internal microcontroller chips. When turned on, illumination gradually increases to the selected levels; when they are turned off, light gently fades.

Outdoor Lighting

POOL AND FOUNTAIN LIGHTING

Swimming, wading, and decorative pools and fountains present special problems for lighting designers. Outdoor lighting must be capable of functioning properly under all weather conditions and wide temperature excursions, but electrification near bodies of water requires additional safeguards. It is imperative that all luminaires and wiring suitable for use near these installations be made to withstand long-term exposure to a wet environment. They must also incorporate features that eliminate the possibility of electrical shock to persons in or near them. An electric shock can be received near these installations in several ways, because electrical potentials exist with respect to ground and within the water itself.

Any person in the pool who touches a faulty energized metal enclosure is subject to possibly fatal electrical shock because his or her body will conduct current through the water and pool to earth. For this reason NEC 2002, Article 680, "Swimming Pools, Fountains, and Similar Installations," covers the requirements for the construction and installation of electrical equipment in and around swimming pools and similar installations to minimize shock hazards.

While this chapter focuses on lighting, Article 680 also covers other electrical equipment installed near pools, including transformers, heaters, water circulating systems, and fans. Because of the complexity of the provisions in Article 680, only highlights are presented here. It is expected that anyone contemplating the installation of any electrical equipment in or near pools or hot tubs will study the provisions closely before proceeding.

The following topics are covered by Article 680:

- Transformers and ground-fault circuit interrupters (GFCIs)
- Receptacles, lighting fixtures, lighting outlets, switches, and fans
- Electric pool water heaters
- Underground wiring

- Underwater lighting fixtures
- The bonding of metallic, non-current-carrying parts of a pool installation
- Equipment grounding

RULES FOR RECEPTACLES NEAR WATER

- Receptacles are prohibited within 10 ft from the pool edge, and GFCIs must protect all 120-V AC receptacles between 10 and 20 ft from the inside walls of indoor and outdoor pools. The exception is the installation of a GFCI-protected receptacle for a cord-connected swimming pool recirculating pump. (It can be less than 10 ft but not closer than 5 ft from the inside wall of the pool.)
- At least one 120-V receptacle must be installed at residential pools within the 10- to 20-ft band to eliminate the use of long extension cords, but it can be closer if it is protected by a hinged or sliding door.

RULES FOR LIGHTING DEVICES NEAR WATER

- GFCI protection is required for existing lighting outlets on buildings adjacent to the pools, tubs, or fountains within a space that is at least 5 ft above the water and 5 ft back from the pool edge. However, this rule does not apply if the outlets are more than 12 ft above the water and 10 ft back from the pool edge. New lighting is not permitted within this space around the pool.
- All lighting fixtures must be at least 12 ft above the water level of an outdoor pool, but totally enclosed fixtures with GFCI protection in their supply circuits that have a clearance of at least 7.5 ft can be installed over indoor pools. GFCI protection is not required for all lighting fixtures set back from the pool edge at least 5 ft and mounted at least 5 ft above the deck.

Figure 4-13 illustrates the requirements for overhead conductor clearances above swimming pool water level, diving boards, or platforms and viewing stands.

UNDERGROUND WIRING NEAR WATER

Aside from the electric circuits associated with pool equipment, underground wiring must not be run within the ground closer than a 5-ft horizontal band around the pool. If this rule must be broken because of space limitations, wiring is permitted within this limit if the circuits are in approved rigid-metal, IMC, or nonmetallic conduit or galvanized steel or other corrosion-resistant steel raceways buried at the proper depth.

UNDERWATER LIGHTING FIXTURES

GFCI protection is required for all pool lighting fixtures operating between 15 and 150 V (such as 120 V), but not for fixtures operating at voltages less than 15 V (typically 12-V units). Although all lighting fixtures operating at more than 15 V must be self-grounding, the GFCIs are intended to prevent shock hazard during relamping.

Underwater lighting fixtures suitable for installation in the walls of swimming pools must be positioned not less than 18 in. below the normal pool water level, measured to the top of the lens of the fixture.

Wet-niche lamp fixtures are waterproof, so they can be installed below the waterline of the pool. The lamp is mounted within a water-filled metal housing or forming shell in the side wall of the pool, as shown in the section view Fig. 8-14. Each lamp must have a permanently attached flexible electrical cord that extends at least 12 ft outside the shell. This permits the lamp fixture to be removed and lifted to the pool deck for servicing or relamping. As a result, the pool does not have to be drained and the fixture does not have to be disconnected from its power source. Fixtures that operate at 120 V AC must be connected by three-conductor (two insulated wires plus ground) cable through approved conduit between the forming shells and junction boxes; those operating at 12 V AC must be connected between the forming shells and the low-voltage transformer boxes.

The conduit can be made of an approved corrosion-resistant metal or nonmetallic material. Nonmetallic conduit must contain a No. 8 insulated stranded copper wire for bonding. All forming shells at a pool must be connected by No. 8 solid copper bonding conductor to a pool bonding grid.

Dry-niche lamp fixtures are luminaires that are permanently installed in the pool wall. They are designed for servicing from the rear in a passageway behind the pool or from a "deck box" set in the pool deck.

BONDING OF METAL POOL PARTS

If the swimming pool has underwater lighting fixtures, all associated electrical equipment such as circulating pump motors and lighting fixtures must be bonded together

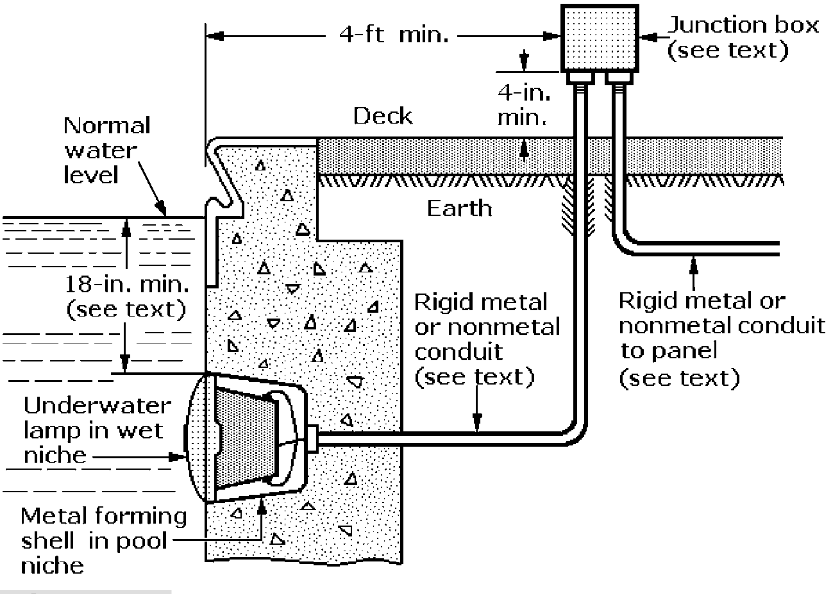


Figure 8-14 NEC-approved installation of an underwater swimming pool lamp.

and grounded. In addition, all non-current-carrying metal parts such as lighting fixture shells, transformer enclosures, water piping, conduits, and ladders within 5 ft of the pool and less than 12 ft above the pool must be bonded together and grounded to the pool's reinforcing bars. The bonding must be done with No. 8 solid copper bare or insulated wire. However, if the pool does not have underwater lighting, only the pump motor circuit requires bonding and grounding.

OUTDOOR FLOODLIGHTING

The specification of lamps and luminaires for effective outdoor floodlighting depends on the size, shape, and color of the objects or surfaces to be illuminated. This makes it difficult to arrive at any simple rule of thumb for floodlight planning. However, certain fundamental illumination principles must be followed in designing a suitable installation. If the floodlighting system is extensive and contains many floodlights, it is normal practice to follow a formal design procedure that includes the preparation of aiming diagrams and doing a lot of calculations.

However, a somewhat simplified design procedure called the *beam-lumen method* has been developed. This method requires the solution of only two equations and the coordination of the results. The equations, presented a little later, identify all of the data required to arrive at a solution to a specific floodlighting design problem. However, inclusion of the necessary data tables and a complete discussion of the variables involved in making practical use of these formulas is beyond the scope of this chapter. Those who wish to solve a specific design problem are advised to obtain a collection of lamp manufacturers' catalogs to study the many commercial reflector lamps available and then refer to a detailed reference on lighting design.

The dimensions required for planning the number and type of floodlights needed for a specific area to be illuminated, as well as the intended locations of the luminaires, can be measured in the field or determined from scale drawings. If the floodlights are to be placed on a nearby building, pole, or tower, its height becomes the perpendicular distance D. The illumination patterns of floodlights resulting from their location at different heights and aiming angles are illustrated in Fig. 8-15.

Lines projected from height D to the limits of the plane of the surface to be lighted are known as *beam-axis distances.* The angles between the beam-axis lines and D are known as the *aiming angles.* An average angle can be determined from these angles for calculation purposes. This value is needed to select the number and type of floodlights required and their beam widths (narrow, medium, or broad).

Comparable data must be obtained if the objective is to floodlight a vertical surface such as a wall or billboard. In this case dimension D becomes a horizontal distance from the luminaire to the plane of the vertical surface, and an average aiming angle is determined from the beam-axis lines.

The average aiming angle is measured between D and the average beam-axis line. It can be seen from Fig. 8-15 that with a 0° aiming angle the beam defines a circular spot, but as the angle increases, the round spot become an ellipse, and its area increases. If, for example, floodlights are to be mounted on a single pole to illuminate a fence along a property line, they should be mounted at different heights and focused at different

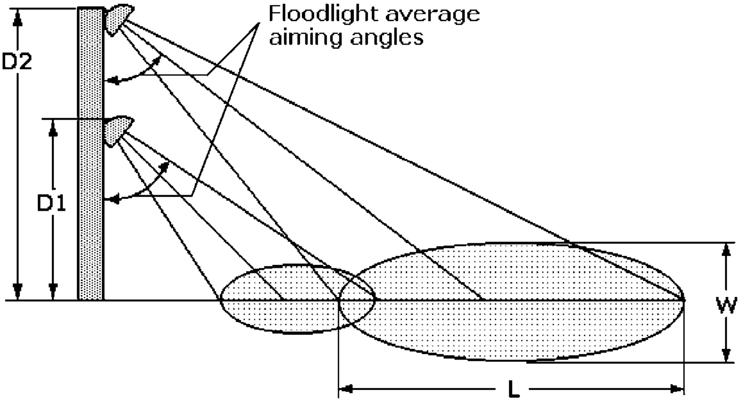


Figure 8-15 **Floodlight illumination patterns depend on their height and aiming angles.**

angles to obtain optimum coverage. However, for computation purposes an average of these various aiming angles is determined.

The first equation used in the beam-lumen method is

$$\text{Floodlights for coverage} = \frac{\text{area lighted} \times \text{coverage factor}}{\text{beam-spot area}} \qquad (1)$$

where

The *area lighted* is in square feet (horizontal or vertical surface).

The *coverage factor* is the minimum number of directions from which each point in the area can be lighted (a factor of 2 is preferred).

Beam-spot area varies as the square of the distance D, and L and W values vary as the distance D. The formula for spot area is $= \pi LW/4$.

The second equation is

$$\text{No. floodlights for footcandles} = \frac{\text{footcandles} \times \text{area lighted}}{\text{LLF} \times \text{CU} \times \text{beam lumens}} \qquad (2)$$

where

Footcandle recommendations are found in tables and typically vary from 5 to 20, depending on the coloration of the surfaces and the brightness of the surroundings.

LLF or *light loss factor* indicates the decline in light output of the floodlights due to dust, dirt, and normal lamp depreciation. An average factor is 0.7, but for extremely dirty locations it can be as low as 0.3.

CU or *coefficient of beam utilization* is the ratio of lumens lighting an area to the beam lumens. These values vary from 0.75 to 0.40 for low utilization.

Manufacturers' catalogs for projector-reflector-type (PAR) and R lamps list:

- Light output in approximate lumens
- Center-beam candlepower (CBCP)—intensity of light produced within the beam width angle in candelas
- Beam spread in degrees

Experience has shown that a floodlighting design based on a small number of floodlights with large efficient lamps is more cost-effective than a design based on a large number of floodlights with smaller, less efficient lamps. The former system is simpler to install, control, and maintain. It is also recommended that the floodlights selected have the narrowest beam spread that can be used to achieve the coverage factor requirements.

It should be kept in mind that large floodlight arrays with many lamps can be an objectionable feature on buildings or property because they are prominent and unsightly.

After selecting the desired footcandles and determining the light loss and coefficient of utilization factors, a specific floodlight can be chosen and its beam lumens can be substituted in Eq. (2). It might be determined that the desired lighting for an unusually shaped structure or an irregular plot of ground can best be achieved with different types of floodlights and different beam spreads. In this case, the surface area should be divided into sections and individual lighting design should be performed for each section.

LOW-VOLTAGE LIGHTING

A low-voltage outdoor lighting system such as the one shown in Fig. 8-16 can be designed from a wide range of available low-voltage luminaires. Commercial units can be purchased that function as walk lights, shaded flare lights, path lights, and flood lights. They can provide lighting to define walkways or driveways, illuminate patios, and accent or illuminate buildings, fountains, pools, or other outdoor objects of interest.

Complete low-voltage lighting kits are offered at prices corresponding to the number and type of lighting fixtures included. The kits all include the 120-V AC to 12-V AC transformer with a built-in timer that permits the lights to be switched on and off according to a precise program. The wiring for low-voltage lighting system wiring is discussed in Chap. 7.

Low-voltage luminaires are designed to accommodate miniature wedge-base incandescent or halogen lamps with ratings from 11 to 20 W. However, some floodlights are rated for as much as 50 W. Outdoor low-voltage lighting kits typically contain six to eight fixtures, but more can be added.

All styles and types of outdoor low-voltage luminaires are mounted on a base stake that permits them to be positioned vertically by pressing them into the ground. Luminaire bulbs, lenses, caps, posts, hoods, reflectors, and other fixture components can easily be assembled by persons without training in

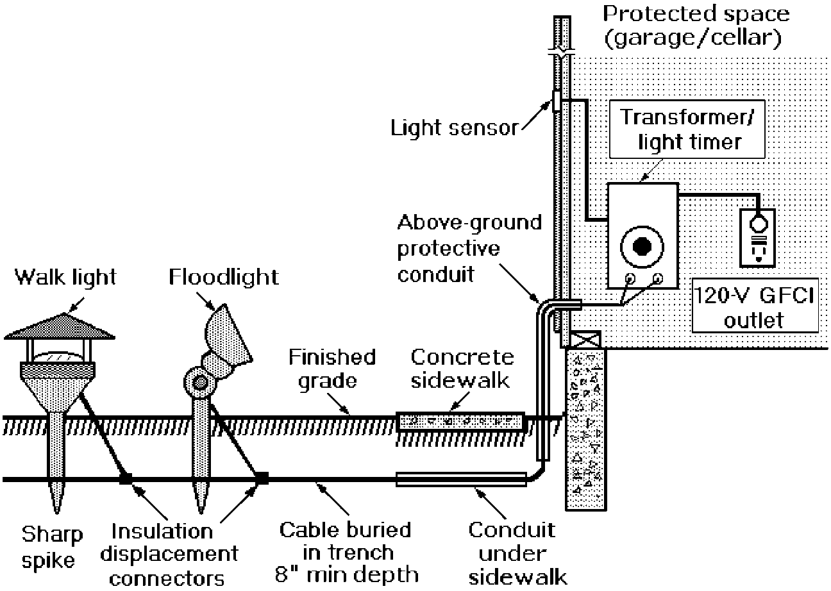


Figure 8-16 Low-voltage outdoor lighting system.

electrical work. The floodlight luminaires include a swivel joint on the mounting stake to permit the lamp to be focused precisely after the supporting stake has been driven into the ground.

The kits typically include lengths of two-wire lighting cable long enough to extend from the transformer to the last fixture in the series. The luminaires include short lengths of two-wire line cord terminated by snap-together insulation displacement connectors (IDCs). The lighting cable from the transformer is inserted between the two parts of the connector, and when pressure is applied to these parts, sharp prongs pierce the insulation of the lighting cable to form a gas-tight bond with the underlying wire.

In planning a low-voltage lighting system, the number, type, location, and spacing of the luminaires should be planned. This will determine the length of the lighting cable needed and the correct power rating for the transformer to be purchased. Commercial low-voltage transformers with ratings from 88 to 300 W are available. The wattage ratings of all of the fixtures to be used should add up to less than the transformer rating:

$$\text{No. lights} \times \text{wattage each light} \leq \text{transformer wattage rating}$$

Glossary of Lighting Terms

American National Standards Institute (ANSI): An organization that develops or coordinates voluntary guidelines and product performance standards for lamps, ballasts, luminaires, and other lighting and electrical equipment.

Average rated life: The average rating in hours when 50 percent of a test group of lamps operating at their nominal voltage and current have failed. For example, a 60-W white light bulb can be expected, on the average, to burn for 1000 hrs.

Ballast: A transformer or circuit that steps AC line voltage down and frequency up for use by fluorescent and HID lamps to achieve the necessary voltage, current, and waveform for starting and operating those lamps. Ballasts can be either electromagnetic or electronic. (See *electronic ballast* and *magnetic ballast.*)

Ballast factor (BF): The ability of a specific ballast to produce light from the lamp or lamps it powers. The value of BF is obtained by dividing the lumen output of test lamps and ballasts by the lumen output from the lamps with a reference ballast.

Bayonet base: A base for low-voltage incandescent lamps with an unthreaded shell having two pin stubs positioned 180° apart. When the bulb is inserted into a mating socket with opposing contoured keyways, pushed down, and turned clockwise, the socket locks the bulb in place.

Beam angle: The angular dimension of the cone of light from reflector lamps (such as R and PAR types) encompassing the central part of the beam out to the angle where the intensity is 50 percent of maximum. Beam angle is also called *beam spread,* a term often included as part of the ordering code for reflectorized lamps. A lamp with a nominal beam angle of 13° is classified as having a 15°-beam angle.

Bi-pin: Two-contact pin bases on both ends of tubular fluorescent lamps that are locked into mating lampholders by twisting the lamp 90°. Medium bi-pin bases are used on 1-in.-diameter T-8 fluorescent lamps; miniature bi-pin bases are used on ⅝-in.-diameter T-5 lamps.

Brightness: The term refers to the intensity of sensation resulting from viewing light sources and surfaces.

Candela (cd) (formerly candle): The unit of *luminous intensity.*

Candelabra: Threaded ½-in.-diameter screw-in-type bases for simulated candle, night, and Christmas tree-style 120-V bulbs.

Candlepower: Luminous intensity expressed in candelas. Plots of luminous intensity, called *candlepower distribution curves,* are used to indicate the intensity distribution characteristics of lamps.

Candlepower distribution: A plot of the variation in luminous intensity (expressed in candelas) in a plane through the center of the lamp or luminaire.

Center beam candlepower (CBCP): The intensity of light produced at the center of a reflector lamp, expressed in candelas.

Chromaticity: The color quality of light that is defined by its chromaticity coordinates. Chromaticity depends only on hue and saturation of color, not luminance (brightness). It applies to all colors, including shades of gray, but chrominance applies only to colors other than grays.

Chromaticity coordinate: One of the two coordinates (x or y) that precisely specify the exact identity or chromaticity of a color in the CIE chromaticity diagram. It is also called a *color coordinate* or a *trichromatic coefficient.*

Chromaticity diagram: A diagram in which one of the three chromaticity coordinates is plotted against another.

Chrominance: That property of light which produces the sensation of color apart from luminance, e.g., color in the form of hue and saturation, produced on a TV screen.

Coefficient of utilization (CU): A factor for determining actual lumens from a luminaire that reach the work surface.

Color: Different visible wavelengths with the ability to excite in the human eye various color sensations.

Color rendering index (CRI): An international numbering (based on a 0-to-100 scale) for rating the color rendering ability of a lamp when referred to a standard light source of the same chromaticity (color temperature). It, along with chromaticity coordinates, is a measure of the ability of the lamp to make colors appear natural under that lamp. The higher the CRI number, the more natural the color appears. For example, CRI ratings of 80 or higher are considered to provide excellent illumination, from 60 to 80 good, and 60 or less poor. The CRI ratings of any two similar lamps are valid only if those lamps have the same correlated color temperature or chromaticity. CRI differences between lamps are not usually visible to the eye unless the difference is more than 3 to 5 points.

Color temperature: The temperature of a black-body radiator in degrees Kelvin (K), the absolute temperature scale. The radiator produces the same chromaticity as a light source being compared with it. Color temperature was originally used to describe the "whiteness" of incandescent lamp light because color temperature is related directly to the filament temperature in an incandescent lamp.

Correlated color temperature (CCT): A term that characterizes the output of a light source that does not have a hot filament. It is a value indicating that the light appears *as if* the source were operating at an actual color temperature, expressed in degrees Kelvin (K).

Edison base: The threaded 1-in.-diameter screw-in base for standard incandescent, halogen, and compact fluorescent lamps (CFLs), typically rated for 120 V AC.

Efficacy: See *luminous efficacy.*

Electronic ballast: An electronic circuit ballast for fluorescent lamps and HID lamps. These ballasts operate at frequencies of 20 to 60 kHz, and eliminate the flicker and noise of magnetic ballasts.

Footcandle (fc): A unit of illuminance equal to 1 lm/ft^2. It is also equal 10.76 lux, but 10 lux is commonly used as its equivalent.

Illuminance: The density of *luminous flux* incident on a surface, measured in *footcandles* or *lux.*

Illumination: A term meaning the act of illuminating or the state of being illuminated.

Incident angle: The angle between a ray of light reaching a surface and a line normal (perpendicular) to that surface.

Indirect lighting: Light arriving at a surface after reflecting from one or more surfaces (usually walls and/or ceilings) that are not part of the luminaires.

Infrared (IR) radiation: Electromagnetic energy radiated in the wavelength range of about 770 nm to 1 mm (0.77 to 1000 μm). IR emission cannot be seen by the human eye, but can be sensed as heat by the skin.

Initial light output: Lamp light output expressed in lumens, after 100 hrs of seasoning.

Instant-start: A method for starting fluorescent lamps in which the applied voltage across the electrodes required to strike an electric arc is up to twice as high as it is for other starting methods. This high voltage is necessary because the electrodes are not heated prior to starting. It is more energy-efficient than *rapid* or *preheat starting,* but results in greater wear on the electrodes during starting. The life of instant-start lamps switched on and off frequently can be reduced as much as 25 percent relative to *rapid-start* operation. For longer burning cycles (such as 12 hr per start), lamp life differences due to starting method are likely to be negligible.

Kilowatt (kW): A measure of electrical power equal to 1000 W.

Kilowatt hour (kWh): The standard measure of electrical energy and the unit used by electric utilities for billing customers' consumption of electric power. A 100-W lamp operated for 10 hr consumes 1000 W ($10 \times 100 = 1$ kWh). If the utility charges 1 cent/kWh, the cost of electricity for 10 hrs of operation is 10 cents.

Lamp envelope: The shape of either the bare lamp or the capsule surrounding the lamp. Common shapes include quad, triple-tube, four-tube, coiled-tube, A-line, circular, square, globe, capsule (bullet), reflector, and decorative.

Lamp life (lamp rated life): The median life span of a very large number of lamps. Half of the lamps in a sample are likely to fail before the rated lamp life, and half are likely to survive beyond the rated lamp life. Rated life is based on standard test conditions. For discharge light sources, such as fluorescent and HID lamps, lamp life depends on the number of starts and the duration of the operating cycle each time the lamp is started.

Lamp lumen depreciation (LLD): The reduction in lamp light output that progressively occurs during lamp life.

Lamp rated life: The median life span of a very large number of lamps. Half of a test group will fail before reaching rated life and the other half will exceed rated life. Any lamp, or group of lamps, can vary from the published rated life.

Light center of length (LCL): The distance from the center of the light source to a point on the base, measured in inches. For screw bases the point on the base is the bottom contact; and for bayonet, candelabra, and medium bayonet bases it is the top of the base pins.

Light loss: The reduced light output caused by a circuit-level power reducer expressed as a percentage of the light output without the circuit-level power reducer (full system output minus reduced output with a lighting-circuit power reducer divided by the full system output times 100).

Light loss factor (LLF): A fraction that represents the amount of light that will be lost due to dust, grit, or stains on a lamp and its reduction of the lamp's light output over time.

Louver: A fixed shield, usually divided into small cells, that is attached to the face of a luminaire to reduce direct glare.

Lumen (lm): The unit of *luminous flux* equal to the flux through a unit solid angle (steradian) from a point light source of 1 candela or to the flux on a square foot of surface, all points of which are 1 ft from a point source of 1 candela. A candle provides about 12 lm, and a 60-W white incandescent lamp provides about 860 lm.

Lumen maintenance: A measure of how a lamp maintains its light output over time. It can be plotted as a graph of light output versus time or numerically.

Luminaire: The preferred term for *light fixture,* it is the assembly of all elements of a lighting fixture, including lamp(s), socket(s), reflector or diffuser, and the necessary wiring to connect it to the power supply. Fluorescent and HID luminaires include ballasts.

Luminaire angle: The vertical (altitude) angle used in luminaire photometry to express the direction of the light output being measured. Light coming straight down is at 0°.

Luminaire efficacy: See *luminous efficacy.*

Luminaire efficiency: The ratio, expressed as a percentage, of the light output of a luminaire to the light output of the luminaire's lamps. Luminaire efficiency accounts for the optical and thermal effects that occur within the luminaire under standard test conditions.

Luminance (L): The photometric quantity most closely associated with the perception of brightness. It is measured in units of *luminance intensity* (candelas) reflected in any direction per unit of projected area (ft^2 or m^2).

Luminance contrast: A value that quantifies the relative brightness of an object against its background. It can range from 0 to 1. The closer the luminance contrast is to 1, the greater is the relative brightness of the object against its background.

Luminous efficacy: A quantity denoting the effectiveness of light sources. It is the ratio of the measured light output or luminous flux (lumens) to the total power (watts), expressed in lumens per watt (lm/W).

Lux (lx): The International System (SI) unit of illuminance on a surface 1 m^2 in area on which there is a uniformly distributed flux of 1 lm.

Magnetic ballast: A ballast for fluorescent and HID lamps. It includes a transformer and magnetic components for 60-Hz operation. (See also *ballast* and *electronic ballast.*)

Maximum overall length (MOL): The total length of a lamp measured from the top of the bulb to the bottom of the base, typically expressed in inches.

Mean lumens: The average light output of a lamp over its rated life. For fluorescent and metal-halide lamps it is measured at 40 percent of rated life; for mercury, high-pressure sodium, and incandescent lamps, it is measured at 50 percent of lamp life.

Miniature base: The threaded ⅜-in.-diameter screw-in base for miniature incandescent lamps for flashlights, decoration, and toys, typically rated 1.5 to 12 V.

Mogul base: The threaded 1½-in.-diameter screw-in base for large street and factory incandescent lamps, typically rated for 240 V AC.

Nanometer (nm): A unit of wavelength equal to 10^{-9} m.

Phosphor: An inorganic chemical compound in powdered form that is deposited on the inner surface of fluorescent tubes and some mercury and halide lamp bulbs. Phosphors absorb short-wavelength ultraviolet (UV) light and transform it to visible light.

Preheat-start: A method for starting fluorescent lamps. See *instant-start* and *rapid-start.*

Rapid-start: A fluorescent lamp starting technique. See *instant-start* and *preheat-start.*

Reflectance (*r*): The percentage of light reflected back from a surface. It is that fraction of the incident light that has not been absorbed or transmitted by the surface.

Slimline single-pin base: Single-pin base on both ends of tubular fluorescent lamps: 1 in. diameter for T-8, 1½ in. diameter for T-12, and ¾ in. diameter for T-6.

Ultraviolet (UV) radiation: Energy in the wavelength range of about 10 to 400 nm. The International Commission on Illumination (CIE) defines the UV bands as UV-A (315 to 400 nm); UV-B (208 to 315 nm), and UV-C (100 to 280 nm).

Underwriters' Laboratories (UL)–listed lighting products: A private organization that tests and lists electrical equipment for safety compliance with recognized UL and other standards. A UL listing on a lamp is not an indication of overall performance. Compact fluorescent lamps with Edison bases and built-in ballasts are UL-listed.

Visible light: Light with wavelength in the range 380 (violet) to 770 (red) nm (0.38 to 0.77 μm) that can be seen by the human eye. It is measured in *lumens.*

Wedge bi-pin base: A wedge shape formed at the base of a miniature low-voltage incandescent or halogen lamp that includes exposed filament leads to make contact with the power source in a socket.

9

TELEPHONE, MULTIMEDIA, AND ALARM SYSTEMS

CONTENTS AT A GLANCE

Overview

Telephone Systems

Wiring System Topology

Structured Wiring Systems

Fiberoptic Cable

Telecommunications Wiring Rules

Residential Automation Systems

Residential/Commercial Security Systems

Residential/Commercial Security Sensors

Advanced Security Systems and Sensors

Fire Alarm Systems

Glossary of Telecommunications Terms

Overview

This chapter covers, among other topics, home and office telephone wiring. This was work formerly done exclusively by telephone company employees because those companies owned of all the wiring and equipment, inside as well as outside. Because of the deregulation of the telephone industry, this work is now available to electrical contractors, electricians, and other independent telecommunications system installers.

Since deregulation, additional work opportunities for these independent contractors have opened up because of the increasing popularity of structured wiring. These are buzz words for the wiring and cabling being installed in homes and offices to provide access to other audio and visual services beside connections to the public telephone system.

Those services, now called multimedia, include cable television, computer networking, and connections to home entertainment centers for every room where they are desired. Short of installing new structured wiring, there is also an ongoing need to replace existing telephone station wiring with more advanced unshielded twisted-pair (UTP) wiring to support the ever-increasing data rates needed for computer networking. Wiring and cable installation clearly have gone well beyond basic wiring for electric power and lighting.

After deregulation the telephone companies were obliged to set *demarcation points* or *jacks* in homes, offices, and other facilities. They separated their property and responsibilities from those of the property owners. However, the telcos remain responsible for installing and maintaining the telephone feed lines from poles or underground ducts to the customers' demarcation points and making the necessary connections.

In theory, any home or building owner with a basic knowledge of the public telephone system can do any work he or she wants to do beyond the demarcation point, but the penalties for making a mistake that degrades or disables the phone line are high. The telcos must be brought in to make repairs—and that can be very expensive.

In practice, most people call in professionals to do this work. They might be retired or ex-telco employees who do it at reasonable rates, or they might be electricians who have taken the necessary training. Electrical contractors have an advantage in obtaining this work if it is done during new home or building construction because structured and electric power wiring can be installed at the same time.

The National Electrical Code (NEC) includes an article devoted specifically to the installation of communications wiring and equipment. NEC 2002, Article 800, "Communications Circuits," covers telephone installations systems and outside wiring for fire alarm and similar central station systems. It considers the following subjects:

- Conductors outside and entering buildings
- Protection
- Grounding methods
- Communications wires and cables within buildings

The telco still must assign new phone numbers for new lines, but it does not need to be notified about any work planned or executed beyond the demarcation point. The telcos will still do any work the customer wants done on the other side of the demarcation point, but their rates are far higher than those of the independent contractors.

Other topics covered in this chapter include wiring topology, structured wiring for multimedia, rules for telecommunications wiring, home automation systems, security systems and sensors, and fire alarm systems. There is a glossary of telecommunications terms at the end of the chapter for ready reference.

Telephone Systems

Figure 9-1 illustrates a basic home telephone wiring scheme. The demarcation jack can be located either on an outside wall near the entry point of the feed line or inside the building, and it can originate from either a pole or an underground duct. The telco is responsible for maintaining any surge protection devices on its feed lines.

The Federal Communications Commission (FCC) issued FCC Part 68 to outline equipment standards. It describes the minimum requirements for the mechanical properties of wiring devices, electrical performance, dimensions, and material properties. Only equipment that complies with FCC Part 68 may be connected to the network. In addition, NEC 2002, Section 800.4, "Equipment," states that only approved telephone wiring and equipment may be installed on the customer side. It cites Underwriters' Laboratories (UL) 1459-1995, *Standard for Safety, Telephone Equipment,* third edition, as a reference. The customer must be certain that any new telephone equipment purchased conforms to these standards.

WIRED TELEPHONE TECHNOLOGY

The basic principles of the dial-up wired public telephone have not changed in more than a century, but during that time there have been many technical improvements in telephony. These include the introduction of Touch-Tone or pushbutton dialing replacing earlier rotary dialing and smaller, lighter, and more versatile telephones with electronic circuitry and tone generators replacing the earlier electromechanical bell ringers.

Prior to deregulation there were no universally accepted standards for installing and troubleshooting telephone wiring systems. This shortcoming was further compounded

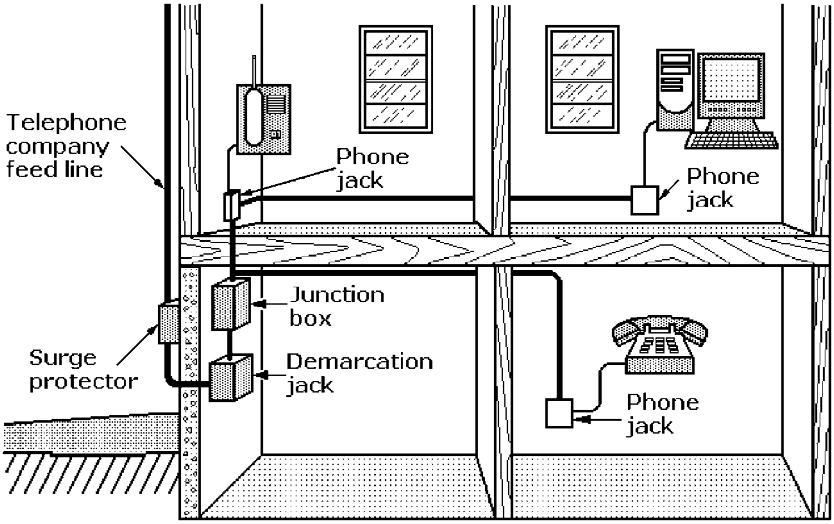


Figure 9-1 Residential telephone system.

by the diversity and number of available telephone services. At that time, the ongoing addition of new equipment and services threatened the reliable operation, adaptability, and maintenance of the system. Deregulation also spurred the demand for national cabling standards capable of accommodating new applications that were acceptable to all telephone operating companies.

Modular telephone accessories were developed to replace the older four-prong accessories used in United States, Canada, and other countries with compatible telephone standards. This made it easier for customers to rearrange existing phones and plug them in. All new homes in the United States and Canada built after 1976 have been prewired for modular-style phone equipment. While some phones with four-prong connectors and hard-wired accessories are reported to be still in service, they will all be replaced eventually. Replacement plugs, jacks, cords, and other accessories are still available for the older systems, as well as accessories for converting them to modular systems.

All new wired telephones use the newer clear plastic miniature RJ-style plugs, as shown in Fig. 9-2. They measure ½ × ⅜ × ¼ in., and have flexible plastic latches that lock them in position when mated with matching ⅜ × ¼-in. jacks. These plugs are used on cord-type and cordless telephones, personal computers, fax machines, and other apparatus that requires a connection to the public dial-up telephone system.

A selection of four modular four-wire telephone accessories is shown in Fig. 9-3. A flush-mounted wallplate with a jack for telephone wiring behind a wall is illustrated in Fig. 9-3*a,* and a surface-mounted wallplate with both a jack and studs for supporting a wall-mounted telephone is pictured in Fig. 9-3*b.* Both wallplates cover standard wall-mounted electrical boxes used for terminating telephone phone wiring within walls. The duplex plug adapter shown in Fig. 9-3*c* permits two telephones or other compatible devices to share a single jack, and the surface phone jack pictured in Fig. 9-3*d* is used where telephone wiring is external, typically stapled along baseboards.

The introduction of the cordless telephone, a radio transceiver, gave customers an opportunity to roam within a range of a few hundred feet of the base unit. However, the cellular telephone has revolutionized telephony because of its complete portability and convenience. However, most experts believe it is unlikely that cellular phones will

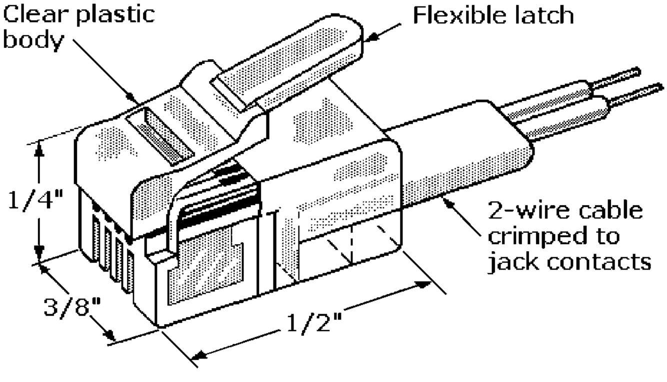


Figure 9-2 Modular telephone plug for mating with modular telephone jack.

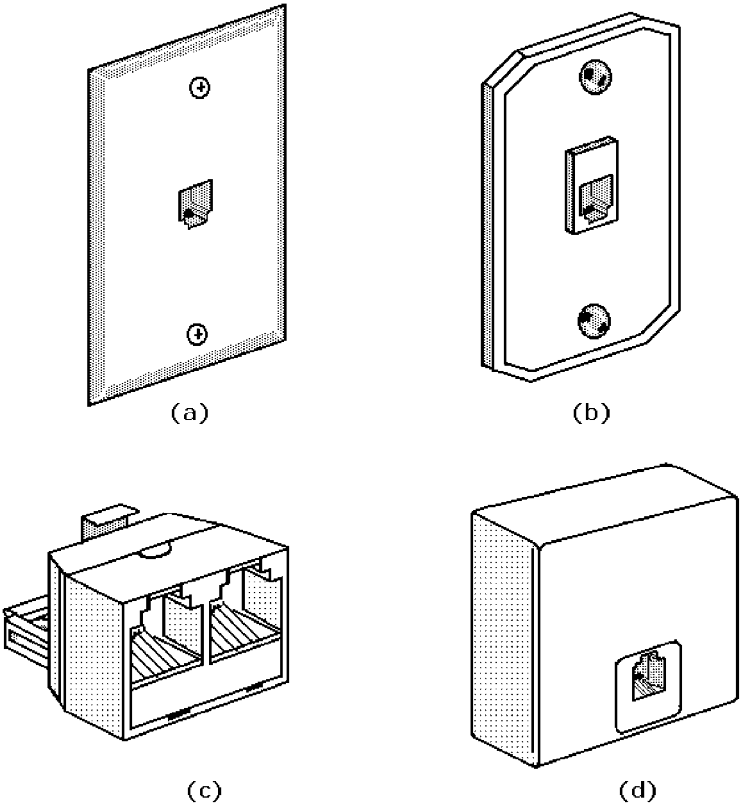


Figure 9-3 **Modular telephone jacks: (*a*) flush-mount wallplate; (*b*) surface-mount for wall phone; (*c*) duplex plug adapter; (*d*) baseboard.**

drive out wired phones in the foreseeable future, especially those in offices and stores that are intended for business use. Moreover, by their very nature, wall- or post-mounted pay or toll phones will always remain wired.

TELEPHONE WIRES AND CORDS

To meet the need for standards, the Telecommunications Industry Association (TIA) prepared TIA/EIA-568-A, defining a wire and cable category rating system based on its ability to carry data efficiently.

- *Category 3* (CAT 3) wire can efficiently carry signals at data rates up to 10 megabits per second (Mbps), typical for voice and ISDNs (integrated services digital networks).
- *Category 5* (CAT 5) wire can carry voice and data at rates up to 100 Mbps.
- *Category 5e* (CAT 5e) wire is an improved version of CAT 5.
- *Category 6* (CAT 6) wires are being developed to handle future higher data rates that are well above the typical high-speed data transmission rates today.

Three different types of wires are used in modern modular telephone systems: handset cords, linecords, and telephone station wire. *Handset cords* connect the handset to the standard telephone. The wiring and connectors for this function differ from those used to connect the phone to standard modular jacks. *Linecord* is conventional nontwisted, unshielded, four-color, four-conductor quad cord that is plugged into a jack to connect a telephone or other device to the phone line. Linecords are typically less than 6 ft long.

Telephone station wire is used for permanent indoor telephone installations beyond the network interface device. It is available in many forms and is capable of conducting data signals as well as phone conversations. The simplest telephone station wire is quad wire with four-color, nontwisted wires as shown in Fig. 9-4*a*. It contains two wire pairs: red R1 and green T1, and yellow R2 and black T2. The T stands for *tip,* and the R stands for *ring,* a reference to old-style telephone plug terminology. These wires regularly supply phones with 6 to 12 V at about 30 mA, but a stronger 90-V, 20-Hz ring signal is sent to "ring" the phones. This voltage level was once required to actuate electromechanical ringers (solenoid and bell), but it has been retained in modern systems.

A single phone line requires only two wires—a T and R pair. If only one numbered phone line is hooked up, the red R1 and the green T1 pair is used first. The black R2 and the yellow T2 pair are used only if a second numbered phone line is to be hooked up; otherwise they remain unused.

Quad wire is no longer acceptable for use in multiline installations. When a new telephone system is to be installed or an old system updated, there is a choice of two

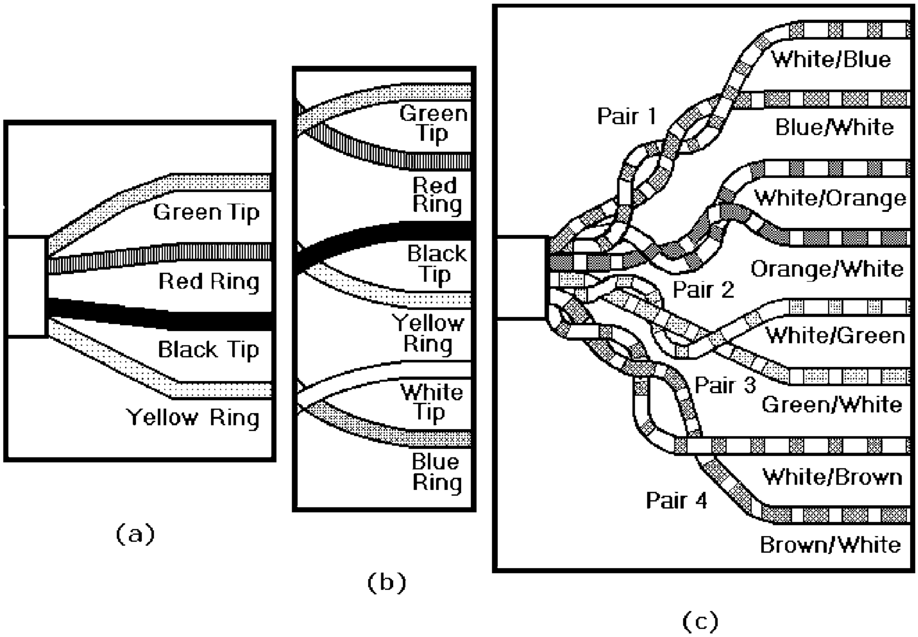


Figure 9-4 Telephone and multimedia cable: (*a*) solid-color, two-pair quad (nontwisted) phone; (*b*) solid-color, three twisted-pair phone; (*c*) band-striped, four twisted-pair multimedia.

TABLE 9-1 STANDARD FOUR-PAIR WIRING COLOR CODES

Pair 1	T	White/blue (green—tip)
	R	Blue/white (red—ring)
Pair 2	T	White/orange (yellow—tip)
	R	Orange/white (black—ring)
Pair 3	T	White/green
	R	Green/white
Pair 4	T	White/brown
	R	Brown/white

Note: For six-wire jacks pair 1, 2, and 3 color codes are used; for four-wire jacks pair 1 and 2 color codes are used.

different cables. One of these is the six-color, six-conductor, three *unshielded-twisted-pair* (UTP) cable shown in Fig. 9-4*b.* It has the same color code for two of its R and T pairs as quad wire. The other option is the four-color band-striped, eight-conductor, four UTP cable shown in Fig. 9-4*c.*

The four colors of the bands in four UTP are blue, orange, green, and brown. The insulated conductors are coded as follows.

- All wires with insulation in any of the four colors with wide stripes alternating with thin white stripes are R conductors.
- All wires with insulation with wide white stripes alternating with thin stripes in any of the four colors are T conductors.
- Four-wire pairs are assigned in the color order given in Table 9-1: (1) blue, (2) orange, (3) green, and (4) brown. For example, a blue-and-white striped pair is assigned to the first telephone line installed, and the orange pair to the second.

Wiring System Topology

Home and office wiring in the past was typically installed in a pattern that looks like a branching tree, as shown in Fig. 9-5. Given the fanciful name of *daisy chaining,* this method made it easy to add new telephone lines by hooking them onto the nearest branch.

Following deregulation, most new phone installations in homes and offices began to use *home-run* or *star topology,* as shown in Fig. 9-6. Home-run/star topology requires more wiring because there is a separate cable back to an interface box for every telephone or device requiring a telephone connection. This change was motivated by the demand for multiple phone lines to meet existing and future demands of homes and offices. The real advantage of star topology is that it simplifies signal tracing and making

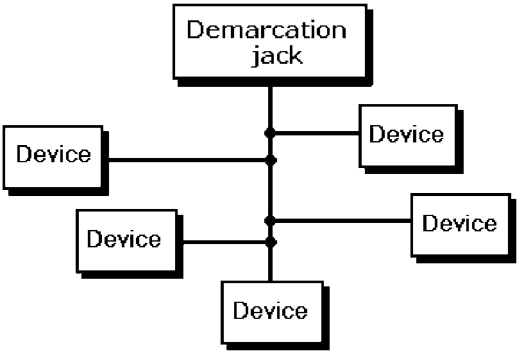


Figure 9-5 "Daisy-chain" or continuous-loop wiring topology.

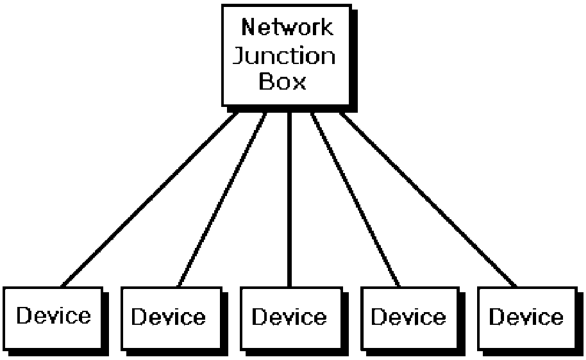


Figure 9-6 Home-run or star wiring topology.

repairs. The flexibility of home-run topology and its elimination of interference and cross-talk between telephones justifies its higher cost, if any, for installation.

Home-run topology is relatively easy to install in new homes or offices under construction where the wall studs are not covered, but admittedly is more difficult and expensive to install in older buildings with finished walls. In either case, the cost of the additional cable is a fraction of the installation labor cost.

Today home builders are installing more telephone wiring than might immediately be needed because of the anticipated demand for more telephone and computer outlets. Some builders connect all the wires to jacks whether or not they will be used immediately; others install only the specified jacks but leave spare cables with adequate slack in the walls at convenient locations where they can be fished out later.

Structured Wiring Systems

High-speed *structured wiring and cabling* are being installed in accordance with home-run topology in many new and renovated homes and offices. This wiring permits the installation of multipurpose outlets with jacks for telephones, computers, cable television, and audio and video signals from an entertainment center. Structured wiring also permits terminals in every room where it is desired for security systems and closed-circuit TV for internal and external monitoring of activities.

STRUCTURED WIRING DISTRIBUTION CENTER

The *structured wiring distribution center* or *central hub* is a stand-alone cabinet containing input terminals for the distribution of voice, data, video, and audio signals. It is usually located in a room that is easily accessible for doing maintenance work or making wiring changes. The center allows the structured network to be customized and updated as newer technologies or products become available.

The center cabinet contains routers, cable or DSL modems, switches or hubs for computer networks, distribution jacks for phones, and TV signal splitters. Connections to the panel are made from the telephone demarcation jack and the sources for cable or satellite TV. Connections can also be made for closed-circuit TV cameras. AC power is connected to the center to power circuits that require it.

STRUCTURED WIRING DISTRIBUTION MODULES

Distribution modules are interface devices in structured wiring distribution centers that route the various signals throughout the system. Each module contains at least one input port for receiving an input signal to be distributed or redistributed, and one or more output ports for routing those signals to the intended outlets in the rooms being served.

Many manufacturers offer modules designed for easy installation in distribution cabinets. These modules give users wide flexibility for customizing their systems or making any desired changes after the initial installation. The functions of the various distribution modules are as follows.

- *Telecommunications modules* distribute voice and data signals received from various RJ-45 jacks within the home network or from the outside world. These modules typically include Category 5 data-grade or Category 3 voice-grade jacks.
- *Computer network modules* form home or office networks when used with and organized for Gigabit Ethernet (100BaseT) cards and software. These modules typically include BNC jacks.
- *Camera modules* distribute video and audio signals received from closed-circuit TV cameras to all assigned TV monitors. A video distribution module is usually required. These modules also typically include BNC jacks.
- *Audio modules* route audio signals received from home entertainment stereo systems to speakers located in the various rooms being served. These modules typically include banana jacks or binding-post jacks.
- *Video modulators* receive and distribute audio/video signals from cable and digital satellite service (DDS), UHF, VHF, VCRs, and laser disk players. They also distribute closed-circuit TV (CCTV) camera signals on one or more unused cable channels. The selected broadcast channel is programmed by a “frequency agile” modulator. The video sources can be controlled by handheld infrared remote controllers.
- *Infrared controllers* distribute video source signals to multiple audio/video systems in different locations. The controller sends a coded infrared signal to a video target, which then transmits the signal over the existing coaxial cable system to an emitter at the video source.
- *Power modules* supply DC power converted from the AC line for powering patchcords to the amplifier or panel and those modules that require DC power.

MULTIMEDIA OUTLETS FOR STRUCTURED WIRING

Complementary modules terminate the wires or cables from the distribution center in flush- or surface-mounted wall boxes in each room served. These boxes provide access to all of the signals from the distribution center.

Many different brands of proprietary multimedia distribution centers and modules are on the market, but at present there are no accepted industry-wide standards for these systems. As a result, it is usually necessary to purchase all the system components from one vendor to assure system compatibility. However, despite that limitation, many manufacturers' product lines include enough compatible components to give the buyer flexibility in configuring distribution centers and outlets for the service desired.

WIRE AND CABLE IN STRUCTURED WIRING

To gain the benefits of structured wiring, the telephone wiring must be at least Category 5 unshielded twisted-pair, or CAT 5 UTP, which has replaced the more common CAT 3 UTP phone wire. In addition, the video cabling must be broadband RG-6 coaxial cable rather than the lower-performing RG-59 coaxial cable. Also, all wiring in the structured network originates from the distribution center service panel in home-run topology, with dedicated wires and cables going to each multimedia outlet.

STRUCTURED WIRING NETWORK CONFIGURATIONS

Connections are made to all rooms where multimedia services are to be provided. The rooms selected are usually a home office, living room, family room, kitchen, den or study, and all bedrooms. Some people even want them in bathrooms.

There is no general agreement on what constitutes a starter installation for a structured wiring multimedia system. The closest to agreement is that at least the following wire and cable connections should be made for each room to be served:

- Two CAT 5 cables (CAT 5e preferred)
- Two RG-6 quad shielded coax cables
- One dual CAT 5/dual coax outlet

The two RG-6 cables permit the use of bidirectional TV, and the two CAT 5e cables serve telephones and computers and permit local area networking (LAN) between two or more computers. This installation will support both current and developing technologies, including multiple communication devices in the home office (computers, fax machines, phone lines, etc.) and extensive home theater capabilities (DVDs, CDs, etc.).

If a network laser or inkjet printer is to be accessible by all computers at all times, it is recommended that a separate network cable be run to it. Alternatively, a small hub can be placed at an outlet to permit the computer and printer to share one cable. Additional wiring provides for different arrangements or the accommodation of split needs.

In homes or offices where the media requirements are subject to change or upgrading, it is recommended that 2-in.-diameter PVC conduit be run vertically from the attic to the basement to make it for easier to pull future wires, cables, or fiberoptic cable. However, structured wiring in homes and small offices will not include fiberoptic cable in the foreseeable future because there are no standards for its use in these locations, and the cost of installing fiberoptic cable for this application is prohibitive.

Nevertheless, there are efforts underway to merge all hard-wired telecommunication signals into a unified fiberoptic broadband carrier. When sufficiently developed and made not only cost-effective but relatively inexpensive, fiberoptic cable could replace all copper-wire conductors. It would make continuous transmissions directly to the receiving devices possible. Fiberoptic networks will also be installed in home-run topology.

Despite the complexity of structured wiring, nonengineers can install their own multimedia networks if they are willing to learn how to do it. The task has been made easier because manufacturers are offering complete kits of the compatible components needed to structure a workable system. As in the case of home telephone wiring, professional technicians trained to install and test these networks are in business to provide this service.

The most important first step in forming a structured wiring network is pulling the wires and cables in the walls and terminating them with multimedia outlets. It has been estimated that doing this installation in homes with finished walls costs about 4 times as much as doing it during new construction when the walls are uncovered.

The contractors that install these systems generally offer basic and upgraded levels of networking. At the basic, lowest-price level, this usually includes pulling wires and cables in the walls, installing a central control panel, three to six multimedia outlets, and one or two additional phone outlets.

The next upgrade might include installing additional multimedia outlets so there is at least one in each of the rooms to be served. Provision can also be made for distribution of audio signals from a home entertainment center, a computer LAN network, and one or two security video cameras.

MULTIMEDIA BENEFITS

The benefits of structured wiring for multimedia are:

- Instantaneous access to the Internet.
- Convenience of four or more telephone lines with separate numbers.
- Network-wide sharing of audio and video signals from a single VCR, DVD, or CD player, and TV signals from a single source, typically a home entertainment center. Speakers and TV sets can be installed in all wired rooms.
- Private local area computer networks (LANs) to connect two or more computers and permit the computers to share files and a printer/scanner.
- Closed-circuit TV cameras to augment the security system. It will be possible to view persons at the front door, watch children playing in the backyard, or check on a baby sleeping in a crib from all of the installed TV sets.

Standards have been developed by the Telecommunications Industry Association (TIA) in collaboration with the Electronic Industry Alliance (EIA) for these networks in accordance with the Federal Communications Commission (FCC). An example is

ANSI/TIA/EIA-568B for residential communications cabling. These standards are becoming electrical code requirements for home and business network wiring installations.

Fiberoptic Cable

Fiberoptic cables are versatile conductors that support ultrawide bandwidth, permitting high-speed digital data transmission, and they are more reliable than copper-wire twisted pairs. At the present time, only organizations such as large corporations, the government, and financial institutions can afford fiberoptic systems.

Media systems engineers would prefer all-digital fiberoptic cable systems because they are easier to install and maintain than copper-wired systems, and they provide more reliable communications. Category 5 communication cable is now widely used for telephone, fax, and computer hookups, and Category 6 cable is under development, but in the future it is expected that all telecommunications will be carried primarily over fiberoptic cable.

Telecommunications Wiring Rules

The following general rules apply to telephone and telecommunications wiring.

- Leave about 18 in. of spare wire inside bore holes in the wallboard at phone outlets, to allow for repairs and changes.
- Telephone outlets and power outlets and telephone grounds and power grounds should always be separated by at least 6 in.
- Telephone wiring should always be separated by at least 6 ft from open high-voltage wiring, lightning grounding wire, and grounding rods. However, telephone wiring can be as close as 6 in. from high-voltage wiring that is run in conduit.
- Where practical, all telephone and multimedia wires and cables should be run within inner walls; running external wires should be avoided wherever possible. If it is necessary to run external cable and wires, underground conduit should be used.
- Before adding a second telephone line to an existing cable using solid-color non-twisted quad cable, a check should be made to determine that the first line is connected to the green and red terminals of the phone jacks. The second pair should then be connected to the remaining black and yellow terminals of the phone jacks.
- Twisted-pair cables are required to meet the standards for multiline residential telephone wiring. When wiring telephone jacks, the correlation between twisted-wire pairs and jack terminals should be maintained. For example, with three-pair solid-color twisted pairs, twisted pair 1 (green and red) should be connected to terminal pair 1; twisted pair 2 (black and yellow) to terminal pair 2; and twisted pair 3 (white and blue) to terminal pair 3.

- At the completion of a new installation, it should be inspected visually before being tested. The color matching at all interconnects and the polarity at the head end (demarcation) point should be verified. All pairs should be tested for continuity shorts with other pairs, shorts to ground, and polarity. Only test instruments designed specifically for telephone wiring should be used.
- NEC 2002 requires that structured cabling be installed at least 6 in. away from the electrical wiring already in the walls.

Residential Automation Systems

Several different kinds of home and small office automation systems that do not depend on multimedia networks are available. Some are based on low-voltage wiring or other dedicated wiring systems. More recently, systems have been proposed that provide a network of transmitters and receivers which communicate via coded switching signals sent over existing AC power wiring.

Transmitter modules send command signals containing specific addresses and directions to receiver modules directing them what to do. The command signals can order the receiver modules to turn lights and appliances on or off, or dim or brighten illumination. These expandable systems can be tailored to meet the owner's requirements. These futuristic systems have been demonstrated in laboratory experiments, but as yet no market for them has developed.

Accessories developed for use with these systems include programmers, controllers, and wireless radio-frequency transmitters for remote control. Passive infrared transmitters and photocell controllers can add home-security features to these systems. A telephone transponder would allow the user to control the network from anywhere in the world with a Touch-Tone phone.

SMART HOME AUTOMATION

The next step in home or office automation systems, called a "smart" system, integrates the multimedia home network with modules for activating building service equipment such as unified heating and air-conditioning systems, lighting, home appliances, and security systems. It could, for example, link all of these services to a computer so they could be controlled either from a central panel, a handheld remote controller, or over the Internet.

According to the developers of these systems, it would be possible, for example, to control room temperature by keying commands into a central panel, transmitting radiofrequency or infrared signals from the handheld controller, or by transmitting a digital code over the Internet from a distant location.

Despite their technical feasibility, these concepts are still in the prototype stage in university and industrial laboratories. No commercial equipment is yet available, and no estimates of the cost of a complete working system have been published.

Until an accepted standard for the software has been established, and a market for these systems has been identified, equipment manufacturers will have little or no incentive to develop commercial products.

A first step is believed to be the embedding of microcontrollers in the next generation of kitchen appliances. These would permit them to be connected to the Internet, making it possible for service technicians in a central location to diagnose faults in the appliances. With this information a service technician could be dispatched with the right kit of parts. It is expected that feature would reduce the time and cost of making appliance repairs.

Residential/Commercial Security Systems

A security system is a complete network of both passive and active devices that protects against burglary, vandalism, and fire. Although security systems for homes and government or military organizations are based on the same principles, there are vast differences in the systems. A basic security system has the following parts.

- *Control unit:* A central hub powered from the AC line but backed up by batteries in case of power failure or a willful cutting of the power lines.
- *Sensors:* Devices that detect alarm conditions such as the breaking of a glass window, the unauthorized opening of a door or window, or the presence of an intruder either inside or outside of the protected area.
- *Alarms:* Devices that are activated when a sensor detects an alarm condition. They can be audible alarms such as horns, bells, or buzzers, visual alarms such as a flashing lights or messages on a computer monitor, or silent alarms such as vibrators. The vibrations can be sensed by persons within range of them. Alarm signals can also be sent over telephone lines.

There are both self-contained and multiple-component security systems. An example of a self-contained security system is a battery- and/or AC line-powered smoke detector, carbon monoxide detector, or independent motion or occupancy detector.

This section considers only multiple-component security systems because they require electrical wiring to be run from a control unit to the various sensors in the system. These can be passive devices such as mercury switches on doors and windows or conductive strips applied to the glass on the windows. They can also be active devices such as ultrasonic, infrared, or radio-frequency transmitter–receiver pairs or closed-circuit TV cameras. Typically, wiring for a security system will be in the home-run format, with direct wire connections between each sensor and the controller or control panel.

An acceptable multicomponent security system will protect the entire perimeter around a home, office, factory, or warehouse. It will alert the owner, occupant, or security guard or agency, and warn the prospective intruder or intruders that they have been detected. It will also act to prevent damage caused by the forcible break-in of a burglar or property damage by a vandal.

Many security systems include automatic message dialers that are activated when the control unit responds to an indication of a break-in or attempted break-in. These dialers can be part of the control unit or separate units. The phone dialer can transmit either a tape-recorded or a digitally stored message. It is programmed with an identification message and the phone number of the police station or private security agency.

If the system is to dial the local police directly, registration or permits may be required. However, if the system is installed by a private security contractor, the call will be made to that agency, which will alert an employee on duty who will then make a live call to the local police station.

The simplest multicomponent security systems include a control unit that monitors the status of all sensors and sounds either a silent or audible alarm when one or more sensors detects an alarm condition. The control unit can be connected to various switches that are either normally open (N.O.) or normally closed (N.C.), depending on their type. These switches are wired in more "loops" out from and back to the control unit. When a switch is opened or closed, it activates a common security alarm.

When all switches are in their normal states and the system is activated, it is said to be "armed" or "set." If any switch is not in its normal condition, the security system is "tripped." Also, if power to the control unit is turned off, the system is "disarmed." There are many possible modes of operation based on this simple scheme.

A system might have separate loops to protect the front and back doors, and a single loop to protect all of the ground-floor windows. One of these loops might have a built-in time delay to permit the occupant/owner to get inside the house or building to disarm the system so that an outside remote key switch is not needed.

If normally closed switches are wired in series in a loop, when any one switch is opened (signaling that a door or window is open), the control unit actuates an alarm. By contrast, in a loop with normally open switches, the switches are wired in parallel so that when one switch is closed (signaling that an intruder has entered), the control unit actuates the alarm. However, normally closed switches wired in series in the loop are preferred because they form a continuous loop. This permits the control unit to monitor loop continuity so the alarm can still be actuated even if a switch fails or the loop wire is cut.

Practical security systems include switches that are more unconventional than simple mercury, magnetic reed, or contact switches in or on doors or windows. The switches can be parts of glass-breakage detectors, or they can be continuous lead-foil strips bonded to window glass that will set off the alarm if the strip is sheared as a result of the glass being broken. More elaborate systems have switches that are integral parts of infrared or ultrasonic motion detectors that can activate outdoor floodlights or turn on closed-circuit TV cameras or video recorders.

As in telephone or structured wiring, security system wiring is most economically and speedily installed before building walls are closed in. However, if the installation is done after the walls are finished, the wiring should be as inconspicuous as possible.

Baseboard wiring should not be used because it is obvious and can easily be cut by an intruder. Installation might require drilling holes in door or window frames and pulling the wires through the walls back to the control unit by way of the basement or attic.

Residential/Commercial Security Sensors

The following sensors are typical of those included in security systems. The choice of sensors will depend on such factors as the level of security protection required, the budget for system installation, the limitations on the effectiveness of certain sensors in specific locations, and barriers and obstacles within rooms or outside areas being monitored.

- *Motion detectors,* also called *occupancy sensors,* mounted inside or outside the premises, can trigger either a silent or audible alarm or turn on lights, as appropriate, when they detect the motion of an unwanted intruder. See "Motion Detectors" in Chap. 6 for more information.
- *Combination floodlight and motion detector units* packaged to function outdoors can be mounted on walls or posts.
- *Wired windows or door screens:* If screen wire is cut or the screen is removed, electrical contacts will be broken, setting off a security alarm.
- *Low-voltage contact switches* between doors and windows and their frames that are wired into loops will initiate an alarm if the doors or windows are opened. Magnetic reed and contact switches can be used in these locations.
- *Pressure mats* appear to be ordinary floor mats, but they contain spring-loaded conductive surfaces that act like contacts of an normally open switch. When a person steps on the mat, the contacts are closed and an alarm is actuated.
- *Lead foil strips* that act like normally closed switches are cemented around the inside edges of picture windows that cannot be opened. If the glass is broken, the continuity of both the strip and loop will be broken, and an alarm will be actuated.
- *Glass-breakage detectors* attached inside glass windows can be either normally open or normally closed switches. They come in disk-shaped cases several inches in diameter. The switches are mercury-, pendulum-, or electronic-tuning-fork-type. They can respond and actuate an alarm when the window is broken or subjected to the vibrations caused by an attempted forcible entry. However, they can initiate a false alarm if the window is vibrated by wind gusts or heavy vehicular traffic. These detectors are most reliable when applied to relatively small panes of window glass that are securely installed in their frames.
- *Panic buttons* are switches wired into a security system and located in close proximity to the owner's bed or near an entry doorway. Handheld remote controls linked to the security system by infrared or radio signals perform the same functions.
- *Closed-circuit TV* provides a higher level of security. One or more TV cameras can be mounted outside or inside the building so that the occupants can monitor attempts of a person or persons attempting to enter, or view those who have gained entry. The TV camera can be paired with a concealed video camera that records these violations.

- *Keypads* are data entry terminals, typically wall-mounted, that permit the system to be armed or disarmed by the owner or occupant. Typical keypads include indicator lights to display security system status.

Some simple commercial motion sensors have both threaded bases and sockets. The sensor is screwed into the lampholder, and the lamp to be controlled is screwed into the sensor's socket. These sensors provide hands-free light switching for persons carrying large objects into a room. They will switch off the lights after the person has left and, in general, save energy by keeping off lights in unoccupied rooms.

More sophisticated units using the same technology as the less sophisticated units but with wider fields of view are more effective in security systems. They can be mounted on walls or ceilings and adjusted for optimum coverage. They also turn a light on after sensing infrared emission from moving objects such as people or animals, and turn the light off after the heat source has left the room. Energy saving might not be as important in a security application.

When mounted on an 8-ft ceiling, the lenses of some of these detectors have viewing angles up to 110°, and coverage that can exceed 2000 ft^2. Motions of large heat sources can be detected more than 50 ft away, and the movements of smaller heat sources such as a hand or a raccoon can be detected more than 30 ft away. An internal microprocessor continually analyzes, evaluates, and adjusts the infrared sensitivity of the semiconductor element, avoiding the need to compensate for seasonal changes. Some units contain an internal photocell and isolated relay option that activates the system at dusk and deactivates it at dawn to prevent the lamps from being turned on by natural light.

Advanced Security Systems and Sensors

Government agencies such as the U.S. Department of Defense and the National Security Agency have more extensive and sophisticated security systems than would be needed or would be affordable to home or business owners. In addition to many of the same kinds of sensors, these facilities are surrounded by electrified fences, and security stations are manned by armed guards around the clock. Some high-security government buildings have angled entryways or masonry barriers inside the buildings to foil armed individuals attempting to shoot their way in. They also have unusual barred windows and skylights with rotating bars that spin to resist the efforts of anyone trying to saw through them.

Specifications for high-level security systems require that security circuits be isolated from power and lighting circuits in separate conduits and have their own emergency power supplies to prevent security from being compromised by a power outage.

High-level security systems include advanced sensors not used in residential and commercial applications.

- *Breaking-glass detectors* filter out extraneous noise to focus on the unique audio frequencies of breaking glass. These sensors are able to avoid possible false alarms from foil strips or commercial glass-breakage detectors. When sounds in a narrow band of frequencies are detected, alarms are actuated.

- *Vibration sensors* containing a pendulum suspended between live electrodes can detect shock waves transmitted through rigid brick or concrete-and-steel structures by the hammer blows or power saws of persons intent on entering the building. The vibrations cause the pendulum to strike the live electrodes, completing the circuit and triggering an alarm. These sensors are built into the walls so their locations will not be visible to intruders either inside or outside the building. These sensors can be used to protect bank vaults, fine art galleries, or secure rooms for storing currency, jewelry, precious metals, or classified documents.

Fire Alarm Systems

The primary function of a fire alarm system is to alert the occupants of a building to give them enough time to leave the building safely after smoke or flames have been detected. They should also give persons trained and properly equipped to fight fires advanced warning so that they can begin to suppress the fire. All fire alarms that are either self-contained units or multicomponent systems have four basic elements:

1. Sensors or initiating devices
2. Controls for activation or testing
3. Warning devices, audible or visual
4. Power source

FIRE ALARM CODE REQUIREMENTS

The following codes apply to fire alarm systems:

- NFPA 70: National Electrical Code
- NFPA 72: National Fire Alarm Code
- NFPA 90A: Standard for Installation of Air Conditioning and Ventilation Systems
- NFPA 101: Life Safety Code
- BOCA, SBCCI, ICBO: Applicable codes and standards relating to fire prevention published by these organizations

FIRE ALARM SYSTEM CLASSIFICATIONS

NFPA 72 defines seven classifications for fire alarm systems:

1. Household fire alarm systems
2. Protected-premises (local) fire alarm systems
3. Auxiliary fire alarm systems
4. Remote supervising-station fire alarm systems
5. Proprietary supervising-station fire alarm systems
6. Central-station fire alarm systems
7. Municipal fire alarm systems

Only the first two systems will be discussed here. They are most likely to be installed in residences, offices, business establishments, small factories, or stores, as contrasted with the more elaborate systems found in high-rise buildings, shopping malls, schools, and other public buildings. In these locations there are likely to be direct communications links to a municipal fire alarm system for transmitting a fire alarm to the public fire service communications center. The systems could also include communications links between related rooms or business units.

A *household fire alarm system,* the simplest of the seven systems, consists of devices that produce an alarm signal in the household to notify the occupants of the presence of a fire so that they can escape safely. This system can be as simple as a wall- or ceiling-mounted smoke or flame detector.

A *protected-premises system,* as illustrated in the block diagram Fig. 9-7, is a local fire alarm system. It is the one most widely used in commercial and institutional buildings. Chapter 3 of NFPA 72 defines the requirements for this type of system. It consists of a control panel with initiating and signaling circuits.

An alarm from this system can be initiated by an alarm switch after the glass on the front of the alarm switch box is broken with the attached hammer. The alarm switch can be actuated manually or in response to automatic fire protection equipment.

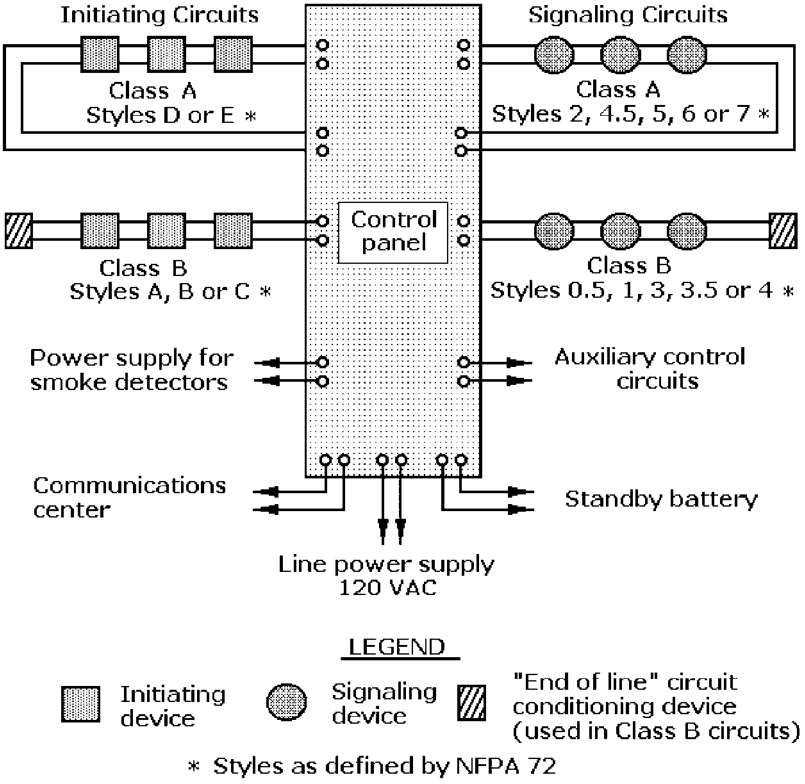


Figure 9-7 **Typical local protective fire alarm signaling system.**

Associated fire suppression equipment might include sprinklers that release water when heat from an open flame blows a fuse or extinguishers that discharge carbon dioxide or other fire suppressants when sensors detect high ambient heat. This equipment can also be backed up by smoke and flame detectors connected to audible and visual alarms.

CLASSES AND STYLES OF ALARM EQUIPMENT

Initiating device circuits (IDCs), *notification appliance circuits* (NACs), and *signaling line circuits* (SLCs) are designated by both class and style:

- *Class A circuits* can transmit alarm signals when properly initiated.
- *Class B circuits* are not capable of transmitting an alarm beyond their locations.

There are designations of style for IDCs, NACs, and SLCs. They depend on the capability of the circuit to transmit alarm and trouble signals during certain specified conditions such as single-open, single-ground, wire-to-wire short, and loss of communications signal.

- An IDC can be designated as style A, B, C, D, or E, depending on its ability to meet specified alarm and trouble performance requirements under abnormal conditions defined in NFPA 72. These are single-open, single-ground, wire-to-wire short, and loss-of-carrier fault conditions.
- An NAC can be designated as style W, X, Y, or Z, depending on its ability to meet specified alarm and trouble performance requirements under abnormal conditions defined in NFPA 72. These are single-open, single-round, wire-to-wire short, and loss-of-carrier fault conditions.
- An SLC can be designated as style 0.5, 1, 2, 3, 3.5, 4, 4.5, 5, 6, or 7, depending on its ability to meet specified alarm and trouble performance requirements under abnormal conditions defined in NFPA 72. These are single-open, single-ground, wire-to-wire short, and loss-of-carrier fault condition.

All styles of Class A circuits interconnected by wiring or fiberoptic cable must be installed so that the outgoing and return conductors exiting from and returning to the control unit, respectively, are routed separately. In other words, the outgoing and return (redundant) circuit conductors cannot be run in the same multiconductor cable, enclosure, or raceway unless they meet one of five exceptions stated in NFPA 72.

FIRE ALARM SECONDARY POWER SUPPLIES

A protected-premises (local) fire alarm system, such as that shown in the diagram Fig. 9-7, must have a secondary power supply capable of operating for at least 24 hrs. At the end of that period, the supply must be capable of operating all alarm notification appliances used for the safe evacuation of people or to direct aid to the location of an emergency for 5 min. This supply can be a standby or battery-powered source.

FIRE ALARM INSTALLATION GUIDANCE

Automatic fire detectors and smoke alarms should generally be spaced to cover 900 ft^2 per head. However, this spacing should be modified if architectural or structural features within the building, such as partitions or closets, interrupt contiguous ceiling area. In addition, because of the possibility that rooms or spaces will be exposed to different ambient temperatures, local environmental conditions might dictate closer detector and alarm spacing.

In designing any fire alarm and fire prevention system, the designer must determine what state or municipal codes apply at the time the design is initiated. Experience has shown that there is often a lag time of several year before local and state codes are modified to reflect the latest changes in the published standards from the many agencies involved in setting fire prevention standards.

It is also essential that the fire alarm/fire prevention system designer coordinate the design with the architect, structural engineer, and contractor responsible for the installation of this equipment, to determine its effects on national and local fire alarm system requirements. The objective is to make certain that the most cost-effective equipment will be installed, and that any interference problems that might lead to system malfunction and false or nuisance alarms will be eliminated. The activation of sprinklers or other fire extinguishers due to false signals can result in unnecessary property damage and high costs for labor to clean up and repair the site and to replace the furnishings.

Advances in solid-state electronics and communications have had a profound effect on fire alarm system technology. For example, there are now “smart” automatic fire detectors that can be programmed with profiles of anticipated environmental condition so that they will not be falsely actuated and cause nuisance alarms.

There are also digital communications systems that can link many elements in the system more reliably than earlier analog communications systems. Many new fire alarm subsystems are available commercially as off-the-shelf items. The installation of these tested and approved products in a system will eliminate the need for custom fabrication of components and the time required to test them for compliance. In addition, they can reduce labor costs, saving the time required to install the systems. The off-the-shelf components can be individually tested regularly and replaced easily if they are found to have developed faults.

Glossary of Telecommunications Terms

Bandwidth: The total digital data-carrying capacity of a cable, connector, or other component. Bandwidth can be expressed as a frequency at the half-power points or as megabits per second (Mbps), which refers to the rate at which computer data information is transmitted over cable. One megabit per second is 1 million bits of digital data, and a gigabit per second (Gbps) is 1 billion bits. Category 5e (CAT 5e) twisted-pair wire, coaxial, and fiberoptic cables are capable of transmitting high data rates, but fiberoptic cables have the greatest capacity for carrying data.

Blocks: Specialized insulation displacement connectors (IDCs) for making connections between voice and data cables. Blocks save time for the installer by eliminating the need to strip insulation from the wire ends to make a secure joint. There are two kinds of blocks: 66 and 110. See also *insulation displacement connectors (IDCs).*

Cable, Category 3: A performance designation for twisted-pair cable and connecting hardware that can support transmission frequencies up to 16 MHz and data rates up to 10 Mbps. Although Category 3 can support low-speed data transmission, it is now used primarily for wiring telephones.

Cable, Category 4: A performance designation for twisted-pair cable and connecting hardware that can support transmission frequencies up to 20 MHz and data rates up to 16 Mbps. It is now rarely used for high-speed telecommunications because Category 5 cable is superior in its ability to transmit high frequencies and data rates.

Cable, Category 5: A performance designation for twisted-pair cable and connecting hardware cable that can support transmission frequencies up to 100 MHz and data rates up to 100 Mbps, optimizing performance for all data and telephone systems. These rates offer more than sixfold increases in both frequency and data rate over Category 3 cable. Category 5 cable has become the standard cable for use in multimedia structured wiring for the foreseeable future because of its performance, low cost, and wide availability.

Cable, Category 5e (enhanced): A performance designation for twisted-pair cable and connecting hardware that can support transmission frequencies over 100 MHz and data rates exceeding 100 Mbps. It provides an even wider margin of performance over standard Category 5 products. However, it has not yet become as popular because of its higher cost and lower availability due to lower-volume production.

Crosstalk: Noise or interference caused by electromagnetic coupling from one signal path (copper-wire pair) to another. The two different kinds of crosstalk are near-end (NEXT) and far-end (FEXT).

Daisy-chain topology: A term describing the obsolete serial wiring technique in which each telephone or multimedia outlet is wired in series from the previous outlet. A single voice or data cable runs from its point of entry into the building and loops around to all the jacks in the home or office. If the wires or jacks in one room are damaged, all of the jacks in the loop downstream from the fault could be disabled. Troubleshooting is difficult with wiring in this topology because faults are hard to isolate. See also *home-run topology.*

Electromagnetic interference (EMI): Interference in signal transmission or reception caused by the radiation of electrical and magnetic fields. EMI is a problem only for communication over copper-wire pairs, not for fiberoptic cables.

Gastight connection: A secure metal contact-to-wire connection made when sharpened connector prongs or “teeth” shear the insulation on a wire and penetrate its surface to provide a connection that is unaffected by any oxidation caused by exposure to moisture.

Home-run (star or radial) topology: A wiring scheme in which individual wires or cables are run directly from a centralized distribution point or hub to each outlet in the system (electrical, telephone, or multimedia). It is now the preferred telecommunications wiring technique although it requires more cable than *daisy-chain topology.* Home-run topology permits conductors or services to be added or changed without disturbing any other conductors or outlets. If an outlet or conductor is damaged, only that outlet will be disabled and service to the other outlets is not affected. See also *daisy-chain topology.*

Hub: Equipment that serves as the centralized connection point for a network or a portion of the network, such as structured wiring. Hub hardware can be active or passive.

Insulation-displacement connectors (IDCs): Connectors that can make permanent "gastight" electrical and mechanical connections when pressure is applied to them so that their sharp metal "teeth" clamp down on insulated wire, shearing the wire insulation and penetrating into the underlying wire. See also *gastight connection.*

Jack: (1) An older name for a telecommunications outlet. See also *modular outlet.* (2) A female telecommunications connector such as a telephone or audio jack.

Local area network (LAN): A data network that connects computers within a single building or campus.

Modular outlet: In structured wiring systems, a female outlet that allows telephones, computers, fax machines, and other related equipment to be plugged into a telecommunications network. Modular outlets can have four, six, or eight contact positions for connecting up to eight wires.

Modular plug: In structured wiring systems, a male plug terminating a copper-wire equipment or patch cord that connects to a modular outlet. Category-rated modular plugs generally have eight contact positions.

Modules: In structured wiring systems, standardized devices packaged in similar cases that snap into boxes or housings to form outlets for structured wiring systems. They can include telephone and data jacks, coaxial jacks for TV, audio jacks for music and sound, and ST and SC jacks for fiberoptic cable.

Multimedia: A term applied to many different kinds of information and entertainment services and signal formats. Examples are telephone and computer data communication, radio broadcasts, cable and satellite TV, and the output of VCRs, DVDs, and audio CDs.

Radial topology: See *home-run topology.*

Star topology: See *home-run topology.*

Structured wire bundle: A bundle of wire and cable used in structured wiring systems. It might consist of two RG-6-coaxial cables and two Category 5 or 5e UTP cables.

Structured wiring system: A wiring system consisting of bundles of wire and cable distributed to outlets in each room being served by a multimedia system. It can accommodate voice, data, audio, video, and security signals.

Twisted pair: A pair of insulated copper wires that have been twisted around each other to create a balanced signal transmission path and reduce electromagnetic interference. Category-rated (e.g.,.CAT 5 and CAT 5e) copper data cable is twisted-pair cable.

Unshielded twisted pair (UTP): A twisted pair of insulated copper wires that do not have metal-foil or mesh shielding. An example is CAT 5 cable. See also *twisted pair*.

Wide area network (WAN): A network that connects data communications equipment, primarily computers, spaced apart over long distances and used for such applications as exchanging data between branches of the same corporation located in different cities.

ELECTRIC MOTORS AND STARTERS

CONTENTS AT A GLANCE

Overview
Motor Frame Sizes
Nameplate Information
AC Motor Principles
Single-Phase AC Motors
Starting versus Running Watts
Polyphase AC Induction Motors
AC Motor Starters
DC Motor Principles
DC Motor Characteristics
Permanent-Magnet DC Motors
DC Motor Starting
Glossary of Motor Terms

Overview

For well over a century, electric motors of various kinds have been powering machine tools, process machinery, street cars, appliances, pumps, fans, tools, and many other products. Electric motors are being been purchased as independent sources of mechanical power for a wide range of systems and as components embedded in manufactured products such as machine tools, material handling equipment, and appliances. Motors range in size from fractional-horsepower clock motors to industrial giants rated for more than 500 hp, and they provide the driving power for equipment as diversified as electric trains, elevators, escalators, street cars, cranes, and ocean-going ships.

Electric motors are broadly classified as direct current (DC) or alternating current (AC), although universal motors can be powered by either AC or DC. Motor identification and classification are complicated and can be quite confusing because of the similarities in features and construction that span the divide between AC and DC motors. To clarify the situation, Fig. 10-1 shows the interrelationships of the leading characteristics of motors. It identifies the four generic types of DC motors and the five generic types of AC motors, excluding the universal motor. There are both single-phase and polyphase induction and synchronous motors, and both single-phase and polyphase induction motors can have either squirrel-cage or wound rotors.

The electric motors discussed in this chapter can be catalog or even off-the-shelf distributor models, or they can be custom-designed and built specifically for one customer. The most versatile motors are classified as general-purpose, but many custom-built models are essentially variations of general-purpose models with additional features to adapt them for more efficient performance of some specialized task. If these motors fill an important applications niche they will be sold to other customers, and if demand for them increases they might become catalog or production models and continue to be made in volume. Among the specialized motors available today are agricultural motors, brakemotors, chemical service, compressor-duty, explosion-proof, fan and blower, food-processing washdown, pressure washer, and even poultry and woodworking motors.

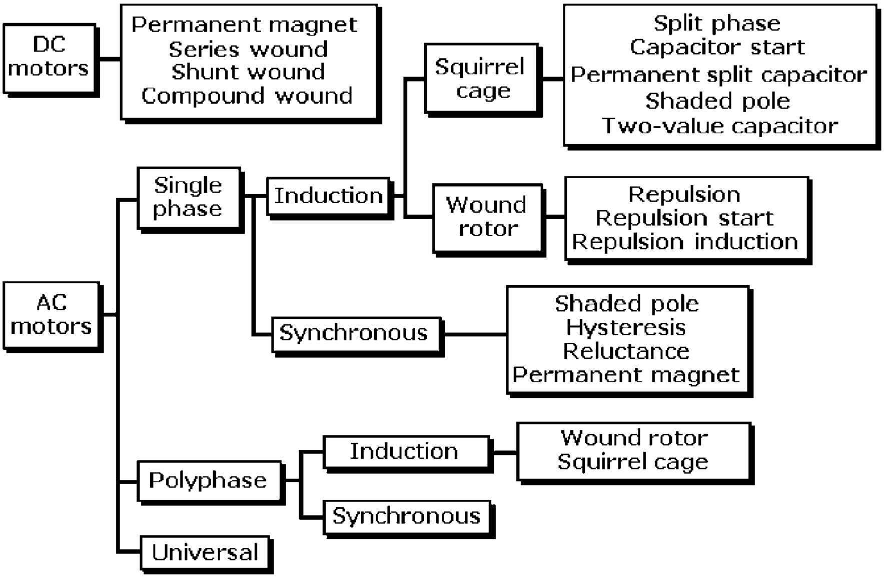


Figure 10-1 Classification of AC and DC motors.

These applications call for differences in starting torque, starting current, horsepower rating, and other parameter such as full-load slip. They also call for different dimensions, construction, and materials. There are motors with open drip-proof or totally enclosed frames. Washdown motors are made to withstand the frequent washing needed to remove spilled food or chemicals. Splash-proof motors can resist liquids spilled on them, and explosion-proof motors with completely enclosed frames confine any internal electrical arcing that could ignite fires or set off explosions.

Electricians and equipment installers run approved wiring to the outlets rated for higher current needed for the motors in washing machines, clothes dryers, and air conditioners, which are equipped with the proper mating plugs. They must account for their voltage requirements and wattage and install them in properly rated branch circuits. Some building service equipment with motors, such as furnaces, hot-water heaters, air-conditioning systems, fans, and pumps, are permanently wired in branch circuits.

Most motors in homes and offices are single-phase, fractional-horsepower AC units, but integral-horsepower AC motors power equipment such as elevators and HVAC equipment in high-rise buildings, shopping malls, hospitals, and factories.

Because of their prominent use, the focus in this chapter is on AC motors and controls. The principal types of AC motors are described and their characteristics are compared. However, most motors in automobiles, streetcars, electric-powered trains, aircraft, and industrial and military motion-control systems are DC motors. Common DC motors are also described in this chapter, and their characteristics are compared. Finally, a glossary of motor terms is included at the end of the chapter for ready reference.

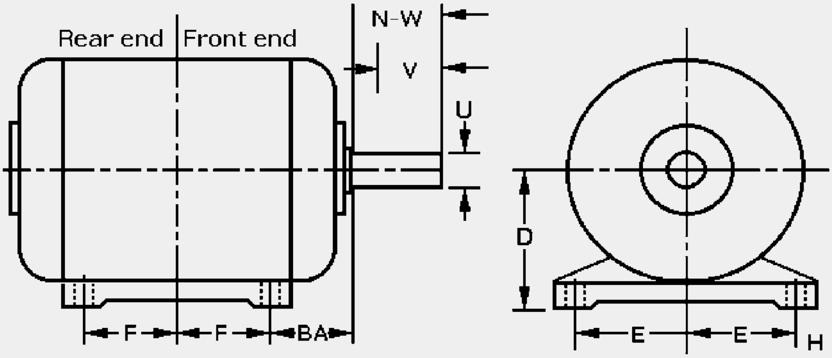
Motor Frame Sizes

Motor frame or housing sizes and their mounting dimensions have been standardized by the National Electrical Manufacturers Association (NEMA), primarily to assure that existing commercial motors can be replaced with new ones without altering their space requirements, mounting holes, or couplings. Frame numbers correlate with the physical size of motor frames or housings; for example, a NEMA 42 motor frame has both a diameter and a length of about 6 in., while a NEMA 445T motor frame has a diameter of about 20 in. and a length of about 24 in., both exclusive of shaft length.

Table 10-1 is a condensed table of NEMA motor frame-size dimensions, limited to smaller motors to provide an overview of NEMA frame-size organization. It contains only the four dimensions that generally define the overall size of the motor: D, 3E, 2F, and BA. It does not include the NEMA-defined dimensions for:

- H: Slots in motor bases
- N-W: Projections of shafts beyond the BA dimension

TABLE 10-1 MOTOR DIMENSIONS FOR NEMA FRAMES



Some key standardized dimensions established by the National Electrical Manufacturers Association (NEMA) are listed below. They apply to all base-mounted motors that carry a NEMA frame designation. Letter designations for dimensions not listed are explained in the text. All dimensions are in inches.

NEMA FRAME	D	2E	2F	BA
42	$2\frac{5}{8}$	$3\frac{1}{2}$	$1\frac{11}{16}$	$2\frac{1}{16}$
48	3	$4\frac{1}{4}$	$3\frac{3}{4}$	$2\frac{1}{2}$
56			3	
56H	$3\frac{1}{2}$	$4\frac{7}{8}$	3 and 5	$2\frac{3}{4}$
56HZ	$3\frac{1}{2}$			
66	$4\frac{1}{8}$	$5\frac{7}{8}$	5	$3\frac{1}{8}$
143T	$3\frac{1}{2}$	$3\frac{1}{2}$	4	$2\frac{1}{4}$
145T			5	
182	$4\frac{1}{2}$	$7\frac{1}{2}$	$4\frac{1}{2}$	$2\frac{3}{4}$
184			$5\frac{1}{2}$	
182T			$4\frac{1}{2}$	
184T			$5\frac{1}{2}$	
213	$5\frac{1}{4}$	$8\frac{1}{2}$	$5\frac{1}{2}$	$3\frac{1}{2}$
215			7	
213T			$5\frac{1}{2}$	
215T			7	

TABLE 10-1 MOTOR DIMENSIONS FOR NEMA FRAMES (*CONTINUED*)

NEMA FRAME	D	2E	2F	BA
254U			$8\frac{1}{4}$	
256U			10	
	$6\frac{1}{4}$	10		$4\frac{1}{2}$
254T			$8\frac{1}{4}$	
256T			10	
284U			$9\frac{1}{2}$	
	7	11		$4\frac{3}{4}$
286U			11	
284T			$9\frac{1}{2}$	
284TS	7	11	$9\frac{1}{2}$	$4\frac{3}{4}$
286T			11	
324U			$10\frac{1}{2}$	
326U			12	
	8	$12\frac{1}{2}$	$10\frac{1}{2}$	$5\frac{1}{4}$
324T			12	
326TS			12	
364T	9	14	$11\frac{1}{4}$	$5\frac{7}{8}$
365T			$12\frac{1}{4}$	
364U			$11\frac{1}{4}$	
	9	14		$5\frac{7}{8}$
365U			$12\frac{1}{4}$	
404T			$12\frac{1}{4}$	
	10	16		$6\frac{5}{8}$
405T			$13\frac{3}{4}$	
444T			$14\frac{1}{2}$	
	11	18		$7\frac{1}{2}$
445T			$16\frac{1}{2}$	

- U: Shaft diameters
- V min: Shaft lengths available for coupling pinion or pulley hubs

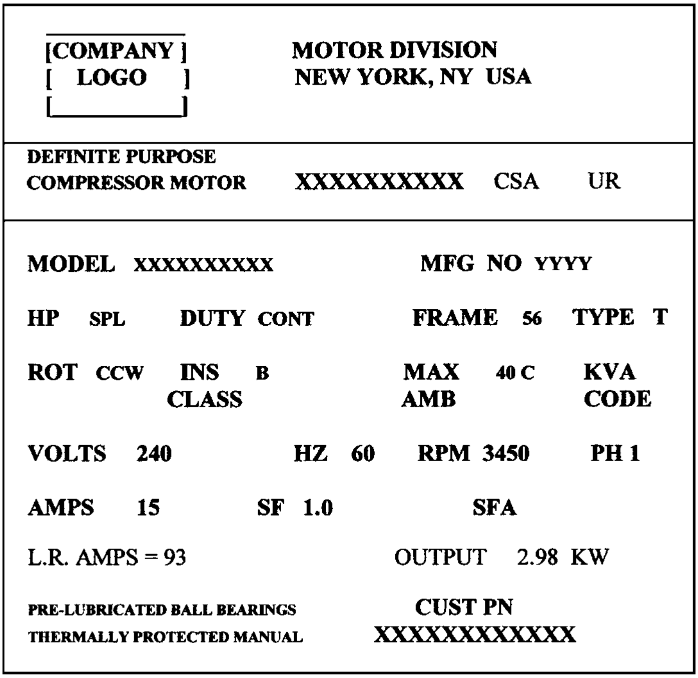
NEMA also specifies face-mounting dimensions for certain small motors, designated as C and J. These dimensions cover such variables as shaft diameter, length, and type, and both rabbet and bolt-circle diameters. NEMA also has standards for hub dimensions on sump pump motors and flange-mount dimensions for oil burner motors. Most NEMA frame numbers include suffix letters with the following meanings:

- C: Face mount
- H: Has 2F dimension larger than same frame without H suffix
- J: Face mount for jet pumps
- K: Has hub for sump pump mounting
- M, N: Flange mount for oil burner
- T, U: Integral-hp motor dimension standards set by NEMA in 1953 and 1964
- Y: Nonstandard mounting
- Z: Nonstandard shaft (N-W, dimensions)

Nameplate Information

Nameplates for single-phase and polyphase induction motors include information needed for the proper application, installation, operation, and maintenance of the motors. Figure 10-2 illustrates the nameplate format for a compressor motor. The abbreviations CSA and UL on the upper right side of the nameplate are the logos for the Canadian Standards Association and Underwriters' Laboratories Inc. If their motors are recognized by UL and approved by CSA, manufacturers are permitted to put the CSA and UL logos on their nameplates. Manufacturers include their own identification numbers as well as the motor's serial and model numbers. NEMA Standard MG 1 requires the following information on the nameplate, as applicable:

- Manufacturer's type and frame designation (TYPE and FRAME)
- Horsepower output (HP)
- Shaft rotation direction (ROT)
- Maximum ambient temperature for which motor is designed (MAX AMB)
- Insulation system designation (INSUL CLASS)
- RPM at rated load (RPM)
- Frequency (HZ)
- Number of phases (PH)
- Rated load current (AMPS)
- Voltage (VOLTS)
- Rating or duty (RATING)
- Locked rotor current (L.R. AMPS)



[COMPANY]
[LOGO]
MOTOR DIVISION
NEW YORK, NY USA

DEFINITE PURPOSE
COMPRESSOR MOTOR XXXXXXXXXX CSA UR

MODEL XXXXXXXXXX MFG NO YYYY
HP SPL DUTY CONT FRAME 56 TYPE T
ROT CCW INS CLASS B MAX AMB 40 C KVA CODE
VOLTS 240 HZ 60 RPM 3450 PH 1
AMPS 15 SF 1.0 SFA
L.R. AMPS = 93 OUTPUT 2.98 KW
PRE-LUBRICATED BALL BEARINGS
THERMALLY PROTECTED MANUAL
CUST PN XXXXXXXXXXXXX

Figure 10-2 Example of a motor nameplate.

- Service factor (SF)
- Words “THERMALLY PROTECTED” if motor is protected as specified in MG 1
- Words “OVER TEMP. PROT.” followed by a type number identifying protection type for motors rated above 1 hp equipped with overtemperature devices or systems

AC Motor Principles

Induction motors are common forms of *asynchronous motors.* They are called induction motors because currents flowing in their rotors are *induced* by alternating currents. There are two principal types of induction motor—*single-phase* and *polyphase.* Polyphase induction motors are classed as *squirrel-cage* or *wound-rotor.*

Polyphase induction motors have wound stators and either squirrel-cage or wound rotors. They operate in accordance with the same physical principles, and their stators are made the same way, but rotor construction differs. Polyphase motors are the simplest and most robust electric motors now being built. They act like AC transformers but have stationary primary windings and rotating secondary windings. The stator primary windings are connected to power sources, and their short-circuited rotor windings produce mechanical torque in response to the induced secondary current. This motor torque is produced by the interaction of the secondary rotor currents with the electromagnetic flux or field that exists in the air gap between the stator and rotor. Induction motors are discussed in detail later in this chapter.

Single-phase motors are classified into three general classes: (1) *commutator motors,* (2) *induction motors,* and (3) *synchronous motors.* Most single-phase AC motors are fractional-horsepower motors. Induction motors require additional components and special methods for starting, so they are further classified according to starting method: (1) *split-phase,* (2) *repulsion-start,* and (3) *shaded-pole.* Single-phase AC motors are discussed in greater detail later in this chapter.

Synchronous motors are constant-speed motors that operate in absolute synchronism with AC line frequency. As with squirrel-cage induction motors, speed is determined by the number of pairs of poles, and is always a multiple of the line frequency. Synchronous motor sizes range from subfractional self-excited units for driving clocks to large integral-horsepower DC-excited units for industrial applications.

Integral-horsepower synchronous motors are generally more efficient than induction motors with the same horsepower and speed ratings. The normal value of field current in a synchronous motor provides a unity power factor and minimum stator current. For a given load, varying the field excitation can alter the power factor from a low lagging to a low leading condition, providing a convenient means for correcting power factor.

The two major types of synchronous motors are *nonexcited* and *DC-excited.* Nonexcited motors, made in reluctance and hysteresis designs, have self-starting circuits and do not require external excitation. DC-excited motors, generally made in integral-horsepower sizes, require DC supplied either through slip rings from a separate source or a DC generator connected directly to their shafts.

A synchronous motor rotor is first brought up to synchronous speed by one of the two methods. The excited rotor poles are then attracted by the rotating stator's magnetic field, and the rotor continues to turn at synchronous speed. In this way, the rotor is *locked* into step magnetically with the rotating magnetic field. As with squirrel-cage induction motors, speed is determined by the number of pairs of poles, and is always a multiple of line frequency.

If for some reason the rotor is forced out of step with the rotating stator magnetic field, the attraction is lost, no torque is developed, and the motor will stop. Thus a synchronous motor develops torque *only* when it is running at synchronous speed.

Single-Phase AC Motors

As stated earlier, the three general classes of single-phase motors are commutator, induction, and synchronous. Induction motors with squirrel-cage rotors include split-phase, repulsion-start, and shaded-pole motors, and the four types of split-phase motors are resistance-start, split-phase (SP), capacitor-start (CS), permanent split-capacitor (PSC), and the two-capacitor start/one-capacitor run motors.

Commutator motors with wound armatures can be universal, repulsion, or repulsion-induction motors. An example of a single-phase, fractional-horsepower synchronous motor is the Warren motor developed to drive electric clocks and timers.

Most single-phase AC motors have fractional horsepower ratings from $^1/_{20}$ to $^1/_2$ hp, although some are rated up to 5 hp. Motors in this class are most widely used where the only power available is a single-phase 120/240-V, 60-Hz power source.

SPLIT-PHASE MOTORS

The *split-phase* (SP), or more accurately, the *resistance-start, split-phase, induction-run motor,* is recommended for medium-duty applications. It can run at constant speed even under varying load conditions where moderate torque is acceptable. Split-phase motors have squirrel-cage rotors and both a *main* or *running* winding and a *starting* or *auxiliary* winding. The schematic diagram for an SP motor, Fig. 10-3*a,* shows the starting winding in series with a centrifugal switch and the main winding in parallel across the AC line. The starting winding is wound with fewer turns of smaller-diameter, higher-resistance wire than the main winding. When energized, current flowing in the starting winding is essentially in phase with the line voltage, but current flowing in the parallel main winding lags behind line voltage because it has lower resistance and higher reactance. This lag "splits" the single phase of the AC line by introducing about a 30° electrical phase difference between the currents in the two windings. Although it is small, this phase difference is enough to provide a weak rotating magnetic field which interacts with the rotor, causing it to rotate.

The typical torque–speed curves for an SP motor, Fig. 10-4, show that starting current is high and running torque is moderate When rotor speed reaches about 80 percent of its rated full-load synchronous speed, its built-in automatic centrifugal switch disconnects the starting winding, protecting it from destructive overload. The SP motor then continues to run on the single oscillating AC field established by its main winding.

SP motors are rated from $^1/_{20}$ to $^1/_3$ hp when operating from a 120/240-V AC line, and full-load speed is from 865 to 3450 rpm. These motors are recommended for applications where motor stops and starts are frequent. SP motors are used to drive fans, blowers, pumps, office machines, and power tools where the load is applied after the motor has reached its operating speed.

CAPACITOR-START MOTORS

The *capacitor-start* (CS), or more precisely, *capacitor-start, induction-run motor,* is a modified split-phase induction motor used for hard-to-start loads. CS motors are efficient and require starting currents about 5 times their full-load currents. The schematic Fig. 10-3*b* shows that the CS motor circuit is the same as the SP motor circuit, except that it includes a centrifugal starting switch and a small-value AC electrolytic capacitor in series with its starting winding.

The typical torque–speed curves for a CS motor, Fig. 10-5, show that it provides about twice the starting torque of an SP motor. The capacitor lowers the motor's starting current and increases the phase difference between currents in the running and starting windings to 90°. (This is about 60° more than the phase difference in SP motors.) The capacitor functions only when the CS motor is started, so it can be relatively small and inexpensive. Both the starting winding and capacitor are disconnected

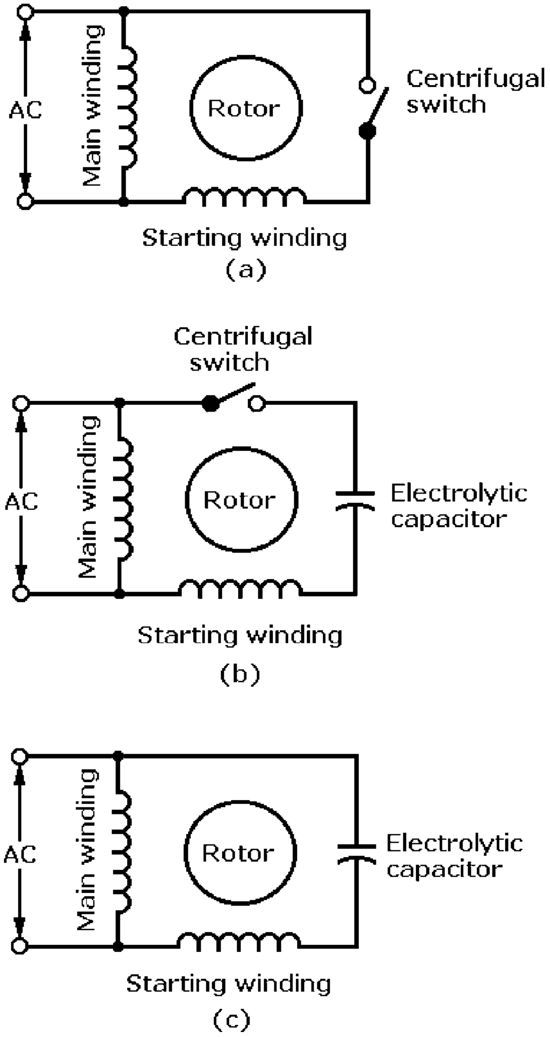


Figure 10-3 Single-phase motors: (*a*) resistance-start, split-phase; (*b*) capacitor-start; (*c*) permanent split-capacitor.

by the centrifugal starting switch when the CS motor reaches about 80 percent of its running speed. The motor then continues to run with only its main winding energized.

CS motors are rated from $\frac{1}{8}$ to $\frac{3}{4}$ hp. They run at constant speed under varying loads, offer high running and starting torques, and high overload capacity. Their range of full-load synchronous speeds matches that of SP motors—865 to 3450 rpm when powered from a 120/240-V AC line. CS motors are used to drive machine tools, refrigerator and air-conditioning compressors, conveyors, pumps, blowers, and fans.

The major components of a fan-cooled CS motor are identified in the exploded view Fig. 10-6. The capacitor in this motor is mounted outside the motor frame in a removable protective housing, to make it easier to replace if necessary.

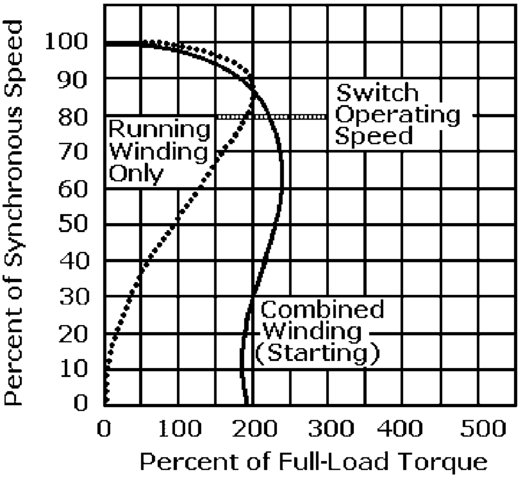


Figure 10-4 Speed–torque curves for a typical split-phase motor.

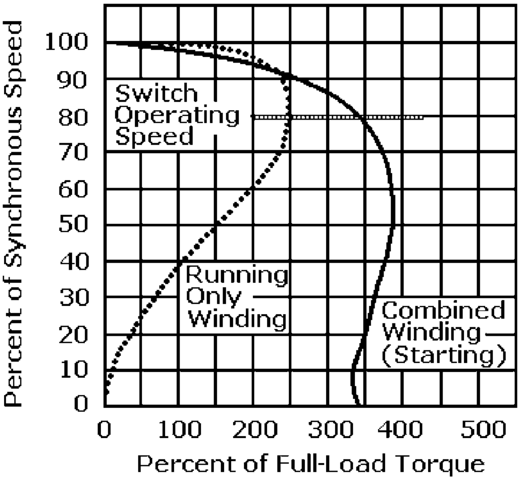


Figure 10-5 Speed–torque curves for a typical capacitor-start motor.

PERMANENT SPLIT-CAPACITOR MOTORS

The *permanent split-capacitor* (PSC) motor is compact, easily maintained, and highly efficient. The schematic for this motor, Fig. 10-3*c,* shows an electrolytic capacitor in series with the starting winding and the main winding connected in parallel across the AC line. These windings are energized during both starting and running.

Unlike both SP and CS motors, PSC motors *do not* include a centrifugal switch. The typical speed–torque curve for a PSC motor, Fig. 10-7, shows the low starting torque and smooth acceleration of this motor. An important feature of these motors is their ability to run at different speeds.

PSC motors are rated from $\frac{1}{4}$ to 1 hp, and they are used to drive refrigerator and air-conditioning compressors, dehumidifiers, garage door openers, floor-polishing machines, and fans for heaters and attic ventilation.

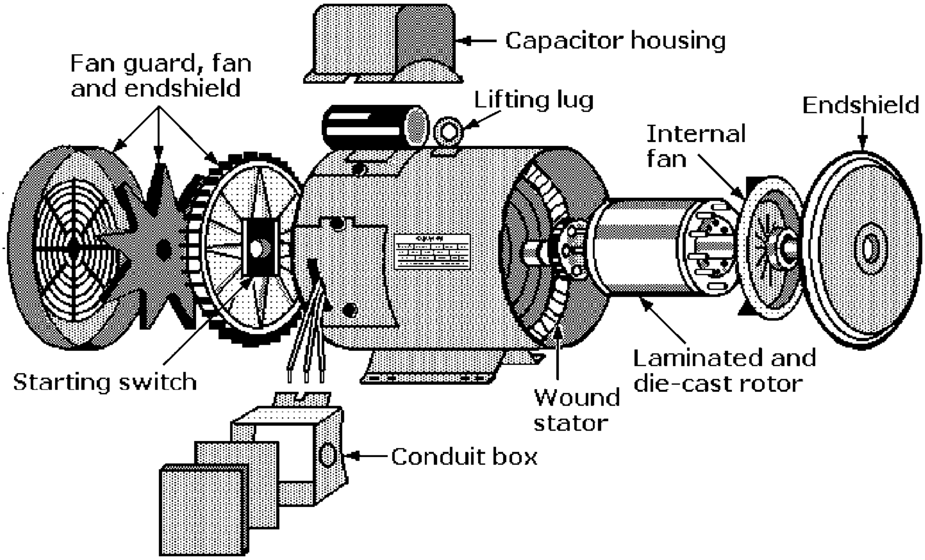


Figure 10-6 Exploded view of a capacitor-start motor in a 182-4T frame.

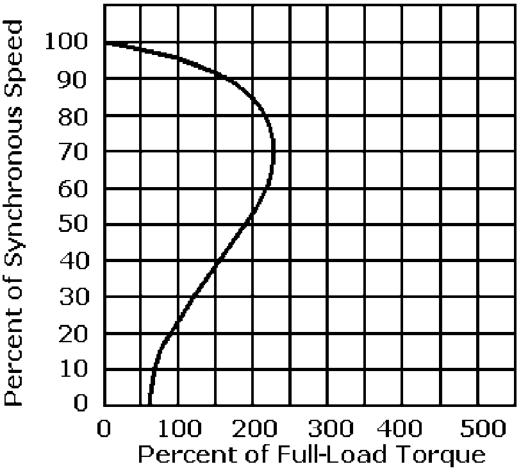


Figure 10-7 Speed–torque curve for a typical permanent split-capacitor motor.

TWO-CAPACITOR START/ONE-CAPACITOR RUN MOTORS

The *two-capacitor start/one-capacitor run motor* is a variation of the permanent split-capacitor motor. The schematic for this motor, Fig. 10-8, shows an electrolytic capacitor in series with a centrifugal switch and in parallel with an oil-type capacitor which is in series with the starting winding. As in the other single-phase motors, the main winding is in parallel across the AC line. The electrolytic capacitor is used for starting and the oil-type capacitor is used for both starting and running. The two capacitors give these motors higher starting torque and lower starting current than PSC motors.

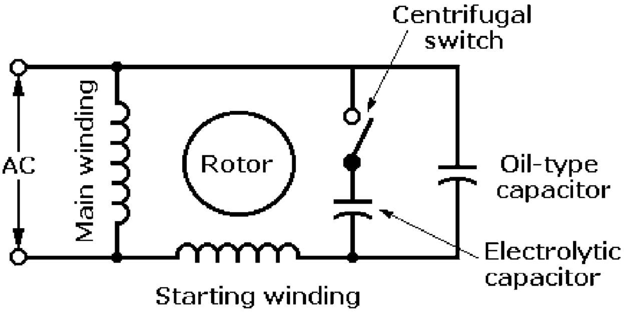


Figure 10-8 Two-capacitor start/one-capacitor run motor.

They also improve the motor's efficiency while reducing its running noise below that of comparably rated PSC motors.

The use of two capacitors for starting and one for running overcomes compromises made in PSC motors and can provide optimum running and starting characteristics. When the motor is started, the two capacitors are in parallel, but as the motor approaches a predetermined speed, the electrolytic capacitor is disconnected by the centrifugal switch.

The PSC motor runs cooler than the other capacitor motors, and its lower starting current contributes to its longer life and the greater reliability of the centrifugal switch. Two-capacitor start/one-capacitor run motors are used in many of the same applications as PSC motors, where their higher performance justifies their higher cost. However, these motors are usually only rated for 1 hp or more.

SHADED-POLE (NONSYNCHRONOUS) AC MOTORS

Shaded-pole AC motors are simple, nonsynchronous induction motors that offer low starting and running torque. With no internal switches, brushes, or special parts, they are inexpensive to make and low in cost. Because of their low efficiency, they are made only with fractional horsepower ratings, for powering clocks and small consumer appliances.

The stator poles of shaded-pole motors have been modified to form short-circuited auxiliary *shading coils,* as shown in Fig. 10-9. The narrow slots cut in the main poles form the auxiliary shaded poles, which are about one-third as wide as the main poles. They are wrapped with copper straps as shown.

When the main motor windings are energized, the oscillating magnetic field induced around the main poles induces a current in the shading coils. This current reduces the magnitude of the main magnetic field and causes it to lag in time phase. Because the main and shading coils are separate, a shifting magnetic field similar to a rotating field is established across the pole faces. This field interacts with the motor's squirrel-cage rotor to produce a small starting torque that can rotate the rotor in only one direction.

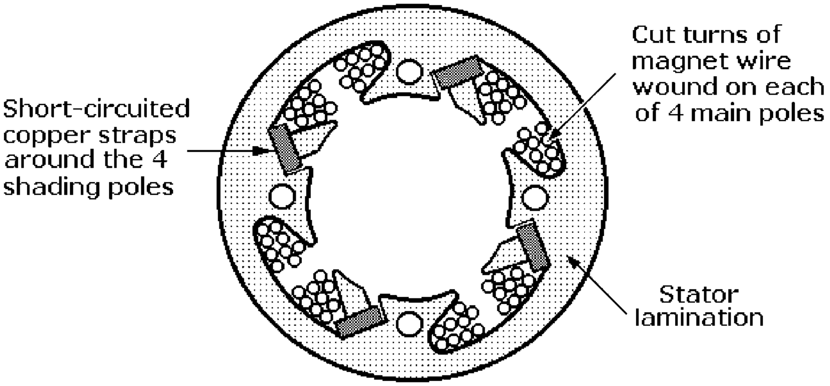


Figure 10-9 **End view of the stator of a four-pole shaded-pole motor with four shading poles.**

Shaded-pole motors run quietly, without vibration. They are considered "fail-safe" for powering small appliances such as fans, hair dryers, and clocks because they start and turn in only one direction. They are made with ratings from 1/2000 to $^1/_6$ hp, and have full-load speeds of 1450 to 3000 rpm when powered from a 120/240-V AC line. Rotor speed can be changed by controlling the voltage with resistors or semiconductor devices.

REPULSION-START/INDUCTION-RUN AC MOTORS

The *repulsion-start/induction-run motor* (RSIR) is a single-phase, constant-speed AC motor suited for such general-purpose applications as driving pumps and compressors, where high starting torque is required. Its starting torques are higher than those of split-phase motors, although fractional-horsepower capacitor-start motors have similar starting characteristics. RSIR motors are often inaccurately called repulsion-induction motors.

The RSIR motor, as its name implies, starts as a repulsion motor and runs as an induction motor. It has a stator with a single-phase winding and brush-type rotor with DC windings that are connected to a commutator. The rotor automatically converts from its DC starting mode to an AC induction-motor mode when the motor nears full speed.

A conducting ring mounted at the end of the commutator is pressed against the commutator by centrifugal force, short-circuiting it when transition speed is reached. This gives the motor its very high torque per ampere starting feature and its single-phase induction-motor speed regulation characteristics. These motors are made with ratings from about $^1/_8$ to 5 hp, but custom versions up to 40 hp have been built. Full-load speeds for fractional-horsepower RSIR motors range from 900 to 3600 rpm when they are powered from a 120/240-V AC line.

UNIVERSAL AC/DC MOTORS

Universal motors are modified series-wound, brush-type DC motors optimized for single-phase AC operation. They have different winding ratios than comparable DC series-wound motors, and their steel laminations are thinner. A series-wound DC motor run on AC is inefficient, but a universal motor can operate on DC with essentially equivalent AC performance. However, its commutation is poorer than that of a comparably rated DC series-wound motor. Fractional-horsepower universal motors are popular because they offer the highest horsepower per pound and per dollar of any single-phase AC motor, and they can be run from rechargeable batteries. Also, their starting torque is higher than that for the motors running on either an AC or DC supply.

Universal motors have wound stators and armatures and mechanical brush-type commutators. They can run on either AC or DC because their armatures and fields, like those of DC shunt-wound motors, are connected in series. (See also "Series-Wound DC Motors"). They are rated from $^1/_{150}$ to 1 hp, but most are rated under $^1/_2$ hp. Universal motors are the only small motors that can run at speeds greater than 3600 rpm when operating from a 120/240-V, 50/60-Hz line. Their full-load speeds can range from 3000 to 10,000 rpm, and this is why they are so versatile.

Universal motors are classed as variable- or adjustable-speed motors because their speed can be controlled by thyristors, silicon controlled rectifiers (SCRs) or triacs, and variable resistors. These motors power portable tools such as drills, saws, and sanders, as well as vacuum cleaners, food mixers, and other small appliances. Portable power drills driven by universal motors usually have reduction gears to slow their operating speed.

Starting versus Running Watts

In determining the electrical load for single-phase AC motors, their starting watts should be compared with their running watts when making load calculations. Starting watts for most single-phase AC motors rated from $^1/_8$ to 3 hp average about 3 times their running watts, about a 300 percent increase. Some AC motor manufacturers stamp the starting watts on their motor nameplates. Starting watt values are needed for making accurate estimates of the electrical load for branch circuits or entire buildings.

These values for AC motors can be determined by first calculating running watts. This is done by multiplying the nameplate amperes by the nameplate voltage rating. For example, if the nameplate reads 5A @ 120V, multiply those values together (5A × 120 V) to obtain a running watts value of 600 W. Then multiply running watts by a factor of 3 (600 V × 3) to obtain a starting watts value of 1800 W.

Table 10-2 gives approximate starting watts for four types of single-phase AC motors—universal, repulsion-induction, capacitor, and split-phase—recognizing the differences in characteristics among them. This table can be entered either with knowledge of the motor horsepower ratings from $^1/_8$ to 3 hp and/or knowledge of approximate running watts. It will save time and effort in making load estimates.

Polyphase AC Induction Motors

Polyphase induction motors are the most widely used integral-horsepower AC motors because they are simple, ruggedly built, and offer good operating characteristics. The

TABLE 10-2 RUNNING AND STARTING LOADS FOR SINGLE-PHASE AC MOTORS

		APPROXIMATE STARTING WATTS			
MOTOR HP RATINGS	APPROXIMATE RUNNING WATTS	UNIVERSAL MOTORS (APPLIANCES)	REPULSION-INDUCTION MOTORS	CAPACITOR MOTORS	SPLIT-PHASE MOTORS
1/8	275	400	600	850	1200
1/4	400	500	850	1050	1700
1/3	450	600	975	1350	1950
1/2	600	750	1300	1800	2600
3/4	850	1000	1900	2600	X
1	1000	1250	2300	3000	X
1 1/2	1600	1750	3200	4200	X
2	2000	2350	3900	5100	X
3	3000	X	5200	6800	X

X: Motors with higher horsepower ratings are not in general use.

stators of these motors are connected to the AC line, but their rotors are not because they are considered to be secondary windings with current induced in them by the transformer primary winding action of the stator. Because of this, the stator is sometimes called the primary and the rotor is sometimes called the secondary.

Three-phase induction motors offer high starting torque, high power factor, and high efficiency. These characteristics enable them to drive most equipment with loads that must be brought up to operating speed from standstill smoothly and quickly. Figure 10-10 is a typical speed–torque curve for polyphase motors.

Three-phase induction motors can have either squirrel-cage or wound rotors. Both motors operate on the same principles and have the same stator construction. Polyphase motors with squirrel-cage rotors are basically constant-speed machines, but their operating characteristics can be varied by modifying the design of their rotor slots to change torque, current, and full-load speed.

Stator cores of polyphase AC motors are made by stacking slotted sheet-steel laminations and clamping them in a stator frame of cast iron or fabricated steel plate. The copper stator windings are spaced 120 electrical degrees apart in the slots, and their electrical connections can be either be wye or delta.

Squirrel-cage rotors of modern three-phase induction motors are built by stacking round slotted steel laminations to form a cylindrical core. Aluminum is cast in the slots to form secondary conductor bars and short-circuiting rings at the ends of the bars. Rotor bars and end rings have also been cast from copper. The bars are slightly skewed from parallel with respect to the shaft to provide more uniform torque and reduce the humming noise of the magnetic field when the motor is running.

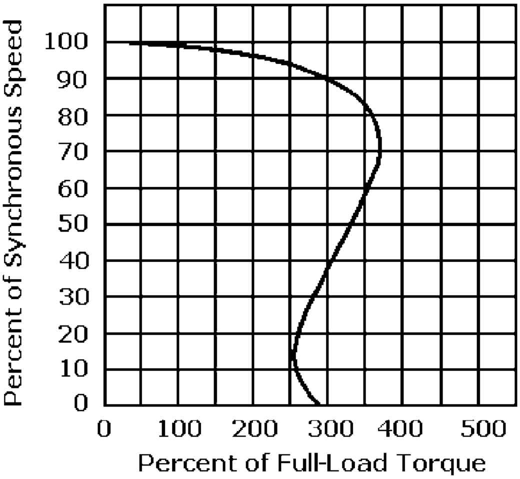


Figure 10-10 Speed–torque curve for a typical polyphase AC motor.

Conductor bars and end rings are not insulated from the core because the rotor currents naturally follow the paths of least resistance, the conductors. The barred rotor suggests a cylindrical "squirrel cage." The rotors of wound-rotor or slip-ring motors are wound from insulated conductors in much the same way as the insulated windings of stators. Rotor phase windings are wye-connected, with the open end of each phase brought out to a slip ring mounted on the rotor shaft and brushes. However, these slip rings and brushes are not connected to a power source because their function is to provide a connection for an external variable-control resistor into the rotor circuit. Wound-rotor motors are less widely used than squirrel-cage motors because of their higher cost and the maintenance of the wound rotors required.

When a three-phase induction motor is energized with three-phase AC power, the windings produce an alternating rotating magnetic field that revolves in synchronism with the line frequency. Rotation direction is determined by the time sequence of the currents in the windings. As the rotating field sweeps past the bars in the rotor at synchronus speed, it induces currents which flow in the conductors to set up a magnetic field with a corresponding polarity. This results in a repulsion–attraction response between the rotating magnetic field of the stator and the induced field in the rotor. The rotor rotates as it attempts to keep up with the rotating magnetic field, and the rate at which the lines of flux cut the rotor determines the induced voltage. Three-phase motor rotation can be reversed by interchanging any two of the three motor supply lines.

The magnetic field rotates at the synchronous speed of the motor determined by the number of poles in the stator and the frequency of the power supply. The synchronous speed N_s a motor is given by

$$N_s = \frac{120f}{P}$$

where f = line frequency in hertz and P = the number of poles of the winding.

When the rotor is at rest, voltage is at a maximum, but as rotor speed increases, the current and related torque are reduced. The maximum speed of the induction motor is set by the synchronous speed, but if rotor speed ever reaches synchronous speed, the induced current and torque would fall to zero and the rotor would spin to a stop. To prevent this, the rotor always runs at a speed less than synchronous speed. Nevertheless, even at a slower speed, enough rotor current flows to provide sufficient torque to overcome internal losses and still drive the load.

The difference or lag between rotor speed and synchronous speed is called *slip,* and it is expressed as a percentage of synchronous speed. At full load, synchronous slip is typically 3 to 5 percent. Synchronous slip S_s is given by

$$S_s = \frac{100\,(N_s - N_a)}{N_s}$$

where N_s = synchronous speed in rpm and N_a = actual speed in rpm.

Polyphase motors are built in ratings from $1/6$ to 500 hp. They are widely used to power grinders, lathes, drill presses, industrial pumps, compressors, and conveyors. They also drive high-speed continuous-process newspaper and magazine printing machines, farm equipment, cranes and hoists, and many other kinds of materials handling equipment.

AC Motor Starters

A prime requirement for an AC motor starter is that the motor starting torque be sufficient to start the load under the worst-case line-voltage and load conditions. Secondary requirements for the starter are that it have the ability to accelerate the motor smoothly, be easy to maintain, and be reliable and efficient. Also, the ability of motor and power supply line to withstand the peak current when the starter transfers the motor to full voltage should be considered in selecting the starter.

Induction motors can be connected directly across the power line without damaging them, but that connection method sets up a voltage surge on the power lines because of the heavy starting currents drawn. As a result, motors rated for more than 7.5 to 10 hp are usually started at reduced voltage. The maximum allowable horsepower rating of a motor that can be started on full voltage without causing undesirable power-line effects depends on its design, the power-line capacity, and the local power utility's regulations.

As can be expected, the starting torque exerted by an induction motor started on full voltage exceeds the starting torque of one started on reduced voltage. In fact, that torque is proportional to the square of the applied voltage. For example, if the starting voltage is reduced to 80 percent of its rated value, starting torque will be only 64 percent of the full-voltage starting value. Reduced starting voltage lowers starting current, but it also increases the time needed for the motor to accelerate because of reduced starting torque.

The nature of the load being started also influences the starting method to be used. If the load is vulnerable to damage from the shock of a sudden start and high acceleration, only reduced-voltage starting should be used. When a full-voltage AC motor starter can be used, an *across-the-line starter* is generally recommended. However, when the starting inrush must be lower, *reduced-voltage starters* are recommended. These include the *autotransformer, primary resistance,* and *semiconductor starters.*

ACROSS-THE-LINE STARTERS

AC across-the-line starters are relatively simple circuits, easy to install and maintain, and inexpensive. A typical starter consists of a three-pole contactor with a thermal overload relay for protecting the motor. These starters connect motors directly to the line, applying full voltage to the motor terminals. Because of this the motors will draw inrush currents 6 to 10 times their running current. This is not objectionable in most motor installations, and this overcurrent will not damage the motor or the machinery being driven. These starters are particularly suitable for squirrel-cage motors.

Figure 10-11 is a schematic diagram of a magnetic across-the-line AC starter connected to a three-phase AC motor. The starter is controlled by a three-wire stop–start pushbutton control circuit. These starters are usually equipped with thermal overload relays in each phase, as shown in the figure. The three-wire pushbutton control provides undervoltage protection for the motor.

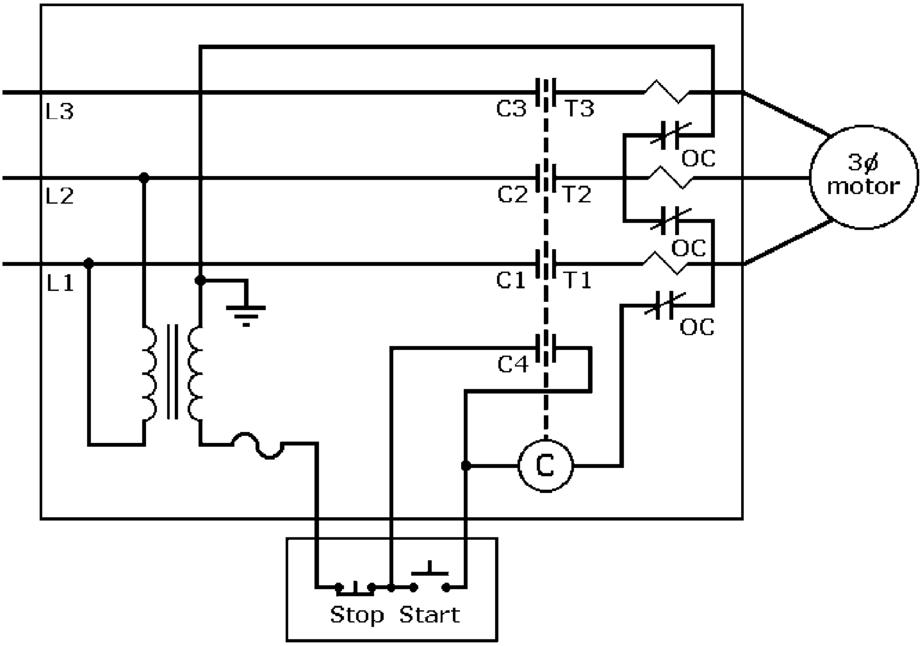


Figure 10-11 Schematic of an across-the-line motor starter circuit powered by a three-phase, three-wire supply.

Figure 10-12 is a schematic diagram for another across-the-line motor starter connected to a three-phase AC motor and powered from a three-phase, 440-V AC supply. However, the stop and start pushbuttons are in a 110-V AC circuit stepped down from 440 V AC by a transformer, and the main power switch is ahead of the starter. The 110 V from the transformer also powers other external control circuits.

AUTOTRANSFORMER STARTERS

Autotransformer starters have two autotransformers connected in open delta to provide reduced-voltage starting. Figure 10-13 is a schematic for an *automatic open-transition autotransformer starter.* It has a five-pole starting contactor S and a three-pole running contactor R. Three taps are included, giving 50, 65, and 80 per-

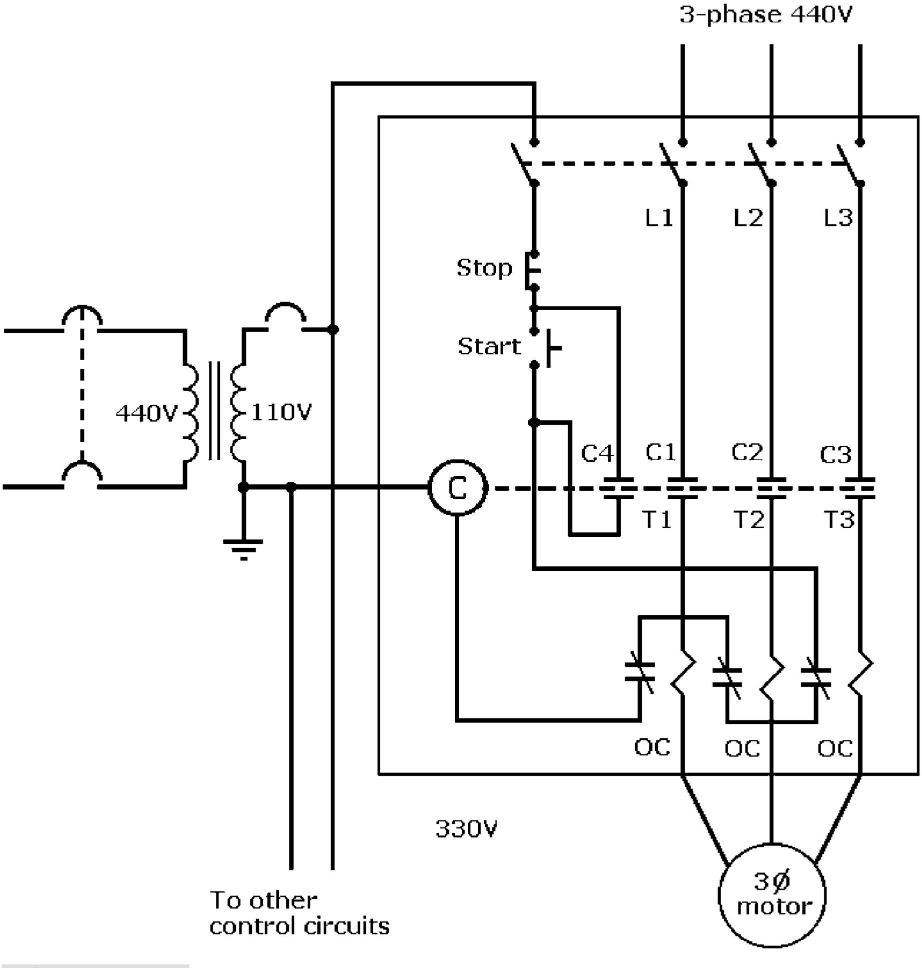


Figure 10-12 Schematic for an across-the-line motor starter powered by three-phase, 440 V AC but controlled by 110 V AC.

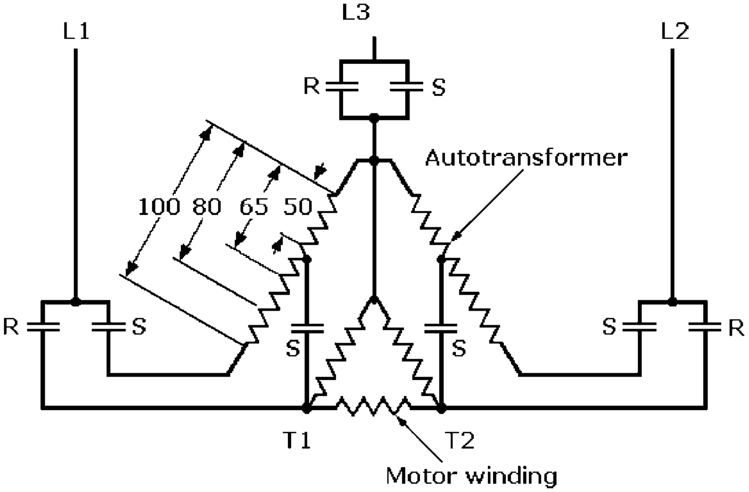


Figure 10-13 Automatic open-transition autotransformer motor starter.

cent of full line voltage. Motor current is proportional to the voltage on the motor terminals. Line voltage varies as the square of the impressed voltage, and is therefore lower than with resistor-type starters. Torque also varies as the square of the impressed voltage. A 50 percent voltage tap will provide 25 percent starting torque. Connections should be made to the lowest tap that will give the required starting torque.

There is also a *closed-transition autotransformer starter* that disconnects the motor from the power line during the transfer period, a function that the open-transition starter does not perform. Motor acceleration is nonlinear with both of these starters because the torque developed by the motor remains essentially constant during each indexed step. There are also manually operated autotransformer starters controlled by a lever that extends outside the starter enclosure. These are equipped with low-voltage release magnets.

PRIMARY-RESISTOR STARTERS

The primary-resistor starter connects the motor to the line through a series resistor. The voltage drop across the resistor reduces the voltage at the motor terminals. As the motor accelerates, the current drawn from the power line declines, and the voltage drop across the resistor is lowered. This increases the motor voltage at the terminals. Motor torque increases constantly as motor speed increases. After a definite time lapse, a timer operated by the main contactor energizes the accelerating contactor, which short-circuits the starting resistor and permits full voltage to be applied to the motor.

Compared with the autotransformer starter, the primary-resistor starter draws more power from the line on starting, but it provides smoother acceleration because there is no transfer period during which the motor can lose speed.

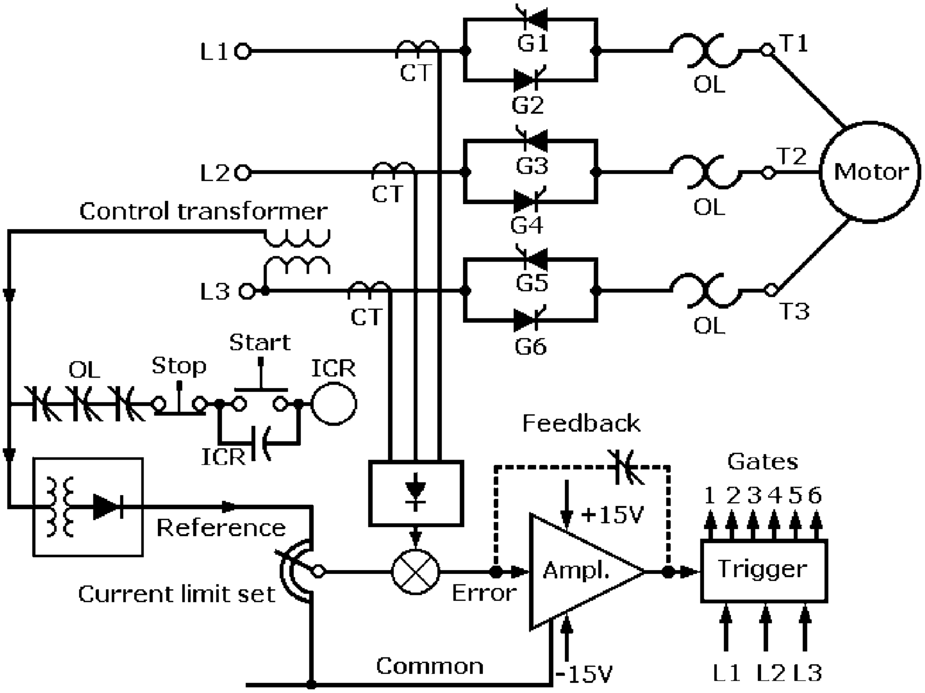


Figure 10-14 Schematic of a solid-state starter for a three-phase AC motor.

SEMICONDUCTOR AC STARTERS

Semiconductor AC starters include paralleled back-to-back phase-controlled silicon controlled rectifiers (SCRs) in series with two or three of the conductors to the motor, as shown in Fig. 10-14. The SCRs are controlled during the starting period to maintain about 300 percent line and motor current by gradually increasing the motor voltage from its initial value. Starting is smooth because the current and starting torque can be adjusted easily. A solid-state starter is usually specified where the line current is critical and where repetitive motor starting limits the life of electromagnetic contactors.

DC Motor Principles

Direct current (DC) motors operating from DC convert electrical energy into mechanical energy as rotary torque, just as AC motors convert electrical energy into torque. The fundamental physical principle on which every electric motor operates is that a conductor carrying a current within a magnetic field experiences a force. If a conductor carrying DC current is placed at right angles to a magnetic field formed by either an electromagnet or a permanent magnet, it will experience a force perpendicular to the field and to itself. This force is proportional to magnetic flux density, the current in the wire, and the length of the wire conductor.

By winding the wire into loops or coils, its effective length can be increased, thus increasing the interaction between the wire and the magnetic field. DC current enters one end of the coil and exits from the other end. The resultant forces acting on a single wound wire coil generate a rotary torque.

The rotating member of a DC or universal motor is usually called the *armature,* to distinguish it from the rotating member of an induction motor, usually called the *rotor.* Torque produced on the coil of the armature is proportional to the sine of the angle between the magnetic field and the coil. Thus, as the coil becomes perpendicular to the magnetic field, its rotation ceases and the armature and shaft will stop unless a means is found to keep it moving in the same direction (clockwise or counterclockwise). The device most often used to perform this switching action is the mechanical commutator, a ring assembly formed from insulated conductive segments.

DC motor armatures have multiple coils wound on cores made of stacked steel laminations. The ends of each coil are brought out and connected to opposing commutator segments. DC enters the commutator segment from a carbon *brush,* flows through the coil, and exits from the opposite segment to another brush. Commutation keeps the armature rotating so that current flows through the each coil in succession continuously until the power is shut off. Because motor torque is proportional to the number of coils and commutator segments, as their number increases the torque will increase and armature rotation will become smoother.

The three most common DC motors are shunt-wound motors, series-wound motors, and compound-wound motors. Because each of these motor designs has advantages and disadvantages, the selection of the most appropriate motor for an application depends on the motor characteristics best able accomplish the desired task.

DC Motor Characteristics

SHUNT-WOUND DC MOTORS

The *shunt-wound motor* is a brush-type DC motor with its stator field and armature connected in parallel (or shunt) across the DC power supply. Figure 10-15*a* is a simplified schematic showing the shunt and armature in parallel. If the field and armature of a shunt-wound motor are separately excited by independent power sources, speed can be varied by changing the armature voltage while keeping the field voltage constant.

Typical speed–load and torque–load curves for a shunt-wound DC motor are shown in Fig. 10-16. This motor has good speed regulation, as indicated by the shallow decline of speed versus armature current. It is still classed as a constant-speed motor despite the slight decrease in speed with increasing load. By contrast, torque increases with armature current as speed declines slightly. Because the torque of a shunt motor is proportional to the armature current, the starting torque will be 125 to 200 percent of full-load torque, depending on the value of starting resistance. For example, if the starting current of a shunt motor is 150 percent of full-load current, then the starting torque is 150 percent of full-load value. This is indicated by the vertical dashed lines.

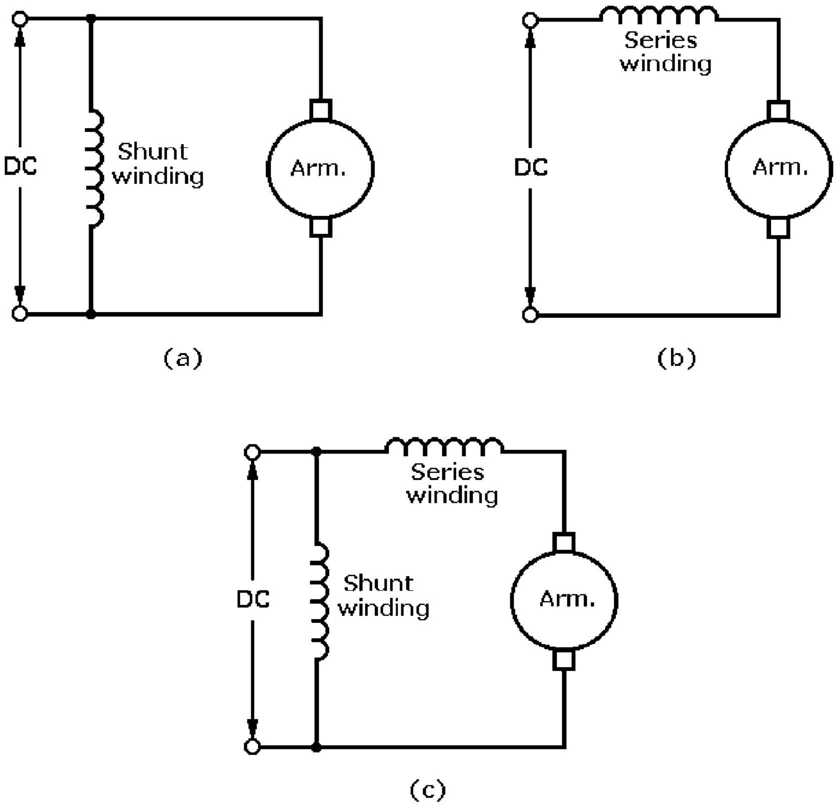


Figure 10-15 Schematics for three common DC motors: (*a*) shunt; (*b*) series; (*c*) compound.

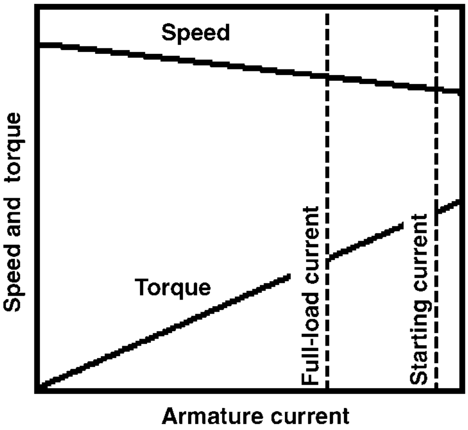


Figure 10-16 Speed–load and torque–load curves for a shunt motor.

This DC motor has become more popular and its versatility has been enhanced because its relatively constant speed can be adjusted with a silicon controlled rectifier (SCR). Armature voltage control is normally used to decrease motor speed below its base speed, the full-load, full-field speed. Normal NEMA base speed ratings for shunt motors operated from electronic controls are 1140, 1725, 2500, and 3460 rpm. These motors can be reversed at rest or during rotation simply by reversing the armature or the field voltage. However, the preferred method is by reversing armature voltage. Shunt motors are used to drive DC generators and generators in DC motor–generator sets.

SERIES-WOUND DC MOTORS

The *series-wound motor* is a brush-type DC motor with its stator field and armature connected in series across the DC power supply. Figure 10-15*b* is a simplified schematic for this motor. Because series-wound motors can be operated from either AC or DC power sources, they are also called *universal motors.* However, motors designed to run efficiently on either AC or DC supplies are modified versions of the DC series-wound motor made specifically for that duty.

Typical speed–load and torque–load curves for a series-wound DC motor are shown in Fig. 10-17. The field magnetic flux varies with the armature current in the series motor. As the armature current approaches full-load value, the saturation of the magnetic circuit and armature reaction prevent the torque from increasing as the square of the current. This causes the torque-versus-load curve to straighten out for heavier loads. The starting current is considered to be 150 percent of full-load value, as represented by the vertical dashed lines.

The series motor develops a large torque, but speed falls significantly with increasing torque and increasing armature current because the armature and field are connected in series. This is a desirable characteristic for applications such as driving cranes, winches, and hoists, where high starting torque is required and heavy loads must be moved slowly, but lighter loads can be moved faster. Series motors also drive electric railroad cars.

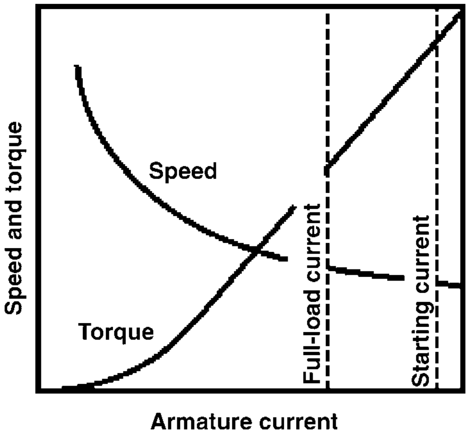


Figure 10-17 Speed–load and torque–load curves for a series motor.

When powered by AC, the series motor provides higher starting torque than any other AC motor, and on DC power it provides higher starting torque than any other DC motor. DC series motors are practical in frame diameters up to about 5 in. Above that size, permanent-magnet DC and shunt-wound motors are more cost-effective. Series motors are usually unidirectional, but bidirectional series motors are available.

Normal operating speeds for series motors can be from 4000 to 10,000 rpm, but under no-load conditions speeds in excess of 15,000 rpm have been achieved. For this reason, the load should never be removed from a series motor. Because speed decreases significantly with increasing load, it is considered to be a variable-speed motor. (For more on universal motors see “Universal AC/DC Motors” in this chapter.)

COMPOUND-WOUND DC MOTORS

There are two variations of the compound motor: cumulative compound and differential compound. The *cumulative-compound motor* combines the operating characteristics of the shunt and series motors. As shown in the schematic diagram Fig. 10-15*c,* the series winding is in series with the armature, and the shunt winding is in parallel across the AC line.

The cumulative-compound motor has a definite no-load speed and can be safely operated at no load. As load is added, the increased magnetic field causes the speed to decrease more than does the speed of a shunt motor. Thus, the speed regulation of a cumulative-compound motor is inferior to that of a shunt motor. Typical torque–load and speed–load curves for a cumulative-compound DC motor are shown in Fig. 10-18. A representative value of starting current for the cumulative-compound motor is 150 percent of full-load current, as indicated by the vertical dashed lines.

Cumulative-compound motors are favored where constant speed is required with irregular loads or suddenly applied heavy loads. Punch presses, shears, and reciprocating machines represent typical loads for these motors.

By contrast, the *differential-compound motor* has a nearly constant speed at all loads, but has poor torque characteristics under heavy loads. For this reason differential-compound motors are no longer used. However, cumulative-compound motors have lost market share to permanent-magnet motors with solid-state SCR controls in fractional-horsepower ratings because of their superior performance

COMPARISON OF DC MOTOR CHARACTERISTICS

The characteristics of series, shunt, and cumulative compound motors with the same full-load horsepower output and light-load speed can be compared by referring to Figs. 10-16, 10-17, and 10-18.

The speed regulation of a shunt motor is superior to that of either a series or compound motor, so it is more suitable for constant-speed applications. This means that compound and series motors are used where good speed regulation is not essential or where varying the speed might be desirable.

On the other hand, the exceptionally high starting torque of the series motor makes it ideal for starting heavy loads at a reduced speed. From its curves, it can be seen that

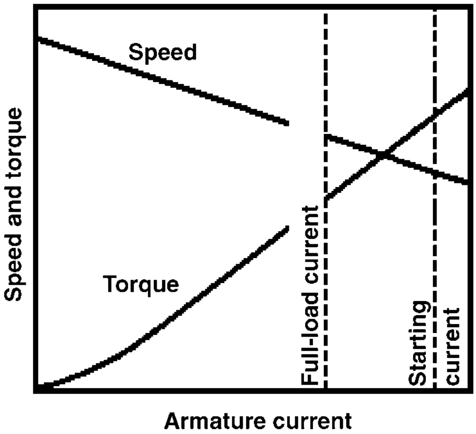


Figure 10-18 Speed–load and torque–load curves for a compound motor.

the series motor develops more torque than compound or shunt motors for a given armature current, at all but the lighter loads. Nevertheless, the character of the load still determines the type of motor to be used.

Permanent-Magnet DC Motors

The permanent-magnet (PM) field motor is a simple, reliable DC motor that offers high efficiency, high starting torque, and a linear speed–torque curve. Figure 10-19 is a cutaway view of a fractional-horsepower PM DC motor. It has a wound armature and uses mechanical commutation. Rare-earth or ceramic magnets have replaced earlier alnico magnets as the sources of permanent magnetic fields in PM motors. This has resulted in lighter, smaller motors whose performance is comparable to heavier, larger motors or better than heavier motors in the same frame sizes. This improved performance, coupled with the ability of PM DC motors to be controlled by solid-state amplifiers or drivers under computer control, has boosted their popularity. PM DC motors are widely used in closed-loop motion-control systems with velocity and position control loops.

BRUSHLESS PERMANENT-MAGNET DC MOTORS

Brushless DC motors exhibit the same linear speed–torque characteristics as brush-type PM DC motors, but they are electronically commutated. The construction of these motors, as shown in Fig. 10-20, differs from that of a typical brush-type DC motor in that they are “inside out.” In other words, they have permanent-magnet rotors and wound stators. Although this geometry is required for brushless DC motors, it has since been adapted by some motor manufacturers for brush-type DC motors.

The mechanical brush and segment commutators of conventional DC motors have been replaced by electronic sensors, typically Hall-effect devices (HEDs). They are located within the stator windings and wired to transistor switching circuitry located

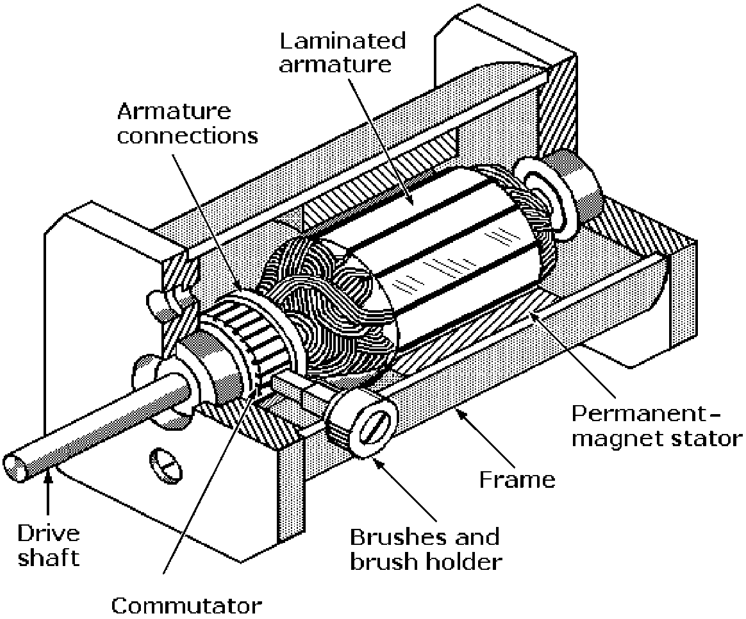


Figure 10-19 Cutaway view of a fractional-horsepower, permanent-magnet DC motor.

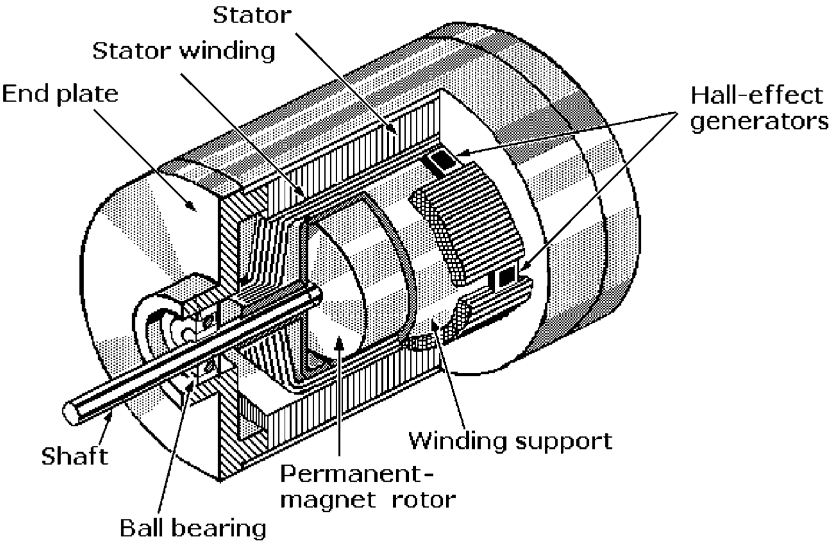


Figure 10-20 Cutaway view of a fractional-horsepower brushless DC motor.

either on circuit cards mounted within the motor housings or in external modules. Generally, only fractional-horsepower brushless motors have the switching circuitry within their housings.

The cylindrical magnet rotors of brushless DC motors are magnetized laterally to form opposing north and south poles across the rotor's diameter. These rotors are typically made from neodymium–iron–boron or samarium–cobalt–rare-earth magnetic materials, which offer higher flux densities than alnico magnets. These magnets permit motors offering higher performance to be packaged in the same frame sizes as earlier motors, or those with the same ratings to be packaged in smaller frames than the earlier models. Moreover, rare-earth or ceramic magnet rotors can be made with smaller diameters than those earlier models with alnico magnets, thus reducing their inertia.

DC Motor Starting

Fractional-horsepower shunt, series, and compound DC motors can be started by connecting the motor directly to DC line voltage. However, motors rated for more than 2 hp generally require reduced-voltage starting. Two requirements must be met in starting DC motors with higher horsepower ratings, especially if they are started under load.

1. Both the motor and the supply lines must be protected from excess current during the starting period.
2. The motor starting torque should be made as large as possible to bring the motor up to full speed in a minimum amount of time.

At starting, when the motor armature is stationary, no internal countervoltage is generated. Thus the only limit on the current being drawn from the supply is the armature resistance. In most DC motors this resistance is very low, about 1 Ω or less. To meet the first starting requirement, an external resistance can be placed in series with the motor armature during the starting period.

Starting resistors are variable resistors whose resistance value in the circuit can be controlled manually or automatically. As the motor speeds up, the countervoltage increases, decreasing the armature current. The starting resistance can then be reduced in successive increments until the motor reaches its full speed.

The second DC motor starting requirement can be met by maximizing the value of magnetic field flux, and by allowing the maximum safe value of armature current to flow when the motor is being started. When starting shunt and compound motors, maximum field flux is obtained by cutting out the shunt-field rheostat. In series motors, field flux is at maximum due to the heavy starting current flowing through the field winding.

If the DC motor is in an adjustable-voltage, adjustable-speed drive, it can be started by advancing the speed control from zero to the desired speed. If a DC motor in a motion-control system is to achieve smooth, high-speed motion without overstressing it, the motion controller must direct the motor amplifier to ramp motor velocity up gradually until it reaches its preset speed. When the motor is to be turned off, it should be ramped down gradually until it stops. This is done by programming a trapezoidal velocity command profile into the motion controller to keep motor accelerations and decelerations within their required limits.

Glossary of Motor Terms

Ambient temperature: The temperature of the air surrounding the motor. The NEMA standard maximum ambient temperature is 40°C (104°F).

Armature: In a DC or universal motor, the assembly of shaft, windings, and commutator that rotates. The comparable assemblies in induction and synchronous motors are called rotors. See also *rotor.*

Armature reaction: Current flowing in the armature winding of a DC motor that produces a magnetic flux which counteracts the flux produced by the field current. This effect reduces the motor's torque and can affect its commutation and performance.

Basic speed: The speed a DC motor develops at its rated armature and field voltage with its rated load applied, measured in revolutions per minute (rpm).

Braking torque: The torque required to stop a motor armature or rotor. This term is also used to describe the torque developed by a motor during dynamic braking.

Breakaway torque: See *locked-rotor torque.*

Breakdown torque: The maximum torque a motor develops at rated voltage without an abrupt drop in speed.

Brush: A spring-loaded conductive carbon or graphite electrode that makes electrical contact with the segments of a commutator as it rotates, connecting the armature windings to the power source. There are two brushes in each motor.

Capacitor: An electrical component that stores electrical energy. Both oil-type and electrolytic capacitors are used in some single-phase AC induction motors.

cemf: See *counter electromotive force.*

Centrifugal cutout switch: A centrifugally operated switch that disconnects components in single-phase induction motors when the rotor reaches a preset speed. It also reconnects them when motor speed drops below that speed threshold. It is used in split-phase, capacitor-start, and two-capacitor start/one-capacitor run motors.

Code: A letter code defining the *locked-rotor* kVA on a per-horsepower basis. Letters from A to V designate the inrush current per horsepower in ascending order.

Commutator: A cylindrical assembly of wedge-shaped copper segments positioned around a motor's armature shaft. The segments are insulated from the shaft and from each other. The motor's brushes ride on the outer surfaces of the segments and electrically connect and switch the armature coils to the power source in a sequence that keeps the armature rotating. See also *brush.*

Counter electromotive force (cemf): The voltage induced in a motor armature when conductors "cut" the magnetic flux of the field. It opposes the armature current and tends to reduce it.

Current at rated load: Current measured in amperes when a motor is operating at its nameplate horsepower, voltage, and frequency, after power factor has been corrected.

Design grade of AC motors—A, B, C, and D: NEMA standard motor designs with a range of torque-versus-speed characteristics that are graded from low to high to meet specific applications requirements. The most common B design has *normal* starting torque, starting current, breakdown torque, and full-load slip.

Duty cycle: The ratio of a motor's operating time to its rest time. A motor that can operate continuously within the temperature limits of its insulation system after it has reached normal operating temperature (equilibrium) is rated as continuous duty (CONT.). A motor that never reaches equilibrium temperature and must be shut down to cool periodically is rated as intermittent duty (INT.).

Electromotive force (emf): A voltage generated within an operating motor. See also *counter electromotive force.*

Field: The magnetic flux formed by current in a stationary part of a motor that interacts with the rotating part of the motor to deliver torque. In DC motors the field is formed by the stationary part of the motor, so the term *field* is also used to identify that part which is called a *stator* in an AC motor.

Frame size: NEMA has standardized motor frame sizes and other motor dimensions. Fractional-horsepower AC motor frame sizes are 42, 48, and 56, and integral-horsepower AC motor frame sizes are 143 to 449.

Frequency: The rate at which alternating current reverses its flow, measured in hertz (Hz). In the United States, Canada, and Mexico it is 60 Hz; in Europe it is typically 50 Hz.

Horsepower (hp): A measure of the rate of work equal to lifting 33,000 lb to a height of 1 ft per minute. One horsepower equals 746 W. For motors it is a function of torque and speed. Horsepower in motors is given by

$$\text{hp} = \frac{T \times \text{rpm}}{5250}$$

where T = torque in pounds-feet (lb-ft) and rpm = revolutions per minute.

Locked-rotor current: The steady-state current measured at a motor when its rotor is motionless and rated voltage at the rated frequency is applied. It can be determined when a motor and load are started, and it is the same as *starting current.*

Locked-rotor torque: The minimum torque a motor will develop at rest with its rotor at any angular position with rated voltage applied at the rated frequency.

Number of poles: In AC motors, the number of magnetic poles in the stator windings determines speed. In DC motors, the magnetic poles in the motor create the field in which the armature rotates, and speed is not influenced by the number of poles.

Power factor (PF): A measurement of the phase difference between voltage and current in an AC circuit. In motors, PF is equal to the cosine of the phase angle difference multiplied by 100 or the ratio of actual power (W) to apparent power (VA).

Pull-in torque: The torque that a synchronous motor develops when pulling its connected inertial load into synchronism upon the application of excitation. It is developed during transition from slip speed to synchronous speed, as the motor changes from induction to synchronous operation.

Pull-out torque: The maximum sustained torque a synchronous motor develops at synchronous speed for 1 min with rated frequency and normal excitation. See also *synchronous torque.*

Pull-up torque: The minimum torque developed by a synchronous motor from standstill to the pull-in point. It must exceed load torque by a margin large enough so that a satisfactory rate of acceleration is maintained under normal voltage conditions.

Rotor: The rotating part of an AC induction motor is analogous to the armature of the DC motor. Rotors of induction motors can be squirrel-cage or wound. Wound rotors are similar in construction to DC motor *armatures.*

Service factor (SF): A number indicating how much above its nameplate rating a motor can be loaded without overheating. For example, a 1.15 SF can produce 15 percent greater torque than the 1.0 SF rating for the same motor.

Slip: The difference between the speed of the rotating magnetic field of the stator and the rotor of a nonsynchronous induction motor, expressed as a percentage of synchronous speed. It generally increases as load increases.

Speed: In motors, speed refers to the shaft revolutions per minute (rpm).

Starting current: The current drawn when the motor is started, a value that is usually higher than running current. It is the same as *locked-rotor current.*

Starting torque: The torque delivered by a motor when it is started, a value usually higher than its rated running or full-load torque.

Stator: The nonrotating part of an AC induction motor that is attached to the frame and usually contains the primary winding. The equivalent in a DC motor is called the *field.*

Surge protection: In motors, surge protection is obtained with a capacitor mounted in the conduit box. It reduces short-period peak overvoltages on the power line caused by nearby lightning strikes or the inadvertent switching or faults in power distribution equipment.

Synchronous speed: The speed of the rotating magnetic field in the energized stator windings of a synchronous motor when the rotor locks in step with that magnetic field. At synchronous speed the motor operates at a constant speed up to full load without slip.

Synchronous torque: The torque developed in a synchronous motor after excitation is applied. It represents the total steady-state torque available to drive the load. It reaches maximum at approximately 70° lag of the rotor behind the rotating stator magnetic field. This maximum value is the *pull-out torque.*

Torque: The turning force delivered by a motor expressed in ounce-inches (oz-in.), pound-feet (lb-ft), or newton-meters (N-m).

Voltage, design: In motors, the nameplate voltage selected during design for operating the motor. NEMA requires that the motor must be able to produce its rated horsepower at the design voltage ±10 percent, although this might not be at its rated temperature rise. For example, a 460-V motor can operate from 480-V line power.

Watt (W): The amount of power required to maintain a current of 1 A at 1 V. Most medium and large motors are rated in kilowatts (kW). One horsepower equals 746 W.

11

EMERGENCY AND STANDBY SYSTEMS

CONTENTS AT A GLANCE

Overview

NEC Requirements for Emergency Systems

Legally Required Standby Systems

Optional Standby Systems

Lighting for Safe Exit

Emergency Power Sources

Rechargeable Batteries

Battery-Powered Standby Supplies

Uninterruptible Power Supplies (UPS)

Emergency Power Functions

Standby Engine–Generator Sets

Emergency and Standby Power Specification

Determining Load Capacity

Glossary of Emergency and Standby System Terms

References for Emergency and Standby Systems

Overview

The primary objective of all emergency and standby electric power systems is the safety of building occupants following a power outage. The danger to occupants during an outage is increased in the presence of smoke, chemical fumes, fire, or earthquake, adding urgency to any required evacuation of the building.

At the very least, emergency and standby power systems should provide lighting to assure the safe, panic-free exit of people from the building. If an outage occurs during a severe storm, emergency power systems will provide minimal lighting for people taking refuge in or remaining in the building until normal power is restored or the storm abates.

The secondary objective of these systems is the protection of property during loss of normal power. By picking up at least part of the load following an outage, minimal lighting will be restored, security systems will remain active, and critical building services such as heating in the winter or ventilation in the summer will be maintained.

Emergency or standby power will also permit orderly shutdown of computer systems or their continued operation to preserve vital data. In stores, active security systems can prevent theft; in large restaurants and cold storage warehouses, loss of perishable food can be prevented; and in factories, loss of materials in process can be avoided.

This chapter covers National Electrical Code (NEC) requirements for emergency systems and explains the differences between *legally required* and *optional standby systems*. Uninterruptible power supplies (UPS) and standby systems are discussed, and guidance on their selection is given. Details on standby engine–generator sets are presented, and the setting of priorities on emergency power loads is discussed. A glossary of emergency and standby power system terms and a short bibliography of publications and standards on the subject are included.

NEC Requirements for Emergency Systems

Emergency systems are generally installed in buildings that are or can be occupied by 1000 or more persons or are more than 75 ft high. These are buildings where artificial illumination is required for safe exiting and for panic control. Examples are hotels, theaters, airports, railroad stations, sports arenas, department stores, and hospitals. Emergency systems are designed to power exit lighting, fire detection and alarm systems, elevators, fire pumps, and public safety communications systems. They might also power ventilation systems considered essential to preserving health and life, or industrial processes where power interruption would result in hazards to life or injury.

NEC 2002, Article 700, "Emergency Systems," covers electrical safety in the installation, operation, and maintenance of emergency systems. These consist of "circuits and equipment intended to supply, distribute, and control electricity for illumination, power or both, to vital facilities when the normal electrical supply or system is interrupted." These are "systems legally required and classed as emergency by municipal, state, federal, or others codes, or by any governmental agency having jurisdiction. These systems are intended to automatically supply illumination, power, or both to designated areas and equipment in the event of failure of the normal supply or in the event of accident to elements of a system intended to supply, distribute, and control power and illumination essential to human life."

The general subjects covered in Article 700 include:

- *Tests and maintenance* of approved emergency system equipment
- *Capacity and rating* of emergency system equipment
- *Power transfer equipment,* including automatic transfer switches
- *Signals and signs* for emergency systems

The circuit wiring provisions of Article 700 include:

- *Identification* of boxes, enclosures, transfer switches, generators, etc.
- *Wiring independence and exceptions*
- *Fire protection* for high-occupancy and high-rise buildings

The section on sources of power gives the response-time requirements for the restoration of emergency lighting, emergency power, or both as "not to exceed 10 seconds" for the specific classes of buildings stated previously. In selecting the emergency source of power, consideration must be given to the occupancy and type of service rendered in those buildings. The occupancy classes are given as (1) assembly, (2) educational, (3) residential, (4) detention and correctional, (5) business, and (6) mercantile.

Article 700 requires that power sources be installed in rooms protected by approved automatic fire suppression systems (sprinklers, CO_2 systems, etc.) or in spaces with a 1-hr burn rating. (Fire can surround or be adjacent to the room for at least 1 hr before its fire-resistant integrity is lost and its contents begin to ignite spontaneously.)

The four emergency power systems approved by Article 700 are

- *Storage batteries* (rechargeable)
- *Generator sets*
- *Uninterruptible power supplies* (UPS)
- *Separate services* (alternate outside utility or inside generation) in accordance with NEC Article 230

The section on emergency system circuits for lighting and power covers:

- *Approved loads* on emergency branch circuits
- *Emergency illumination*
- *Circuits for emergency lighting*
- *Circuits for emergency power*

The section on emergency control lighting circuits covers:

- *Switch requirements*
- *Switch location*
- *Exterior lights*

The section on overcurrent protection covers accessibility of branch-circuit overcurrent devices (fuses and circuit breakers) and ground-fault protection of equipment.

Legally Required Standby Systems

Standby systems are classified by the NEC as either *legally required* or *optional.* Article 701 states that legally required standby systems are “those systems required and so classed as legally required by municipal, state, federal, or others codes, or by any governmental agency having jurisdiction. These systems are intended to automatically supply power to selected loads (other than those classed as emergency systems) in the event of normal service failure.” The article goes on to say that they consist of “circuits and equipment intended to supply, distribute, and control electricity to required facilities for illumination, power, or both, when the normal electrical supply or system is interrupted.”

Legally required standby systems are typically installed “to serve loads that, when stopped during any interruption of the normal electrical supply, could create hazards or hamper rescue or fire-fighting operations.” These loads include the following systems:

- *Heating and refrigeration*
- *Public safety communications*
- *Ventilation and smoke removal*
- *Sewage disposal*
- *Lighting*
- *Industrial process*

Loss of power could permit poisonous gases, toxic biological aerosols, or nuclear contamination to spread throughout the building, causing illness or fatalities.

While the shutdown of any of these systems is unlikely to prevent orderly evacuation from a building or incite panic, their interruption could impede the efforts of emergency services. Their shutdown is also unlikely to be an immediate threat to human life or pose a health hazard if the building is being evacuated. However, the shutdown of exhaust ventilators in a metal plating plant, for example, could result in respiratory injury to the occupants if the fumes are allowed to accumulate over time.

Article 701 is similar to Article 700 except that it reflects the less critical nature of the interruption of the kinds of systems mentioned. The subjects listed as “general” are similar to those in Article 700 except that the circuit requirements are less stringent.

The sources of power are essentially the same, but Article 700 states that the legally required standby service must be clearly separated from the normal main disconnecting means to prevent simultaneous interruption of the power supply, while Article 701.11(E) permits connections to be located ahead of and not within the same cabinet or enclosure as the service disconnecting device. Legally required standby power must be available within the time required for the application "but not to exceed 60 seconds."

As for overcurrent protection, the branch-circuit overcurrent devices in legally required standby circuits must be accessible only to authorized persons, but ground-fault protection of the alternate source equipment is not required.

Optional Standby Systems

NEC Article 702, "Optional Standby Systems," is similar in content to Article 701. It covers standby systems "that are permanently installed in their entirety, including prime movers, and those that are arranged for a connection to a premises wiring system from a portable alternate power supply."

Optional standby systems are defined as "systems intended to protect public or private facilities or property where life safety does not depend on the performance of the system." Optional standby systems are intended to supply on-site generated power to selected loads, either automatically or manually.

Such a system is "typically installed to provide an alternate source of electric power. It covers such facilities as industrial and commercial buildings, farms, and residences and to serve loads such as heating and refrigeration, data processing and communications systems, and industrial processes that, when stopped during any power outage, could cause discomfort, serious interruption of the process, or the like."

The requirements for optional standby systems are similar to those for legally required standby systems, but are generally less stringent because they essentially protect against financial and property losses and do not involve public safety issues. The topics covered in Article 702 include power transfer equipment, audible and visual signal devices, signs, circuit wiring, and the grounding of portable generators.

The shutdown of data processing systems that are not properly backed up by standby systems could result in the loss of valuable data. This loss could result in financial losses for banks, financial institutions, businesses, and research facilities, and lead to costly and time-consuming efforts to reconstruct the lost data.

The shutdown of an industrial process not backed up by an effective standby power system could result in direct financial losses due to the destruction of or damage to raw materials or work in process. In addition, there will be the cost of labor to repair process equipment or rework damaged goods in process, and new business could be lost.

Because the time element for the restoration of power from an alternate source is not as critical for optional standby systems as it is for legally required standby systems, portable gasoline or gas-powered generators can be used. They can pick up part or all of the load without the mandatory time limit of 60 s imposed for restoring power in legally required standby systems.

Lighting for Safe Exit

Most building codes are in agreement about the exit and emergency lighting that enables large numbers of people to exit safely from densely populated buildings such as auditoriums, theaters, hotels, shopping malls, and arenas.

- If the emergency lighting is not used under normal conditions, emergency power must be available for emergency lighting immediately if the normal power fails. Approved switches must be installed to make the transfer rapidly.
- Adequate lighting must be provided in hallways, stairways, corridors, and entryways so that a failure of any one light source will not leave any area dark enough to impede or inhibit the exit of persons from the building under emergency conditions.
- The emergency lighting source should be capable of sustaining the lighting load for at least 90 min. However, in locations such as hospitals, nursing homes, and police, fire and emergency medical stations, sources capable of sustaining lighting at least 5 to 6 hrs, and as much as several days, are recommended.

Emergency Power Sources

Emergency power sources are listed in NEC 2002, Section 700.12, “Sources of Power”:

- *Rechargeable storage batteries* of suitable rating and capacity to supply and maintain the total load for a period of 1½ hrs. The applied voltage shall not fall below 87½ percent of normal. The batteries can be lead–acid or alkali type and must be accompanied by an automatic charger.
- *Engine–generator sets* can be driven by internal combustion engines or other acceptable prime movers. There must be at least a 15-min time delay before they are put on line, to avoid supplying power too soon after an outage of brief duration after which normal line power is restored. The generator sets driven by internal combustion engines must have enough fuel available to sustain the full electrical load for at least 2 hrs. Natural gas–powered generator sets must have alternate sources for both gas and cooling water. If batteries are used to start the generator sets, they must have automatic chargers. Generator sets that require more than 10 s to develop full power must include an auxiliary power source to power the emergency system until the generator can pick up the load.
- *Uninterruptible power supplies* can be either storage batteries or generator sets.
- *Separate electrical service* that is available for emergencies must be widely separated electrically and physically from the normal service.
- *Unit lighting equipment,* essentially standby light sources, should consist of a storage battery, charger, one or more floodlights, and an automatic transfer relay.

Rechargeable Storage Batteries

Rechargeable storage batteries are instantly available sources of electric power. Battery-powered lamps turn on immediately after a power outage, and they can remain on until a standby engine–generator is started and any critical loads are transferred. Small packaged commercial standby lighting units powered from a single rechargeable battery can be mounted on walls. They typically include one or more floodlights focused in a wide illumination pattern to provide for the safe passage of persons exiting a building. An average illumination level of at least 0.4 footcandles (fc) is recommended for this purpose.

Remote emergency exit signs over doorways can be wired to these independent standby lighting units to share the battery during a power outage. Illuminated exit signs provide guidance to exit doors in dark or smoke-filled passageways for people who otherwise could become lost or confused.

Some buildings have centralized banks of rechargeable batteries that power many different emergency floodlights and illuminated exit signs within a building. The batteries are located together in closets where they can be monitored and maintained, making them more reliable than the individual batteries in wall-mounted cases. Some facilities have centrally located uninterruptible power supplies dedicated for emergency use. They supply 120-V AC to standard indoor AC lighting designated as emergency lighting as well as AC-powered exit signs. They can also provide enough 120-V AC power to sustain emergency communication, security, and fire alarm systems.

Battery-Powered Standby Supplies

A *battery-powered standby supply* is able to supply DC power from rechargeable batteries during a power outage. It is installed so that it parallels the normal utility 120-V AC line. It is essentially an *AC-to-DC rectifier* and charger that draws power from the normal AC line to maintain a bank of *rechargeable lead–acid storage batteries,* as shown in the block diagram Fig. 11-1. A *voltage sensor circuit* senses the absence of AC input power following an outage and sends a signal to the *bypass switch,* which automatically opens the AC line and switches in the storage batteries to pick up the emergency load.

These supplies are relatively simple and highly reliable, but the emergency load must be capable of operating from DC power. It will typically include emergency floodlights and audio or visual alarms to indicate the outage of normal power, but it can power lights or services capable of operation from either AC or DC sources. This contrasts with an uninterruptible supply (UPS), which can deliver 120 V AC to sustain the operation of all critical AC-powered lights and services.

The standby supply will continue to function until its batteries discharge below the level required to sustain the load or normal power is restored. When normal AC power

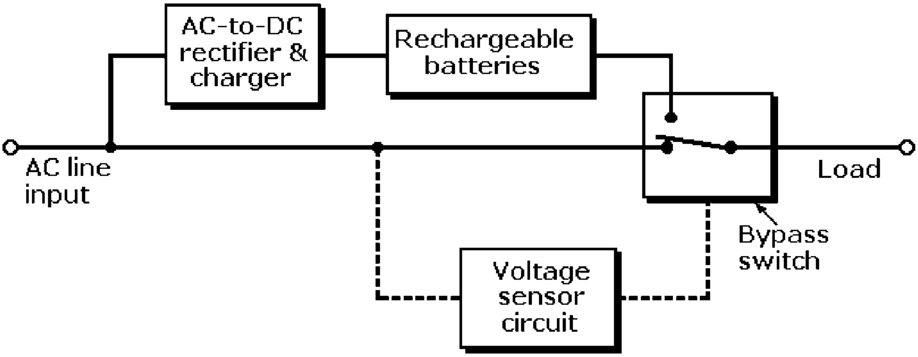


Figure 11-1 Block diagram of a battery-powered standby power supply.

is restored, the voltage sensor circuit switches the bypass switch back to the normal AC line so that it picks up the AC load again. The transfer from normal AC power to batteries and back again is made without interruption. The AC line then recharges the batteries in preparation for the next outage.

Uninterruptible Power Supplies (UPS)

An uninterruptible power supply provides conditioned AC to the load when normal AC line power is available and raw AC power to the load, inverted from rechargeable storage batteries, when normal AC power is interrupted. The UPS includes an *AC-to-DC rectifier* and a *DC-to-AC inverter* in series with a *bypass switch,* as shown in the block diagram Fig. 11-2.

The AC-to-DC rectifier converts the raw AC to DC and feeds it to the DC-to-AC inverter, which inverts it to the conditioned AC that normally powers the load through the bypass switch. The AC-to-DC rectifier includes a charger that keeps the bank of rechargeable storage batteries at full charge.

When an outage of normal AC power occurs, the batteries take over and continue to supply DC to the DC-to-AC inverter to sustain the AC load until the batteries discharge below the level required to sustain the load or normal power is restored.

If a fault occurs within the UPS circuitry under normal conditions, a *converter fault-sensor circuit* detects the malfunction and directs the bypass switch to open the inverter circuit and close the parallel bypass line, allowing normal AC to assume the load. Repairs can then be made to the internal UPS circuitry. The bypass switch can also be operated manually to permit routine maintenance of those internal UPS circuits.

Another kind of uninterruptible power supply based on the energy obtained from a spinning flywheel rather than from rechargeable batteries has been introduced. Caterpillar, Inc., is now offering a line of uninterruptible power supplies that substitute stored flywheel energy for rechargeable batteries to provide constant power protection against sags, surges, or outages that can disrupt normal operations or cause a loss of valuable computer data. Caterpillar claims that its units can make an uninterrupted

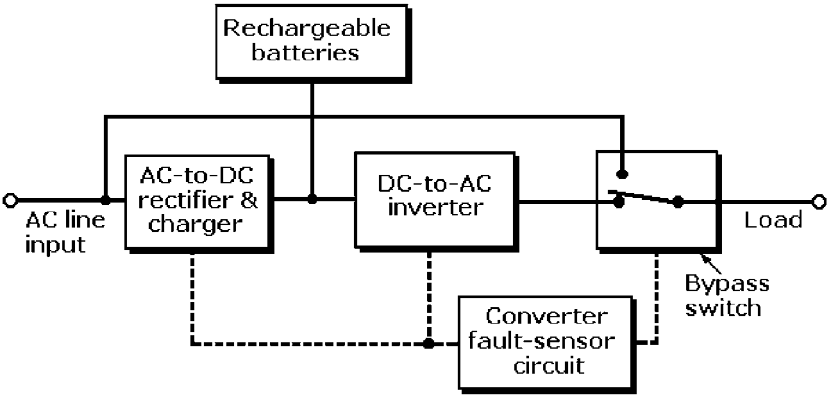


Figure 11-2 **Block diagram of an uninterruptible power supply (UPS).**

transition to a standby engine–generator set, adding that by canceling harmonic distortions, their systems can work seamlessly with those generator sets to increase their total electrical load capacity.

Efficiency of 97 percent is claimed for the systems, and they occupy less floor space than comparably rated conventional UPS systems based on rechargeable batteries. Caterpillar developed the flywheel systems to augment its line of engine–generator sets. According to the company, the combination provides improved protection against extended brownouts and blackouts, and because it has eliminated lead–acid batteries, it is now the most reliable and trouble-free UPS system available.

Emergency Power Functions

In addition to its primary objective of supplying power for emergency lighting to assure the safe and panic-free evacuation of people during emergency conditions, power must be supplied for the continued operation of vital building service functions, even if the building is sparsely populated and not open to the general public. Examples of these functions are the operation of fire detection and alarm systems, selected elevators, fire pumps, and public safety communication systems.

During power outages, facilities such as laboratories or chemical process plants must continue to operate ventilation systems where toxic gases, dangerous biological substances, or radioactive materials are present. If the ventilation system is shut down, these toxic gases or noxious vapors could accumulate rapidly, contaminate the air and injure or incapacitate persons exiting the building, or be the cause of later health problems.

Although less critical from a health and safety standpoint, power for ovens or equipment processing metals, chemicals, pharmaceuticals, or other similar materials must be available following a normal power outage to prevent the loss of raw or partially processed product. Also, emergency power must be available for refrigeration in food processing plants, cold-storage warehouses, and even large restaurants, to prevent the loss of perishable meat and produce.

Standby Engine–Generator Sets

A standby engine–generator set driven by an internal combustion engine is shown in Fig. 11-3. Also illustrated are the necessary support equipment, wiring, plumbing, and fuel source. A standby engine–generator requires a means for automatically starting the internal combustion engine when normal power fails and automatic transfer switches for powering all critical electrical circuits. A 15-min time delay must be installed to avoid premature transfer if normal power is restored within that time interval. As shown in the figure, an on-site fuel supply in a storage tank is provided. The fuel supply must be sufficient for at least 2 hrs of full-demand operation. An AC generator suitable for use with a standby engine–generator is shown in Fig. 11-4.

It is common practice for factories, hospitals, government agencies, and educational institutions that require standby engine–generator sets to supplement them with rechargeable storage battery standby power systems to sustain critical functions until the generator sets can be started, go on line, and pick up the load.

Standby engine–generator sets must not be dependent on the municipal water supply if water is needed for cooling the internal combustion engine. This means that there must be sufficient water available in a storage tank. In general, if dual-fuel-supply tanks are used, a means must be provided for automatically transferring fuel from one supply tank to the other.

Methods for transferring loads from their normal (electric utility or commercial) source to standby generators with *transfer switches* are illustrated in Fig. 11-5. The one-line diagram Fig. 11-5*a* shows how a complete electrical load is transferred to the standby generator with one transfer switch, and the diagram Fig. 11-5*b* shows how only the critical load is transferred. Electrical systems can be served by one or more automatic or manual transfer switches.

The power riser diagram Fig. 11-6 shows the equipment and the wiring specified for a 70-kW, 120/208-V, three-phase standby engine–generator set. In this installation a 500-gal fuel tank is buried in the ground outside the building in which the generator set is located. The boxes marked A through F are electrical distribution subpanels.

Commercial standby engine–generator sets driven by internal combustion engines are available in a wide range of output power ratings. Four different fuels are commonly used for powering these sets: diesel fuel, gasoline, natural gas, and liquefied propane.

Portable diesel or gasoline engine–generator sets capable of outputs from 3.3 to 12 kW are sold as complete packaged units mounted on a carrying frame or platform. They are designed to supply standby power for homes and farms, but they are also purchased for use in mobile homes, recreational vehicles, and boats.

These sets must be located where they can be properly exhausted and will not present a fire hazard. This usually means operating them from an outdoor location, preferably protected from the weather and close to the service entrance and loadcenter. Each set includes an external transfer switch that must be connected to the loadcenter of a home or building, or the equivalent in a mobile vehicle or a boat.

If these engine–generator sets are to be used as standby systems in homes, buildings, or permanently located mobile homes, permission to operate them must be

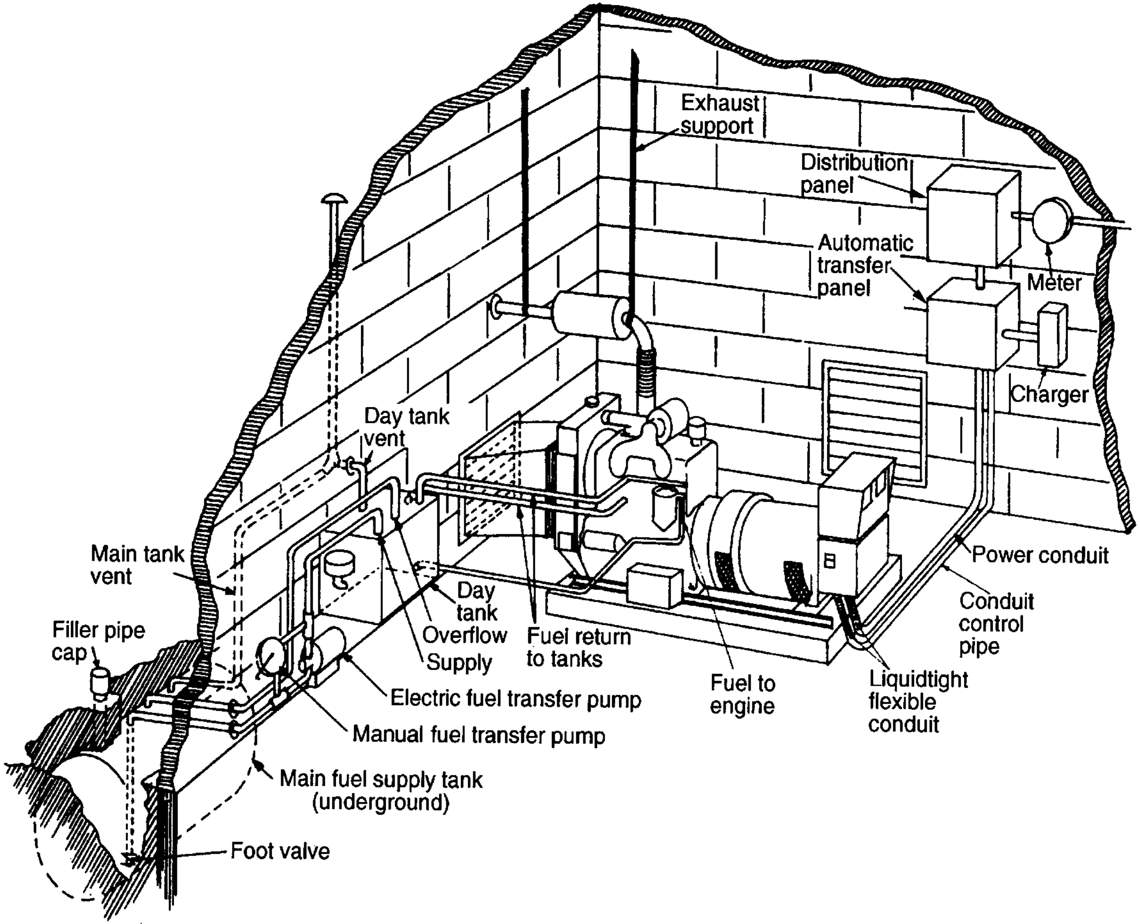


Figure 11-3 Standby engine–generator with the necessary support equipment.

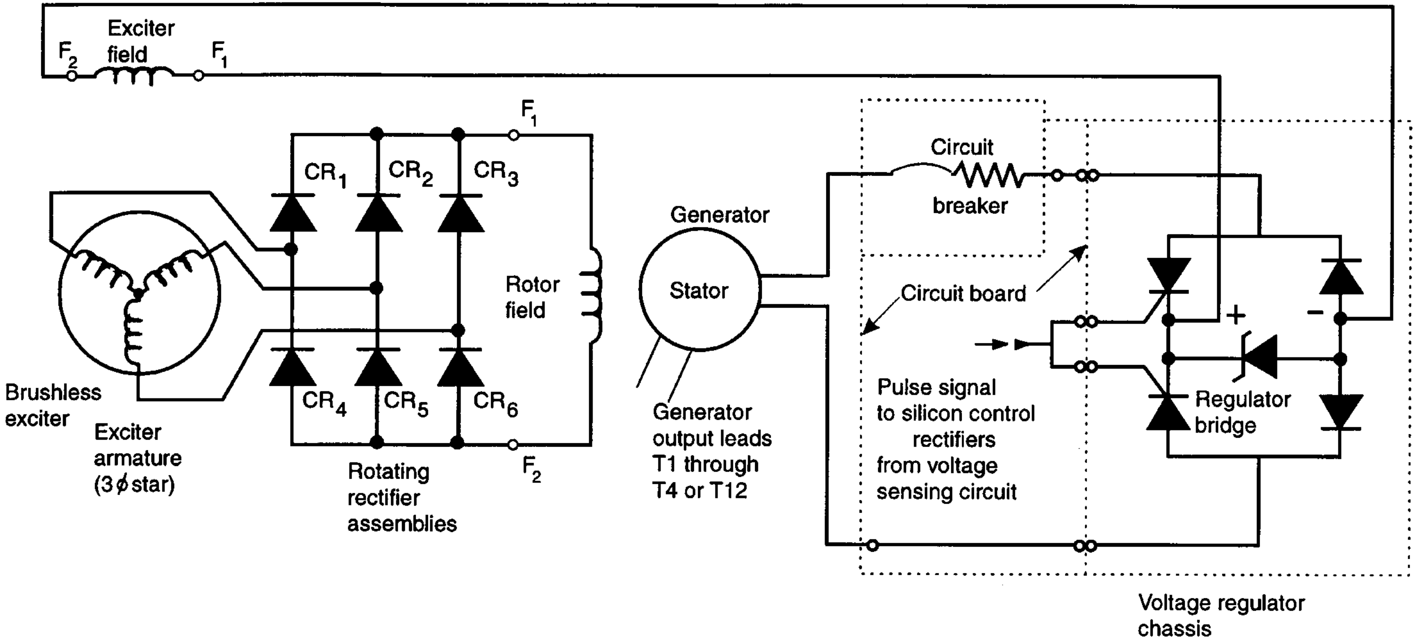


Figure 11-4 Wiring diagram of an AC generator for a standby engine generator.

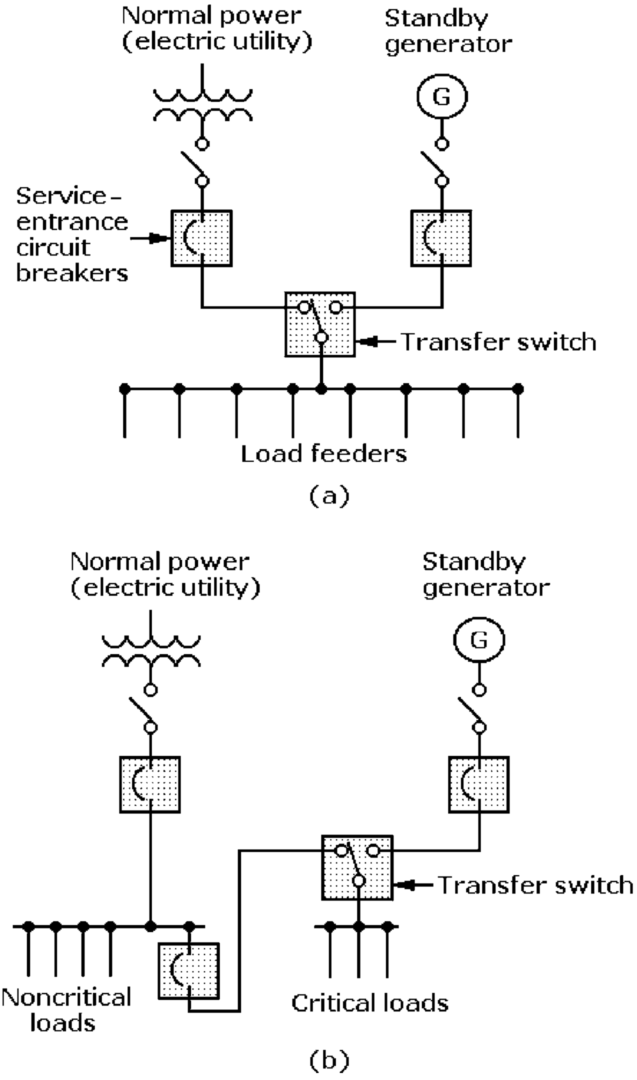


Figure 11-5 **Load-transfer switching for: (*a*) total load transfer; (*b*) critical load transfer.**

obtained from the local electrical utility. The utilities want to be assured that these sets will not interfere with the operation of the power distribution system.

Standby engine–generator sets in this size range are usually used only for powering critical electric loads such as heating plants, air conditioners, refrigerators, and lighting. The sets are connected to the transfer switch by a heavy insulated cable. Engine–generator sets rated for 4.8 kW can power 20-A, 120/240-V AC loads; those rated for 7.2 kW can power 30-A, 120/240-V AC loads; and those rated for 12 kW can power 50-A, 120/240-V AC loads.

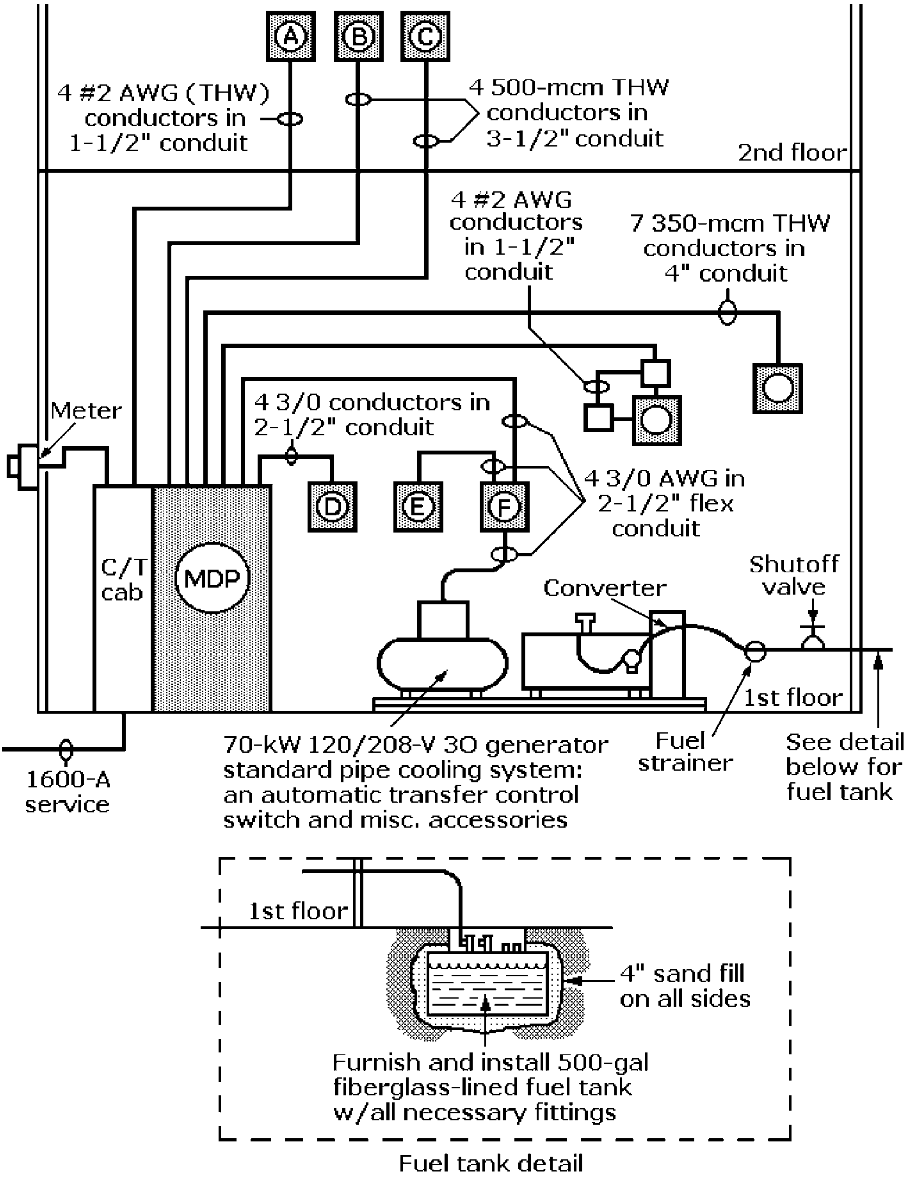


Figure 11-6 Power riser diagram of electric service that includes a standby engine–generator.

Other models of standby motor–generator sets rated for 9 to 25 kW are designed for permanent installation inside buildings. They require permanently installed fuel tanks and exhaust systems that vent to the outside. These sets are equipped with sensors that automatically detect power outages and transfer power to the preselected loads. The branch circuits containing the critical loads must be wired to the transfer switch, and permission to install these sets must also be obtained from the local power utility.

TABLE 11-1 CHARACTERISTICS OF STANDBY DIESEL ENGINE–GENERATOR SETS (Ratings 1800 rpm, 40 to 2000 kW)

Engine: Water-cdiesel, four-stroke, indirect injection
Electric starting at 12 or 24 V DC
Alternator for battery charging
Radiator with blower fan and guards
Air cleaner with dry-type paper element
Main-line circuit breaker with battery tray and cables
Basic fuel tank

Control panel: Microprocessor control, digital AC voltmeter, AC ammeter, and frequency meter; engine shutdowns for low oil pressure, high coolant temperature, low water level, overspeed, and overcrank; display of oil pressure, water temperature, fuel level, hour meter, and battery voltage; emergency stop button and internal clock

Generator: Brushless or four-pole with solid-state automatic voltage regulator and sealed bearing

Assembly: Engine and generator mounted for close coupling on a steel sub base with vibration isolators

Accessory options: Automatic battery charger, manual or automatic transfer switches, base-mounted fuel tank, diesel fuel tanks with 5000-gal capacity, battery, block heater, exhaust silencer, engine gauge panel, fuel/filter water separator, motor-starting AC generator, sound-reduction enclosure

For loads in excess of 25 kW, diesel engine–driven standby generators are most popular. Many manufacturers offer this equipment. Some of the smaller vendors purchase engines and generators from different sources and assemble them into integrated standby systems on a platform. However, large brand-name multinational engine and electrical equipment manufacturers build both the engines and generators for their units.

At least a half-dozen manufacturers offer diesel-powered generator sets capable of producing from about 7 to 2000 kW, although most of their sets are rated for 500 kW or less. Within this range, the output voltage of the sets can either be single- or three-phase, and the frequencies can either be 50 or 60 Hz. Table 11-1 summarizes the typical features of modern diesel engine–generator sets in the 40- to 2000-kW range.

ENGINE–GENERATOR “FARMS”

Some organizations have set up power-generation facilities consisting of multiple engine–generator sets for their own corporate use or to sell the power output to other organizations that require additional power during peak load periods or power outages. These facilities serve large power consumers such as banks or financial institutions with extensive computer installations. These standby generation facilities assure continuity of electric service for their customers’ critical activities so they do not have to depend on local power utilities during brownouts or outages. Multiple engine–generators with load-sharing capability are usually located on one floor so that they can share common resources and around-the-clock supervision and maintenance of the equipment are easier.

Multiple generator sets are preferred to one large engine–generator set because redundancy offers higher overall reliability, and a "block" of power can be put on line or taken off line more efficiently. Also, these facilities normally have enough capability to permit one or two engine–generators to be out of service for maintenance or repair without compromising the assigned loads.

These engine–generator "farms" are usually located in large cities some distance from the computer facilities they serve. They can maintain continuity in computer operations despite fires or other emergencies in or around buildings where computers are located. They prevent the loss of critical computer data and backup records on which their organizations depend.

Two or more engine–generator sets can be connected in a parallel array that includes circuit breakers and two or more automatic transfer switches, as shown in Fig. 11-7. With this arrangement, the generator sets can be assigned selectively to priority loads or nonessential loads as the circumstances permit. They can also be put on line during periods of exceptionally high load. Also, the fuel supply for the facility can be shared among the generator sets.

FUELS FOR ENGINE–GENERATOR SETS

Some engine–generator manufacturers or integrators offer engines that are designed to be powered by either liquefied propane (LP) or natural gas or both. In general, the range of output ratings for engine–generator sets powered from these fuels is more limited than for diesel-powered sets. However, the same options for single- or three-phase power at frequencies of 50 or 60 Hz are available. However, natural gas-powered standby generator sets must not be dependent on a public utility for the gas if they can be powered by locally stored liquefied gas.

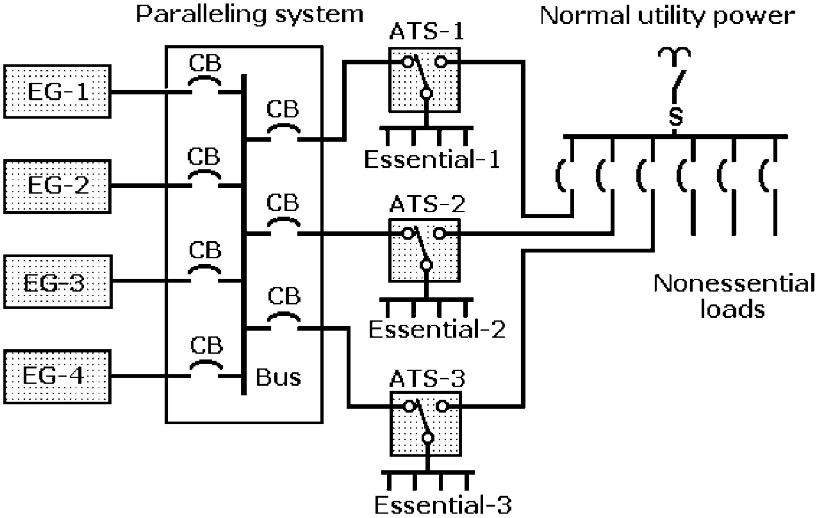


Figure 11-7 Automatic multigenerator paralleling system. ATS = automatic transfer switch; EG = engine generator; CB = circuit breaker.

The decision to specify generator sets powered by alternatives to diesel fuel is dictated by both engineering and economic considerations. One factor to consider is fuel storage space: far more space is required to store the hundreds of gallons of diesel fuel needed at the site than the amount of liquefied propane or natural gas that might be needed. Lack of storage space can pose a serious problem in urban locations for diesel-powered engine–generators. On the other hand, there is also concern about the availability of a continuous supply of gas in the event of a regional disaster such as a hurricane, fire, or tornado.

Where power requirements exceed 500 kW, gas turbine–driven generators can be specified. However, they take more time to start than diesel-electric generator sets and are most efficient only when operating at full load.

Emergency and Standby Power Specification

In selecting emergency and standby sources of power, consideration should be given to the number of occupants of the building, their physical condition, and the type of service required. If, for example, emergency power is needed only for evacuating healthy adults safely from a building, the requirements will be less stringent than those required to sustain all or part of a normal electrical load for an indefinite period. Emergency power requirements are more demanding for hospitals and nursing homes, where patients might need the assistance of others to leave the buildings.

Regulations apply to buildings more than 75 ft tall that can be occupied by more than 1000 persons if they are used for assembly, educational, residential, detention and correctional, business, or mercantile purposes. The emergency power equipment must be installed in spaces fully protected by automatic fire suppression systems such as sprinklers or carbon dioxide systems. Alternatively, they can be placed in rooms able to withstand fire in adjacent rooms for up to 1 hr.

Determining Load Capacity

An important requirement in specifying any standby or emergency electrical power system is determining the load capacity. The size and type of emergency system should be determined after considering the physical condition and convenience of the occupants. The installation should comply with all applicable local codes and standards and be acceptable to the authority that has jurisdiction over compliance.

The ratings and characteristic features of all luminaires that are to be kept on during an outage should be reviewed to be sure that they will perform reliably and that their minimum power requirements can be met.

Emergency power for fire pumps should be provided where water pressure is inadequate to meet fire-fighting requirements. It should also be provided where it has been determined that at least one elevator in a bank should remain operational as an option for the safe evacuation of people, despite the fact that elevators are usually to be avoided if there is a fire in a building.

Ventilating systems must continue to operate in laboratories and industrial plants where toxic chemicals, biological substances, or radioactive materials are present, to safeguard the health of occupants.

Glossary of Emergency and Standby System Terms

Automatic transfer switch: A transfer switch that can transfer the electrical load from one power source to another without manual intercession.

Bypass switch: A transfer switch for an uninterruptible power supply (UPS) that is operated automatically to transfer DC battery power to the DC-to-AC converter to sustain the AC load. The switch can be operated manually for maintenance or repair of the conversion circuitry of the UPS.

Emergency power system: A separate source of electric power that can pick up all or part of an electrical load automatically following an outage of normal power. It can take over loads so rapidly that critical lights and equipment will continue to function, assuring the safety of personnel and preventing property damage or loss.

Manual transfer switch: A switch that must be operated manually to transfer the electrical load from one power source to another.

Normal AC power (also called *commercial power*): Power supplied by a public utility. In some situations, normal power from an alternate commercial source can be switched to provide emergency or standby power as an option to the use of an engine–generator set.

Standby power system: A source of DC battery power that is switched on automatically following an outage of the normal AC line power. It maintains loads such as lamps and other equipment that function with DC power until normal AC power is restored or until the batteries are discharged to the level that they can no longer power the load.

Uninterruptible power supply (UPS): A power supply that normally supplies the load with conditioned AC power from the AC power line when it is present. If an outage of normal AC line power occurs, rechargeable storage batteries supply DC to the inverter to sustain AC power to the load. This continues until normal power is restored or the batteries are discharged to the level that they can no longer power the load. A transfer switch can bypass the internal UPS circuitry to allow the load to be powered from the normal AC line for maintenance or repair of the UPS.

References for Emergency and Standby Systems

Many different publications and standards cover emergency and standby power systems. Some of the more important references on the subject are listed below.

NEC 2002, Article 517, "Health Care Facilities": Subjects include emergency systems, life safety, connection to alternate power sources, and alternate power sources.

NEC 2002, Article 700, "Emergency Systems": Subjects include capacity, circuit wiring, sources of power, emergency circuits for lighting and power, control of emergency power, and overcurrent protection.

NEC 2002, Article 701, "Legally Required Standby Systems": Subjects include circuit wiring, sources of power, and overcurrent protection.

NEC 2002, Article 702, "Optional Standby Systems": Subjects include circuit wiring and grounding.

In addition, the following publications include information on these systems:

ANSI/NFPA 110A-1989, *Stored Energy Systems*

ANSI/NFPA 101-1988, *Life Safety Code*

ANSI/IEEE Standard 446-1987, *IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications*

ANSI/NFPA 110-1998, *Emergency and Standby Power System*

This page intentionally left blank.

12

ELECTRICAL SURGES AND SURGE PROTECTION

CONTENTS AT A GLANCE

Overview

Surge Protective Categories

Surge Protective Devices

Surge Protective Device Specifications

Metal-Oxide Varistors

Transient Voltage Suppressors

Surge Voltage Protectors

Electronic Circuit Fuses

Glossary of Surge Suppression and Electrostatic Discharge Terms

Surge Protection Standards

Overview

An electrical surge is a sudden strong rise in voltage that can appear on power and communications lines entering homes, offices, and other facilities. Surges caused by natural or manmade actions can easily destroy or disable any unprotected electronic equipment connected to the power or communication lines. Electronic products that are especially vulnerable to surges include microprocessors or microcontrollers, such as computers, TV sets, stereo systems, cordless telephones, and fax machines.

A succession of weak surges, powerful enough to stress but not destroy or disable electronic components or circuitry in a single event, can cause the performance of electronic equipment to deteriorate over time. Repeated overvoltages reduce the working lives of both active and passive circuit components by as much as 50 percent. They can also cause the insulation of wires to become brittle because of repeated abnormal heating cycles. Even robust electrical and electromechanical components such as lamps and motors can be degraded from the cumulative effects of surges, so the problem is not confined to electronic circuits.

The highest-magnitude surges are caused by lightning strikes on or near power lines, but destructive surges can also be caused by the on/off line switching of an electric utility's generators, a failure in a transformer, or some malfunction in other distribution equipment. Electrical surges can also be caused by the showers of charged particles from solar flares that enter the atmosphere. They have disabled extensive electric power distribution networks in the recent past.

Electric utilities install surge protective devices on their distribution equipment and ground them adequately, but these measures do not eliminate the possibility of harmful surges being induced on their power lines. A single bolt of lightning generates 20,000 to 40,000 A and about 200 million volts (MV)—enough energy to produce a temperature about 4 times hotter than the surface of the sun. However, lightning does not have to strike a power line or its supporting towers to initiate a destructive surge; nearby lightning strikes have been known to induce surges of 30,000 A or more in power lines. Some utility surge protectors are designed to blow out like a fuse if a surge exceeds 70,000 A.

TV cables and telephone lines can also propagate destructive surges. To counter these, protective devices have been made specifically to decouple surges on these conductors. They protect the such sensitive communications equipment connected to them as computer modems, cordless telephones, and fax machines.

While externally generated, high-magnitude electrical surges propagated over power lines have received most of the attention, lower-level surges can be generated within homes, offices, or other facilities. They can be caused by the switching on and off of appliances such as microwave ovens, washing machines, dryers, air conditioners, heating plants, and pumps. Low-level surges actually pose a more serious threat to vulnerable electronic components and circuits than nearby lighting strikes or the malfunction of electric power distribution equipment, because they occur more frequently.

For this reason, general-purpose protective devices built to thwart both externally and internally generated surges are now available in hardware and electronic products stores. In addition, special-purpose protective equipment is custom-manufactured to solve more complex commercial and industrial surge protection requirements. The number of different devices being made to combat surges is astonishing.

At this time there is no universally accepted terminology in the surge protection and surge arresting industry. The manufacturers of surge-suppressing circuits or assemblies refer to them as *surge protective devices* (SPDs), but the Underwriters' Laboratories (UL) standards and the National Electrical Code (NEC 2002) refer to them as *transient voltage surge suppressors* (TVSSs). To compound this confusion, electronic component manufacturers refer to their semiconductor surge protective devices by similar terms. For example, a modified form of the zener silicon diode that "clamps" excess voltages for surge protection is called a *transient voltage suppressor* (TVS), and a gas-filled tube that ionizes to short out transient overvoltages is called a *surge voltage protector* (SVP).

This chapter discusses a wide variety of SPDs and their key components such as metal-oxide varistors (MOVs), TVSs, and SVPs, and explains how they work. It also covers one-time-only (OTO) fuses that are soldered directly to electronic circuit boards. They are intended to back up specialized circuit breakers and fuses that protect electronics at the equipment level. They complement branch circuit breakers or fuses installed in the loadcenter. A glossary of surge protection and electrostatic discharge protection terms is included at the end of the chapter for ready reference, and a useful list of surge protection standards is also provided.

Surge Protective Categories

Three different surge protective classes or zones have been defined by ANSI/IEEE C62.41, *Recommended Practice on Surge Voltages in Low Voltage Power Circuits.* These classes are illustrated in the pictorial diagram Fig. 12-1.

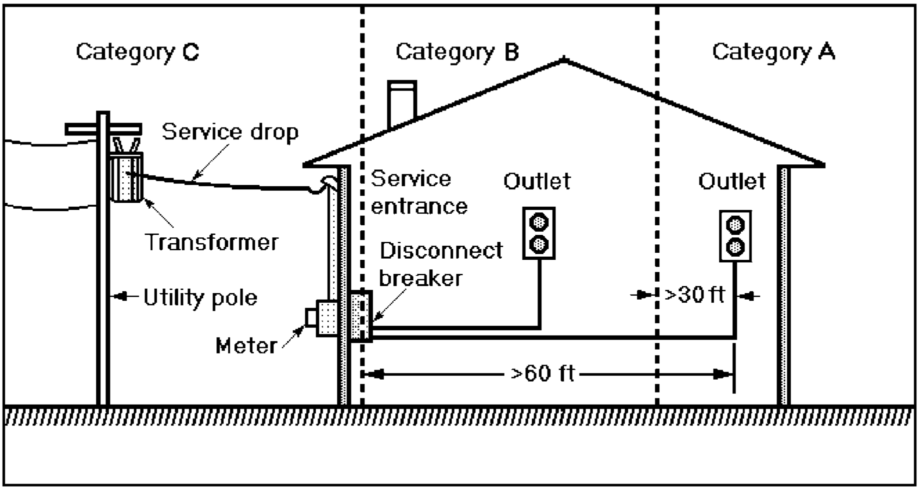
Category C (outdoors) is the region outside the home or building that includes external conductors, and it extends inside to the loadcenter main circuit breaker or *service entrance disconnect breaker.*

It is expected that surges originating outside the building could enter it by way of the service drop from the pole to the building through the watthour meter busbars to the circuit breakers, as well as from other overhead and underground conductors.

Studies have shown that the highest-magnitude natural and manmade surge currents and voltages originate in this Category C zone. Examples of these include lightning strikes on or near power lines and surges set up by the switching or failure of power company generators or other equipment. Both of these sources cause energy surges to be coupled into the building by induction. Consequently, the best surge protection is afforded by surge protective devices (SPDs), sized to withstand high-magnitude surges, that are installed ahead of service entrance disconnect circuit breakers.

Category B (indoors) is a zone within a residence or building that extends at least 30 ft (10 m) from the service entrance disconnect breaker along feeders or branch circuits to electrical receptacles or outlets. As stated previously, the most probable sources of surges within this zone are the on/off switching of electric motors or motor-driven appliances. Other sources are high-voltage or high-frequency medical and scientific apparatus located close to the structure being protected. This equipment is installed in hospitals, private diagnostic facilities, and research laboratories. Consequently, all SPDs installed in the B zone should be sized to withstand the largest-magnitude surges expected from all of these sources.

Category A (indoors) is the zone farthest from the disconnect breaker. It is defined as the zone within the building where the branch circuits extend to all outlets that are more than 30 ft (10 m) from Category B outlets, and more than 60 ft (20 m) from the service entrance disconnect breaker located in the Category C zone.



Category C: Outside and service entrances (line side)
- Service drops from pole to building
- Conducted between meter and disconnect breaker
- Overhead lines to nearby buildings

Category B: Feeders and short branch circuits (line side)
- Distribution panel equipment
- Short branch circuits and feeder lines

Category A: Branch circuits and outlets distant from Categories B and C
- Outlets >30 ft (10 m) from Category B boundary
- Outlets >60 ft (20 m) from Category C boundary

Figure 12-1 **Surge protective operating environments as defined by ANSI/IEEE C62.41.**

ANSI/IEEE C62.41 defines the three exposure levels that characterize the rate of surge occurrence versus voltage level at an unprotected site as follows.

- *Low:* Geographic locations where lightning activity is known to be low, and little load switching is anticipated.
- *Medium:* Geographic locations where medium to high lightning activity is expected, significant load switching is anticipated, or both.
- *High:* Geographic locations where surges greater than those defined as low or medium are expected.

ANSI/IEEE C62.41 has also established precise descriptions of the types of transient voltage and current waveforms expected in each category. These have been identified as *ring waves* and *combination waves.* With the issuance of this standard, SPD manufacturers had a common basis for comparing products. The SPDs can be subjected to well-defined transient waveforms for the categories and geographic regions where they will be located. If the tests are performed in accordance with C62.41, the results will provide objective and consistent data on the effectiveness of the SPD products.

The test waveforms established by this standard are illustrated in Fig. 12-2. The voltage combination and current combination waves are presented in Fig. 12-2*a,* and the 100-kHz ring wave is diagrammed in Fig. 12-2*b.* Standard 0.5-μs, 100-kHz ring waves are expected in Category A and B locations. The values for low, medium, and, high exposure are defined for test purposes.

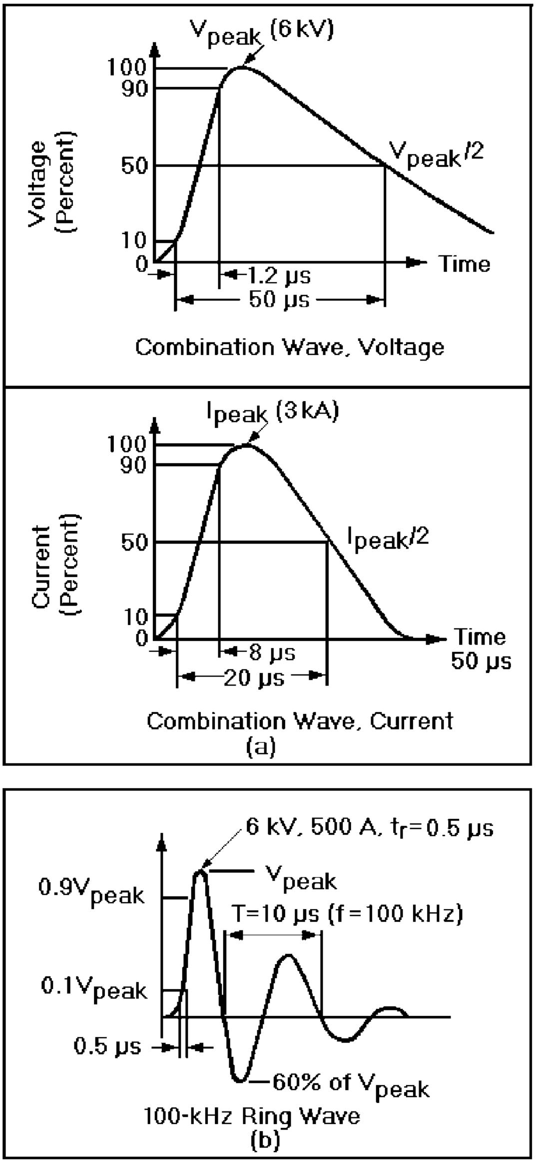


Figure 12-2 **Test waveforms for two types of transient voltage surges defined by ANSI/IEEE C62.41: (*a*) combination wave voltage and current; (*b*) ring-wave transient.**

Combination waves are expected only in Categories B and C. They are simultaneous voltage and current waveforms with the voltage waveform characterized as 1.2/50 μs to 8/20 μs. These numbers state the time-duration limits of the pulse. Here again, for test purposes the low, medium, and high values are given for the two categories.

In 1998, Underwriters' Laboratories Inc. (UL) revised its UL 1449, the industry standard for surge protective devices. A surge protective device must have a UL 1449 surge suppression rating on its label to verify that the device has been tested in accordance with ANSI/IEEE C62.41 standardized waveforms. It can be assumed that devices without this identification are not reliable surge protective devices and should not be purchased or used. This revision specifically addressed the "fail-safe" operation of metal-oxide varistors (MOVs), the most commonly used electronic devices for shunting dangerous surges away from connected equipment.

The latest UL 1449 covers the following subjects related to transient-voltage surge suppressors (TVSSs), the term UL and NEC 2002 use instead of surge protection devices (SPDs).

- Basic TVSS safety tests including leakage current, dielectric withstand, insulation resistance, temperature rise, and mechanical integrity tests.
- TVSSs that will be permanently or cord-connected, and direct plug-in for 50/60-Hz power circuits not exceeding 600 V AC.
- TVSSs installed on the load side of the main overcurrent protection.
- TVSSs with filters for suppressing conducted electromagnetic interference (EMI) or noise, as well as transient voltage surges.
- Suppressed voltage ratings (SVRs) measured from zero ground to the peak of the "clamped" transient level.

Surge Protective Devices

Surge protective devices (SPDs) are factory-manufactured products made in many different configurations to address specific overvoltage situations. Some are permanently installed and others are portable devices that can be moved among outlets as the need for protection changes.

- *Panel-mount modular SPDs* are packaged for installation at main distribution and branch panels. They are available in industrial, commercial, and residential specification grades with features that are relevant to their applications.
- *Meter socket surge adapters* are SPD assemblies in cylindrical cases that can be mounted externally to watthour meter bases to provide surge protection for residences between the service entrance cable and the main circuit breaker.
- *Power-line conditioners* in cord-connected and hard-wired configurations are intended for the protection of business personal computers and their peripherals, fax machines, telecommunications systems, file servers, and computer terminals.

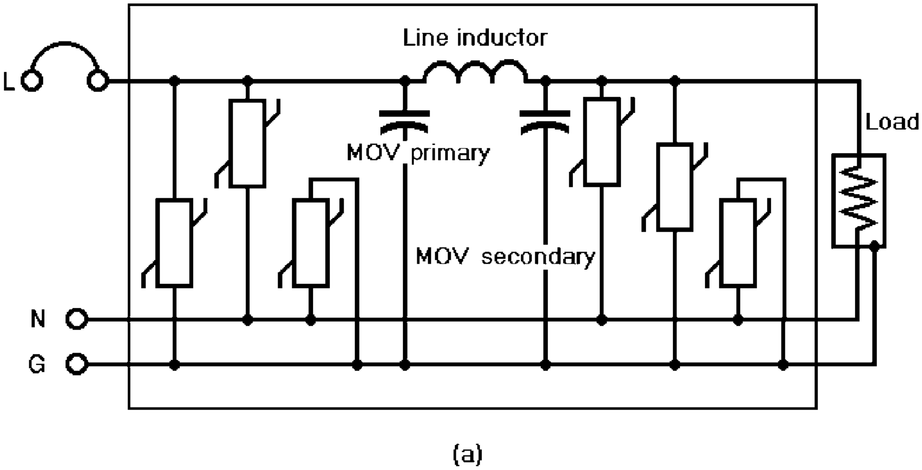
- *Surge protective receptacles* are receptacles that include surge protective circuitry for the protection of computers, medical equipment, telecommunications, and security systems. They provide three-level MOV protection for phase-to-neutral, phase-to-ground, and neutral-to-ground. The are available as duplex and four-in-one receptacles in industrial, commercial, and residential specification grades with additional features that are relevant to those applications.
- *Plug-in SPDs* are portable surge protective circuits packaged in small rectangular cases. They have up to four protected outlets with built-in plugs that can be plugged into wall receptacles and moved to other locations where and when needed. They are offered in industrial, commercial, and residential specification grades.
- *Surge strips* are portable, linecord-connected surge protective circuits with six to eight outlets in long rectangular cases. Most have on/off switches, and many also include LED status indicators. These SPDs are also offered in industrial, commercial, and residential grades. Some models classed as "computer-grade" include RJ-11 phone jacks or F-type coaxial connectors with multiple outlets for the protection of communications circuits.
- *Low-voltage and data-line SPDs* are specialized devices for the protection of residential and commercial communications lines against transient voltage surges. Some models include RJ-45 connectors for the protection against surges over RS-232, Ethernet, digital data service, and telephone lines. Others include BNC connectors for the protection of equipment against surges transmitted over video circuits and F-type connectors for the protection of surges traveling over cable TV coaxial cables.

Two different surge protective device hybrid networks are shown in Fig. 12-3. In Fig. 12-3*a,* three MOV primaries are wired line (L)–to–ground (G), line (L)–to–neutral (N), and neutral (N)–to–ground (G) ahead of the π filter, which consists of two capacitors and a line inductor. The filter is followed by three MOV secondaries. A variation of this hybrid circuit is shown in Fig. 12-3*b.* The three MOV primaries are configured as in Fig. 12-3*a* ahead of the line inductor, and three full-wave transient-voltage suppressor (TVS) diode secondaries are wired in place of the three MOV secondaries.

SPDs generally offer energy dissipation ratings up to 1950 J for the protection of computers. They also include components that provide wide-range electromagnetic interference/radiofrequency (EMI/RFI) noise filtering. Models with noise filtering are most likely to be specified for telecommunications centers or large office complexes containing many computers.

To stop high-energy surges, a surge suppressor should have a high joule rating—the higher the better. For the protection of professional telecommunications equipment, joule ratings should be 750 J or higher.

Many surge suppressors contain *safe thermal fusing,* fail-safe devices that ensure protection against catastrophic overvoltages. *Toroidal balanced chokes* are included to provide nearly instantaneous protection against spikes and surges. When combined with *high-frequency* and *very high-frequency capacitors,* toroidal balanced chokes can also provide EMI/RFI noise filtering.



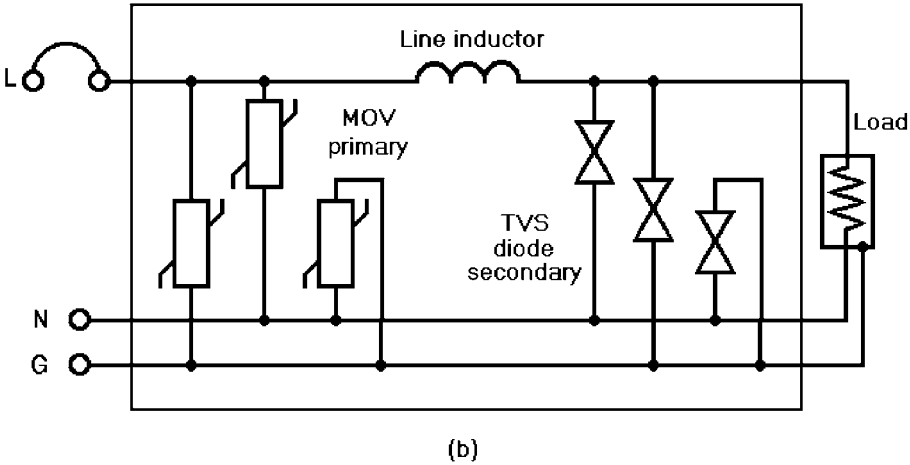


Figure 12-3 Surge protective device hybrid networks: (*a*) MOV primaries and secondaries; (*b*) MOV primaries and transient voltage suppressor (TVS) secondaries.

Surge Protective Device Specifications

The information that follows is representative of typical specifications data for a sample group of surge protective products, taking into account differences in characteristics and performance among the specification grades: hospital, industrial, commercial, and residential, or general-purpose.

Meter socket surge adapters are SPDs located in the bases of watthour meters to intercept surges before they reach a building's main circuit breaker. They are packaged in cylindrical cases that can be connected directly to an external ring- or ringless-type 120/240-V AC single-phase meter base. As Category C protective devices, they are capable of clamping the high transient voltages generated by lightning strikes or the switching of distribution equipment. This early clamping of high voltages before they reach Category A and B point-of-use SPDs improves their efficiency.

Residential-grade meter socket surge adapters can have 65,000 peak A maximum current ratings and nominal clamping voltages per line of 800 V. Some are UL listed for 465-V discharge voltage at 1500 A.

Panel-mount surge protective devices (SPDs) are modular SPD assemblies packaged in NEMA or other suitable cases for mounting in main distribution and branch-circuit panels. Products with industrial, commercial, and residential specification grades have many features in common, including hybrid suppression circuitry and phase-to-neutral and neutral-to-ground protection. These should be UL 1449 listed and meet ANSI/IEEE C62.41 requirements for Categories A, B, and C. The industrial and commercial models are housed in NEMA cases with hinged covers that can be surface- or flush-mounted.

Modular three-phase wye and delta main distribution panel-mounted SPDs have ratings of 120/208 V to 600 V, 60 Hz, and their modules have transient energy ratings of 2000 to 9400 J. The modules can clamp voltages of 425 V peak to 1700 V line-to-line. Modular branch panel-mounted single- and three-phase SPDs have ratings from 120 to 480 V, 60 Hz, and can clamp peak voltages of 450 to 1600 V AC.

Residential-grade panel-mount SPDs have single-phase ratings of 120/240 V, 50/60 Hz, and three-phase ratings of 120/208 V, 50/60 Hz. They can clamp peak combination waves of 480 to 640 V AC, withstand maximum single-pulse transient current of 50,000 A, and dissipate 950 J of single transient pulses. Line-to-neutral UL 1449 ratings for these SPDs are 500 to 800 V AC.

Surge protective receptacles are single and duplex wall-mounted receptacles containing surge protective components. They are available in hospital and industrial specification grades. A hospital-grade 15-A, 120-V, 60-Hz duplex receptacle is shown in Fig. 12-4. A surge protective receptacle can also have ground isolation capability, as indicated by its orange receptacle body or the presence of an orange triangle on its face.

Industrial- and hospital-grade surge protective receptacles can provide three-level MOV protection and can withstand maximum single-pulse transient currents of 13,000 A (line-to-neutral) and 6500 A (line-to-ground and neutral-to-ground). These products can dissipate 320 J of transient energy. Illuminated monitor LEDs on the faces of these receptacles indicate that surge protection is active. The highest-quality products should be UL listed in Standard 1449 and meet ANSI/IEEE C62.41 standards for both Categories A and B.

Plug-in surge protective devices are small, portable SPDs in modular cases with built-in plug prongs that enable them to be connected directly to standard 15-A NEMA wall receptacles. They can protect from four to six outlets. These SPDs are available in industrial, commercial, and residential specification grades. Industrial 15-A, 120-V, 50/60-Hz versions with four outlets can withstand maximum single-pulse currents from 20,000 to 50,000 A, and they can dissipate 360 to 640 J.

These devices offer three-mode protection: 350 V (line-to-neutral), 500 V (line-to-ground), and 400 V (neutral-to-ground). Some residential-grade versions with six

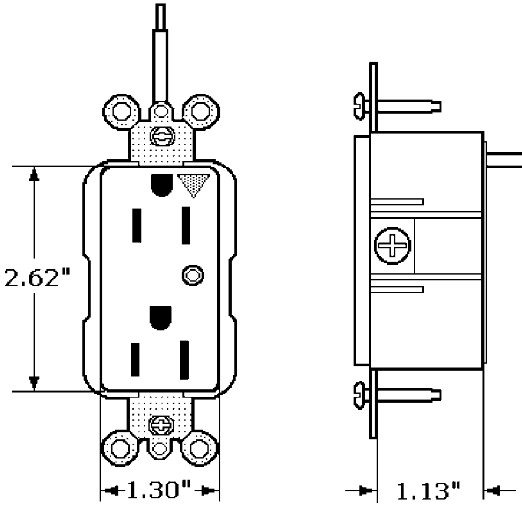


Figure 12-4 Isolated grounding surge protective duplex receptacle identified by its orange body or an orange triangle on its face.

outlets offer 400-V AC protection on all modes. Many of these SPDs include monitor LEDs that, when illuminated, indicate that surge protection is active. The highest-quality products should be UL listed in Standard 1449 and meet ANSI/IEEE C62.41 standards for both Categories A and B.

Plug-strip SPDs are the familiar, portable SPDs with multiple outlets packaged in long cases with linecords attached. They are widely used in offices and homes and are recommended for use with all desktop and laptop computers when the computers are plugged into an AC power line. An example of the many styles and variations in these products is shown in Fig. 12-5. Their surge protective circuitry is inside a rectangular case that typically measures about 12 × 2 × 2 in.

All of these SPDs have attached linecords that are from 6 to 15 ft long terminated with three-prong plugs for 15- or 20-A NEMA receptacles. They can have from six to eight protected outlets. Most are rated for 15 A, 120 V, 50/60 Hz, but 20-A versions are available. The on/off master toggle switches are standard, and some have monitor LEDs that, when illuminated, indicate the protection is active.

Hospital and industrial specification-grade plug-strip SPDs offer MOV protection at all outlets and clamping levels of 400 V (line-to-neutral, line-to-ground) and 330 V (neutral-to-ground). Some are offered with features such as EMI/RFI noise rejection, resettable circuit breakers for overload protection, and audible alarms. They supplement the LED monitors to indicate loss of surge protection. These SPDs should withstand maximum single-pulse transient currents of 26,000 to 52,000 A and dissipate from 320 to 640 J.

General-purpose plug-strip SPDs with lower performance specifications are generally acceptable for use in homes and offices. Available in a wide price and quality range, they can be purchased in hardware, home improvement, appliance, and even drug stores. Some general-purpose plug-strip SPDs combine 15-A outlets with RJ-11 phone jacks

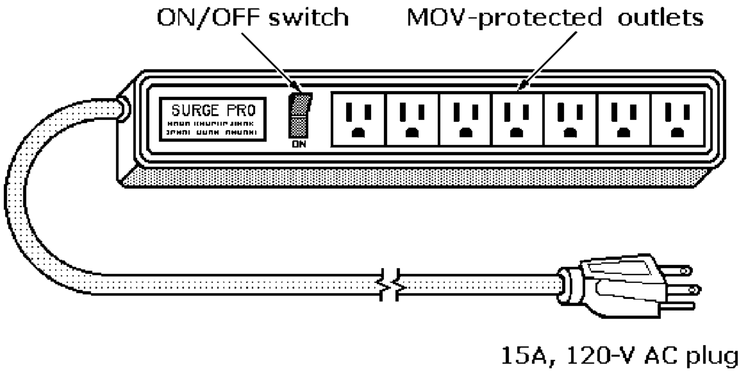


Figure 12-5 **Plug-strip surge protective device provides point-of-use protection for computers and other sensitive electronic equipment.**

for the protection of cordless telephones, computer modems, and fax machines against surges that enter on the telephone lines.

Metal-Oxide Varistors

Metal-oxide varistors (MOVs) are two-terminal variable resistors that protect electronic circuits against AC voltage transients. Widely used as components in SPDs because of their bilateral characteristics, they act like two back-to-back diodes in a single package. MOVs clamp AC voltage during both the positive and negative swings of AC. The nonlinear, symmetrical resistance characteristic of MOVs changes as a function of the applied voltage. When it exceeds the MOV's rating, its resistance drops sharply, effectively making it a short circuit. When the transient has passed, the MOV recovers rapidly.

MOVs are molded from zinc oxide grains and are furnace-fired to fuse them into monolithic blocks. They are capable of absorbing more incident energy than comparably rated silicon TVS diodes without being destroyed. Moreover, they cost less than TVS diodes with comparable ratings. However, MOV clamping characteristics are not as sharp as those of the TVS. MOVs are packaged as conformally coated radial-leaded disks or epoxy-encapsulated blocks with terminal posts. They can be ganged to handle larger values than their rated surge limits.

Transient Voltage Suppressors

A *transient voltage suppressor* (TVS) is a zener-type avalanche PN junction diode optimized to protect circuits by reverse-bias voltage clamping. The TVS diode breaks down and becomes a short circuit when the applied voltage exceeds the device's rated avalanche level. When the voltage (reverse bias) falls below breakdown level, current is restored to its normal level. Silicon TVSs have better surge-handling capabilities than conventional zener diodes, which are not intended for circuit protection. They also have low series resistance values, and response times measurable in picoseconds.

A TVS can perform the dual functions of voltage regulation and protective clamping. A single TVS diode can only protect a DC circuit, but two back-to-back TVSs can protect an AC circuit. Back-to-back dual TVSs for AC circuit protection are available in individual packages. They are more likely to be used for the surge protection of signal and data lines, because they have lower energy-handling capabilities than MOVs.

The three most important characteristics of the TVS are:

- Pulse power (peak pulse power multiplied by the clamping voltage)
- Standoff voltage
- Maximum clamping voltage

Standoff voltages range from 5 to 170 V, and clamping voltages range from 7 to 210 V.

TVSs have many applications in circuit protection. They protect:

- Integrated circuits (ICs) from electrostatic discharge (ESD), power supply reversals, or when power supplies are switched on
- Output transistors from transients caused by inductive load switching
- MOSFET transistors from transients conducted over the power line

Surge Voltage Protectors

Surge voltage protectors (SVPs) are gas-filled tubes that protect vulnerable components and circuits from higher surge voltages than can be withstood by either MOVs or TVSs. They are packaged in either glass or metal tubes.

When an incoming transient voltage exceeds the voltage rating of the SVP, it ionizes the gas within the tube, switching it from a nonconductive to a conductive state. The arc that is formed in the ionized gas becomes a low-resistance path that short-circuits the SVP and also grounds the high currents. When the transient has passed, the gas deionizes, restoring the SVP to its nonconductive state and resetting it. The disadvantage of SVPs is their slower response times than either TVSs or MOVs.

Electronic Circuit Fuses

Fuses for electronic circuits are considered to be electronic components. They are mounted on circuit boards rather than being screw-in or plug-in protective devices. Most fuses for use on circuit boards are one-time-only (OTO), expendable protective devices that must be replaced after blowing. In common with conventional fuses, they contain resistive wires with low melting temperatures, and they respond to overcurrents rather than overvoltages. They defend against overcurrents that pass branch circuit breakers, but they have slower response times than other protective devices.

Glossary of Surge Suppression and Electrostatic Discharge Terms

Clamping voltage: The peak voltage that can be measured after a surge protective device has limited or "clamped" a transient voltage surge. Clamping voltage is determined from ANSI/IEEE Standard C62 testing and evaluated by UL Standard 1449.

Electrostatic discharge (ESD): The rapid discharge or grounding of electrical charge that has built up on nonconductive surfaces, resulting in the generation of high voltages. Charges can build up on floors, furniture, and sheets of paper or plastic, or objects made from them. When a conductor such as a human hand or wire touches a surface with accumulated charge, the charge is quickly drained and can often result in a visible high-voltage electrical arc. Although low in current, ESDs can generate voltages that are high enough to disable or destroy sensitive semiconductor devices and circuits.

Electrostatic discharge (ESD) protective products: A line of products intended to protect electronic devices and circuits against ESD. They include wrist and foot grounding straps, electrically conductive plastic bags, boxes, and tote trays, and conductive floor mats. Spray cans containing soaplike solutions will dissipate ESD on nonconductive surfaces. These products are used on or near benches or work areas where sensitive components or devices are handled.

Joule (J): 1 joule = 0.239 calorie, 0.738 ft-lb, or the amount of energy required to pass 1 A through a resistance of 1 Ω.

Joule rating (J): The measurement of a surge protective device's ability to absorb heat energy created by transient surges, measured in joules. Joule rating is not part of IEEE or UL standards: it is not considered to be as significant a parameter as *clamping voltage. Maximum surge current* and other parameters are recognized by ANSI/IEEE and UL.

Maximum (peak) surge current: The peak surge current that a surge protective device can withstand, based on ANSI/IEEE Standard C62.45 test waveforms.

Metal-oxide varistor (MOV): A two-terminal variable resistor that protects electronic circuits against AC voltage transients. MOVs are widely used as components in surge protective devices because their bilateral characteristics permit them to act like two back-to-back diodes to clamp AC voltage during both positive and negative swings.

Response time: The time that it takes for a surge protective device to react to a transient voltage surge. This parameter is not part of ANSI/IEEE or UL standards because these intervals of time are measured by protective device manufacturers.

SPD: See *surge protective device.*

Suppressed voltage rating (SVR): A voltage rating based on conformance with UL 1449.

Surge arrester: A term defined by Article 280 of NEC 2002 as "A protective device for limiting surge voltages by discharging or bypassing surge current, and it also prevents continued flow of follow current while remaining capable of repeating these functions."

Surge protective device (SPD): A packaged assembly of components for protecting electronic components and circuits from transient voltage surges. This term is widely used in the industry and is synonymous with *transient voltage surge suppressor* (TVSS), used by UL and NEC 2002.

Surge voltage protector (SVP): A gas-filled tube that protects circuits against higher surge voltages than TVSs or MOVs.

SVR: See *suppressed voltage rating.*

Transient voltage suppressor (TVS): A silicon zener-type avalanche PN junction diode optimized to protect circuits by reverse-bias voltage clamping.

Transient voltage surge: A high-speed, high-energy electrical disturbance that can appear on AC power and telecommunications lines. It is caused by nearby or actual lighting strikes, utility equipment switching, and motor-load switching.

Transient voltage surge suppressor (TVSS): This term is defined by Article 285 of NEC 2002 as "A protective device for limiting transient voltages by diverting or limiting surge current; it also prevents continued flow of follow current while remaining capable of repeating these functions." This alternate term for a *surge protective device* (SPD) is also used by Underwriters' Laboratories Inc. (UL).

TVS: See *transient-voltage suppressor.*

TVSS: See *transient-voltage surge suppressor.*

UL 1449: The industry standard for surge protective devices. A surge protective device must have a UL 1449 suppressed voltage rating (SVR) for each applicable protection mode to be considered reliable.

Surge Protection Standards

ANSI/IEEE C62.1-1989, *Standard for Gapped Silicon-Carbide Surge Arresters for AC Power Circuits.*

ANSI/IEEE C62.2-1987, *Guide for the Application of Silicon-Carbide Surge Arresters for Alternating-Current Systems.*

ANSI/IEEE C62.11-1993, *Standard for Metal-Oxide Surge Arresters for Alternating-Current Power Circuits.*

ANSI/IEEE C62.22-1991, *Guide for the Application of Metal Oxide Surge Arresters for Alternating-Current Systems.*

ANSI/IEEE C62.41, *Recommended Practice on Surge Voltages in Low Voltage Power Circuits.*

IEEE C62.45-1992, *Guide on Surge Testing for Equipment Conducted to Low-Voltage AC Power Circuits.* An Institute of Electrical and Electronic Engineers' standard for SPD waveforms.

NEC 2002, Article 280, "Surge Arresters."

NEC 2002, Article 285, "Transient Voltage Surge Suppressors (TVSSs)."

NEMA LS-1-1992, *Standard for Low Voltage Surge Suppression Devices.*

NFPA 780, *Lightning Protection Code.*

UL497, 497A, 497B, *Data/Communication Line Protectors.*

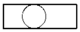
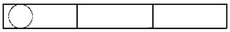
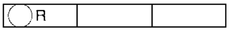
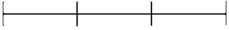
UL 1449, *Transient Voltage Surge Suppressors.*

A

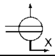
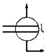
ANSI ARCHITECTURAL SYMBOLS, RECEPTACLE AND PLUG CONFIGURATIONS, AND CIRCUIT WIRING DIAGRAMS

ANSI Architectural Symbols

1. LIGHTING OUTLETS

	Ceiling	Wall
1.1 Surface or Pendant Incandescent, Mercury-Vapor, or Similar Lamp Fixture		
1.2 Recessed Incandescent, Mercury-Vapor, or Similar Lamp Fixture		
1.3 Surface or Pendant Individual Fluorescent Fixture		
1.4 Recessed Individual Fluorescent Fixture		
1.5 Surface or Pendant Continuous Row Fluorescent Fixture		
1.6 Recessed Continuous Row Fluorescent Fixture		
1.7 Bare-Lamp Fluorescent Strip		
1.8 Surface or Pendant Exit Light		
1.9 Recessed Exit Light		
1.10 Blanket Outlet		
1.11 Junction Box		
1.12 Outlet Controlled by Low-Voltage Switching when Relay is Installed in Outlet Box		

2. RECEPTACLE OUTLETS

	Grounded	Ungrounded
2.1 Single Receptacle Outlet		 UNG
2.2 Duplex Receptacle Outlet		 UNG
2.3 Triplex Receptacle Outlet		 UNG
2.4 Quadruplex Receptacle Outlet		 UNG
2.5 Duplex Receptacle Outlet — Split Wired		 UNG
2.6 Triplex Receptacle Outlet — Split Wired		 UNG
2.7 Single Special-Purpose Receptacle Outlet		 UNG
2.8 Duplex Special-Purpose Receptacle Outlet		 UNG
2.9 Range Outlet (typical)	 R	 UNG R
2.10 Special Purpose Connection or Provision for Connection	 DW	 UNG DW
2.11 Multi-outlet assembly	 X in	 UNG X in
2.12 Clock Hanger Receptacle		 UNG
2.13 Fan Hanger Receptacle		 UNG
2.14 Floor Single Receptacle Outlet		 UNG
2.15 Floor Duplex Receptacle Outlet		 UNG
2.16 Floor Special-Purpose Outlet		 UNG

3. SWITCH OUTLETS

3.1 Single-Pole Switch **S**

3.2 Double-Pole Switch **S2**

3.3 Three-Way Switch **S3**

3.4 Four-Way Switch **S4**

3.5 Key-Operated Switch **SK**

3.6 Switch and Pilot Lamp **SP**

3.7 Switch for Low-Voltage switching System **SL**

3.8 Maser Switch for Low-Voltage Switching System **SLM**

3.9 Switch and Single Receptacle  S

3.10 Switch and Double Receptacle  S

3.11 Door Switch **SD**

3.12 Time Switch **ST**

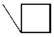
3.13 Circuit Breaker Switch **SCB**

3.14 Momentary Contact Switch or Pushbutton for Other Than Signaling System **SMC**

3.15 Ceiling Pull Switch Ⓢ

4. RESIDENTIAL OCCUPANCIES

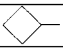
4.1 Pushbutton 

4.2 Buzzer 

4.3 Bell 

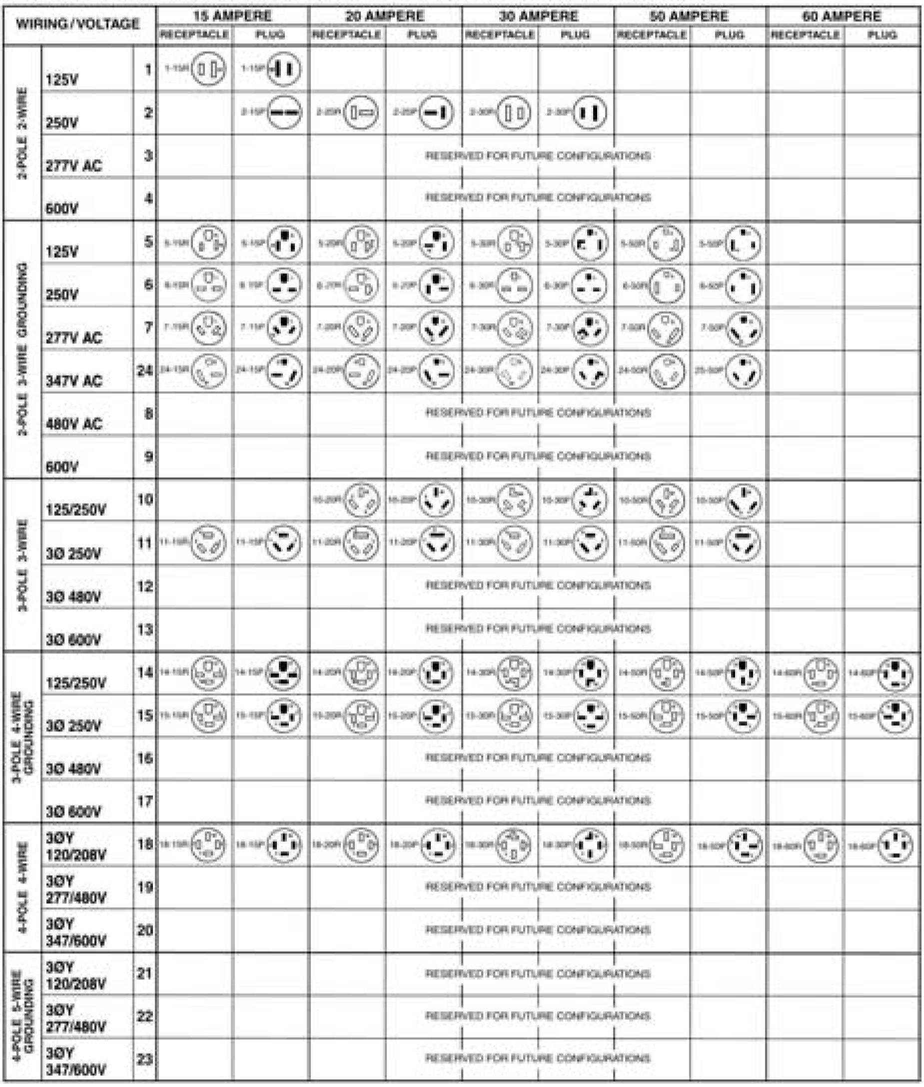
4.4 Combination Bell-Buzzer 

4.5 Chime 

4.6 Annunciator 

NEMA Straight Blade Configurations

NEMA CONFIGURATIONS FOR GENERAL-PURPOSE NONLOCKING PLUGS AND RECEPTACLES



WIRING / VOLTAGE			15 AMPERE		20 AMPERE		30 AMPERE		50 AMPERE		60 AMPERE	
			RECEPTACLE	PLUG	RECEPTACLE	PLUG	RECEPTACLE	PLUG	RECEPTACLE	PLUG	RECEPTACLE	PLUG
2-POLE 2-WIRE	125V	1	1-15R	1-15P								
	250V	2		2-15P	2-20R	2-20P	2-30R	2-30P				
	277V AC	3				RESERVED FOR FUTURE CONFIGURATIONS						
	600V	4				RESERVED FOR FUTURE CONFIGURATIONS						
2-POLE 3-WIRE GROUNDING	125V	5	5-15R	5-15P	5-20R	5-20P	5-30R	5-30P	5-50R	5-50P		
	250V	6	6-15R	6-15P	6-20R	6-20P	6-30R	6-30P	6-50R	6-50P		
	277V AC	7	7-15R	7-15P	7-20R	7-20P	7-30R	7-30P	7-50R	7-50P		
	347V AC	24	24-15R	24-15P	24-20R	24-20P	24-30R	24-30P	24-50R	25-50P		
	480V AC	8				RESERVED FOR FUTURE CONFIGURATIONS						
	600V	9				RESERVED FOR FUTURE CONFIGURATIONS						
3-POLE 3-WIRE	125/250V	10			10-20R	10-20P	10-30R	10-30P	10-50R	10-50P		
	3Ø 250V	11	11-15R	11-15P	11-20R	11-20P	11-30R	11-30P	11-50R	11-50P		
	3Ø 480V	12				RESERVED FOR FUTURE CONFIGURATIONS						
	3Ø 600V	13				RESERVED FOR FUTURE CONFIGURATIONS						
3-POLE 4-WIRE GROUNDING	125/250V	14	14-15R	14-15P	14-20R	14-20P	14-30R	14-30P	14-50R	14-50P	14-60R	14-60P
	3Ø 250V	15	15-15R	15-15P	15-20R	15-20P	15-30R	15-30P	15-50R	15-50P	15-60R	15-60P
	3Ø 480V	16				RESERVED FOR FUTURE CONFIGURATIONS						
	3Ø 600V	17				RESERVED FOR FUTURE CONFIGURATIONS						
4-POLE 4-WIRE	3ØY 120/208V	18	18-15R	18-15P	18-20R	18-20P	18-30R	18-30P	18-50R	18-50P	18-60R	18-60P
	3ØY 277/480V	19				RESERVED FOR FUTURE CONFIGURATIONS						
	3ØY 347/600V	20				RESERVED FOR FUTURE CONFIGURATIONS						
4-POLE 5-WIRE GROUNDING	3ØY 120/208V	21				RESERVED FOR FUTURE CONFIGURATIONS						
	3ØY 277/480V	22				RESERVED FOR FUTURE CONFIGURATIONS						
	3ØY 347/600V	23				RESERVED FOR FUTURE CONFIGURATIONS						

NEMA Locking Configurations

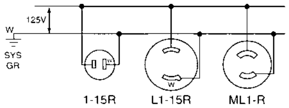
NEMA CONFIGURATIONS FOR LOCKING TYPE PLUGS AND RECEPTACLES

WIRING / VOLTAGE			15 AMPERE		20 AMPERE		30 AMPERE	
			RECEPTACLE	PLUG	RECEPTACLE	PLUG	RECEPTACLE	PLUG
2-POLE 2-WIRE	125V	L1	L1-15R 	L1-15P 				
	250V	L2			L2-20R 	L2-20P 		
	277V AC	L3			RESERVED FOR FUTURE CONFIGURATIONS			
	600V	L4			RESERVED FOR FUTURE CONFIGURATIONS			
2-POLE 3-WIRE GROUNDING	125V	L5	L5-15R 	L5-15P 	L5-20R 	L5-20P 	L5-30R 	L5-30P 
	250V	L6	L6-15R 	L6-15P 	L6-20R 	L6-20P 	L6-30R 	L6-30P 
	277V AC	L7	L7-15R 	L7-15P 	L7-20R 	L7-20P 	L7-30R 	L7-30P 
	347V AC	L24			L24-20R 	L24-20P 		
	480V AC	L8			L8-20R 	L8-20P 	L8-30R 	L8-30P 
	600V AC	L9			L9-20R 	L9-20P 	L9-30R 	L9-30P 
3-POLE 3-WIRE	125/250V	L10			L10-20R 	L10-20P 	L10-30R 	L10-30P 
	3Ø 250V	L11	L11- 	L11-15P 	L11- 	L11-20P 	L11- 	L11-30P 
	3Ø 480V	L12			L12-20R 	L12-20P 	L12-30R 	L12-30P 
	3Ø 600V	L13					L13-30R 	L13-30P 
3-POLE 4-WIRE GROUNDING	125/250V	L14			L14-20R 	L14-20P 	L14-30R 	L14-30P 
	3Ø 250V	L15			L15-20R 	L15-20P 	L15-30R 	L15-30P 
	3Ø 480V	L16			L16-20R 	L16-20P 	L16-30R 	L16-30P 
	3Ø 600V	L17					L17-30R 	L17-30P 
4-POLE 4-WIRE	3ØY 120/208V	L18			L18-20R 	L18-20P 	L18-30R 	L18-30P 
	3ØY 277/480V	L19			L19-20R 	L19-20P 	L19-30R 	L19-30P 
	3ØY 347/600V	L20			L20-20R 	L20-20P 	L20-30R 	L20-30P 
4-POLE 5-WIRE GROUNDING	3ØY 120/208V	L21			L21-20R 	L21-20P 	L21-30R 	L21-30P 
	3ØY 277/480V	L22			L22-20R 	L22-20P 	L22-30R 	L22-30P 
	3ØY 347/600V	L23			L23-20R 	L23-20P 	L23-30R 	L23-30P 

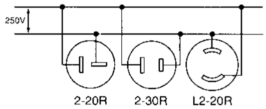
Circuit Wiring Diagrams

WIRING DIAGRAMS FOR NEMA CONFIGURATIONS

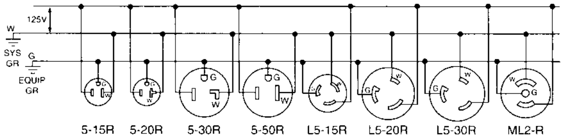
125V — 2-POLE, 2-WIRE



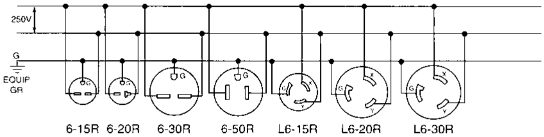
250V — 2-POLE, 2-WIRE



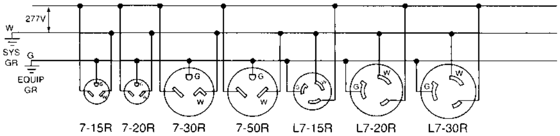
125V — 2-POLE, 3-WIRE GROUNDING



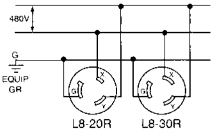
250V — 2-POLE, 3-WIRE GROUNDING



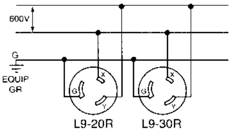
277V AC — 2-POLE, 3-WIRE GROUNDING



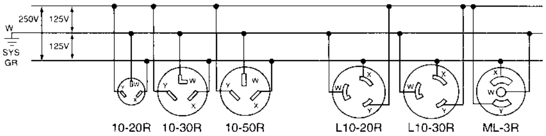
480V AC — 2-POLE, 3-WIRE GROUNDING



600V AC — 2-POLE, 3-WIRE GROUNDING



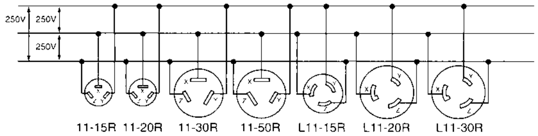
125/250V — 3-POLE, 3-WIRE



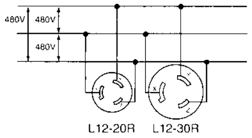
Circuit Wiring Diagrams

WIRING DIAGRAMS FOR NEMA CONFIGURATIONS

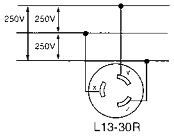
3Ø 250V — 3-POLE, 3-WIRE



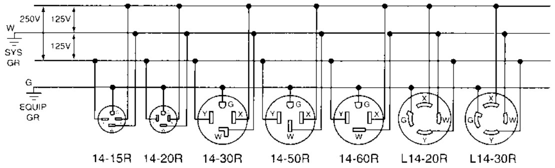
3Ø 480V — 3-POLE, 3-WIRE



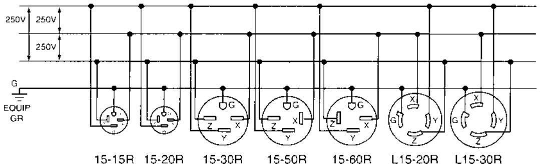
3Ø 600V — 3-POLE, 3-WIRE



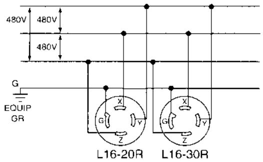
125/250V — 3-POLE, 4-WIRE GROUNDING



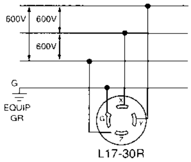
3Ø 250V — 3-POLE, 4-WIRE GROUNDING



3Ø 480V — 3-POLE, 4-WIRE GROUNDING



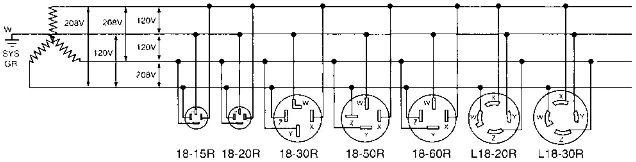
3Ø 600V — 3-POLE, 4-WIRE GROUNDING



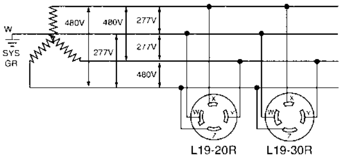
Circuit Wiring Diagrams

WIRING DIAGRAMS FOR NEMA CONFIGURATIONS

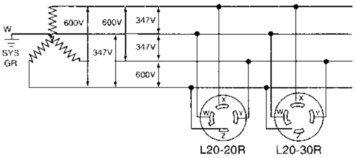
3ØY 120/208V — 4-POLE, 4-WIRE



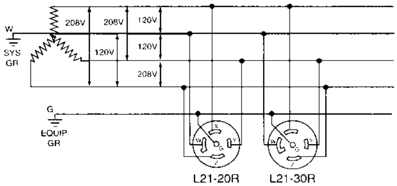
3ØY 277/480V — 4-POLE, 4-WIRE



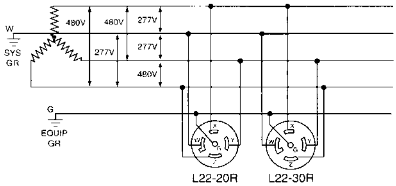
3ØY 347/600V — 4-POLE, 4-WIRE



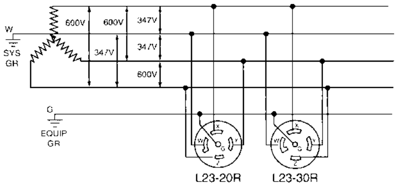
3ØY 120/208V — 4-POLE, 5-WIRE GROUNDING



3ØY 277/480V — 4-POLE, 5-WIRE GROUNDING



3ØY 347/600V — 4-POLE, 5-WIRE GROUNDING



MASTER ELECTRICAL SPECIFICATION

GENERAL PROVISIONS

(A) The Architectural General and Special Conditions for the work of this project shall be part of the Electrical Specifications. The Electrical Contractor shall examine the General and Special Conditions before submitting a proposal.

(B) The General Contractor shall be responsible for all of the work included in this section. The delegation of this work to the Electrical Contractor shall not relieve the Electrical Contractor of responsibility. The Electrical Contractor and subcontractors who perform work under this section will be responsible to the General Contractor.

(C) The intent of the repetition of paragraphs under the General or Special Conditions is to call particular attention to them, and it is not intended nor shall it be assumed that any other parts of the General or Special Conditions have been omitted if not repeated herein.

(D) The naming of a manufacturer or brand with catalog number or other product identification without the words “or equivalent” in the specifications shall indicate that it is the only product approved for purchase. If the words “or equivalent” are used in the specification, they shall be interpreted as establishing a quality or performance standard for the material or product to be purchased. This shall indicate that the Electrical Contractor is not restricted to the use of the named and identified product if a substitute approved by the Architect/Engineer is available. However, where a substitution is requested, it will be permitted only with the written approval of the Architect/Engineer. No substitute material or product shall be ordered, fabricated, shipped, or processed in any manner prior to the approval of the Architect/ Engineer. The Electrical Contractor shall assume all responsibility for additional expenses as required to make changes from the original material or product specified. If a notice of substitution is not furnished to the Architect/Engineer within fifteen (15) days after the General Contract is awarded, then the materials or products named in the specification shall be purchased and used.

(E) The Electrical Contractor shall furnish and present five (5) copies of all electrical drawings, brochures, and installation instructions relating to specified equipment, wiring devices, and accessories to the Architect/Engineer for approval and shall furnish and present five (5) copies of a schedule of the manufacturers of all items for which shop drawings or brochures are not presented. No equipment shall be ordered, purchased, or installed prior to the approval of shop drawings, brochures, installation instructions, and schedules. Approval by the Architect/Engineer is intended to establish conformance with the project design concept and the requirements of the drawings and specifications.

(F) The Electrical Contractor shall examine the drawings of all trades whose work relates to or is dependent on electrical work to become fully informed of the extent and character of their specified work and be able to coordinate it while avoiding possible interference with the electrical work.

(G) Before submitting the bid, the Electrical Contractor shall visit the site and examine all adjoining existing buildings, equipment, and space conditions on which his or her work is in any way dependent to anticipate any possible space restrictions or constraints that could affect timely completion of the electrical work in accordance with the intent of the specifications and drawings. The Electrical Contractor shall report to the Architect/Engineer any conditions that might prevent the specified electrical work from being performed in the manner intended. No consideration or allowance will be granted to the Electrical Contractor for failure to visit the project site, or for any alleged misunderstanding of the materials to be furnished or work to be done.

TEMPORARY POWER

(A) The Electrical Contractor shall provide temporary services to structures other than permanent or substantial buildings for electrical service, usually of short duration or during the construction of permanent buildings. The Electrical Contractor shall install a treated pole, minimum Class 7, or equivalent, in the solid earth where no building exists, and provide a substantial and adequate support, guyed as necessary. Such a support may be a 4- by 6-inch sound timber securely attached to the framing of a building, and extending no more than 3 feet above the supporting structure if unguyed or 8 feet if guyed.

(B) The Electric Utility will provide a charge to install and remove its lines, appurtenances, and metering equipment. The Electrical Contractor shall pay the Electric Utility the total cost in advance, and pay for electric current consumed based on the appropriate service classification. The Electrical Contractor shall provide an application for service, a security deposit, and an inspection certificate.

(C) Service entrance, metering equipment, and other wiring on temporary installations shall be installed in the same manner as required for permanent installations. Inspections and approval shall be required prior to the Electric Utility making service connections.

ELECTRICAL DRAWINGS AND SYMBOLS

(A) The Electrical Drawings are diagrammatic and indicate the general locations of all materials, equipment, luminaires, and wiring devices. These drawings shall be followed as closely as is practical. The Electrical Contractor shall coordinate the work under this section with the architectural, plumbing, heating and air conditioning, and other trade drawings for the exact dimensions, clearances, and roughing-in locations. The Electrical Contractor shall cooperate with the other trades if field adjustments are required to accommodate the work of others.

(B) The drawings and specifications are complementary, each to the other, and the work required by either shall be included in the Contract as if called for by both.

(C) If directed by the Architect/Engineer, the Electrical Contractor shall, without an extra charge, make reasonable modifications in the layout as needed to prevent conflict with the work of other trades or for the workmanlike execution of the work specified.

(D) The standard or modified electrical symbols used on the drawings for this project are identified in a Master Symbol List in the specifications and they are also identified where used on the drawings. Not all symbols will appear on any one drawing.

WORK INCLUDED

(A) The work consists of the furnishing and installing of a complete exterior and interior electrical system. The Electrical Contractor shall provide all supervision and labor, and furnish and install all materials, equipment, wiring devices, and all other fixtures and fittings as indicated on the drawings and as necessary to complete the system.

(B) The intent of the specifications and drawings is to call for finished work that has been tested to demonstrate that it is operational.

(C) Any apparatus, appliance, material, or work not shown on the drawings but called out in the specifications, or vice versa, or any incidental accessories necessary to complete the work in all respects and make it ready for operation, even if not specifically specified, shall be furnished, delivered, and installed by the Electrical Contractor without additional expense to the Owner.

(D) Minor details not usually shown or specified, but necessary for the proper installation and operation of a system or equipment, shall be included in the Electrical Contractor's estimate, as if specified herein or shown.

(E) With submission of the bid, the Electrical Contractor shall give written notice to the Architect/Engineer of any necessary items or work that have been omitted from the drawings or specifications. In the absence of such written notice, it is mutually agreed that the Electrical Contractor has included the cost of all required items in his or her proposal, and that the Electrical Contractor will be responsible for the approved satisfactory functioning of the entire system without extra compensation.

WORK NOT INCLUDED

(A) The furnishing, installing, and wiring of equipment and controls that shall be performed by others or the Electrical Contractor as follows:

1. Heating, ventilating, and air conditioning equipment, and electrically powered or driven major appliances requiring permanent installation, unless otherwise indicated, shall be furnished and installed by others but connected by the Electrical Contractor at the locations indicated on the drawings.
2. Telephone system wiring or cable, panels, and instruments within and outside the building shall be furnished, installed, and wired by the telephone company or other qualified and approved subcontractor.

CODES AND FEES

(A) All materials and workmanship shall comply with all applicable codes, state laws, local ordinances, industry standards, and electric utility and insurance carrier requirements.

(B) In cases of conflict between all applicable codes, state laws, local ordinances, industry standards, and insurance carrier and electric utility requirements, the Electrical Contractor shall bear all costs related to the correction of any such conflict.

(C) *Noncompliance:* Should the Electrical Contractor perform any work that does not comply with all applicable codes, state laws, local ordinances, industry standards, and insurance carrier and electric utility specifications, the Electrical Contractor shall bear all costs related to the correction of any such noncompliance.

(D) Applicable codes, standards, and specifications shall include, but not be limited to, the building codes and industry standards, codes, and specifications listed below:

1. Building Codes
    - **a.** National Building Code
    - **b.** Local Building Codes
    - **c.** National Electrical Code (NEC)
    - **d.** State Electrical Codes
    - **e.** Local Municipal Electrical Codes

2. Industry Standards, Codes, and Specifications

- **a.** AMCA—Air Moving and Conditioning Association
- **b.** ANSI—American National Standards Institute, Inc.
- **c.** ASHRAE—American Society of Heating, Refrigeration, and Air Conditioning Engineers
- **d.** ASME—American Society of Mechanical Engineers
- **e.** ASTM—American Society for Testing and Materials
- **f.** EIA—Electronic Industries Association
- **g.** IEEE—Institute of Electrical and Electronic Engineers
- **h.** IPCEA—Insulated Power Cable Engineers Association
- **i.** NEC—National Electrical Code (NFPA No. 70-2002)
- **j.** NEMA—National Electrical Manufacturers Association
- **k.** NFPA—National Fire Protection Association, Inc.
- **l.** OSHA—Occupational Safety and Health Administration
- **m.** UL—Underwriters' Laboratories Inc.

BASIC ELECTRICAL MATERIALS AND WIRING DEVICES

General

(A) All wire, cable, conduit, conduit fittings, cabinets, panel boxes, wiring devices, and miscellaneous hardware and fittings shall be new and undamaged, and bear the UL label where applicable, and be as specified for use in each specific location.

(B) Samples of specific wire, cable, conduit, fittings, cabinets, panels, and boxes procured for use shall be made available to the Architect/Engineer for approval when requested.

(C) *Equipment Finish:* All factory-finished electrical boxes, cabinets, and panelboards shall be furnished in the manufacturer's standard color and finish. The Electrical Contractor shall notify the Painting Contractor when all exposed unpainted electrical equipment, except conduit, and those factory-finished cabinets and panelboards that are to be painted can be cleaned, primed as required, and finish-painted in the colors selected by the Owner in accordance with the Painting Section of these specifications.

Conduit

(A) Rigid steel conduit shall be used for service entrance and main feeders, and branch circuits where shown on the drawings and in the specifications. Rigid steel conduit shall be made from low-carbon steel that has been hot-dip galvanized inside and outside, and the ends shall be threaded to accept threaded fittings. Other finishes may be substituted if approved by the Architect/Engineer. All conduit shall be UL approved.

(B) Electrical metallic tubing (EMT) may be used for branch circuits and raceways other than for service entrance and main feeders, unless prohibited by the NEC or local ordinances. All EMT shall be UL-approved, pressure-connected type, and galvanized inside and outside, and shall comply with ASA C-80.3 for zinc-coated EMT with fittings of the same type, material, and finish.

(C) Conduit diameters shall be as indicated on the drawings, or as stated in fill schedules in the current NEC. Provision shall be made for including a green insulated grounding conductor where specified or as shown on the drawings.

(D) Conduit fittings shall be appropriate for each application, and shall be manufactured by ____________ or approved equal.

(E) All conduit joints shall be cut square, threaded, reamed smooth, and drawn up tight. Bends or offsets shall be made with an approved bender or hickey, or hub-type conduit fittings. The number of bends per run shall conform to those stated in the current NEC.

(F) Concealed conduit systems shall be run in a direct line with long sweep bends and offsets. Exposed conduit runs shall be parallel to and at right angles to building lines, using conduit fittings for all turns and offsets.

(G) Transitions between nonmetallic conduits and metallic conduits shall be made with the manufacturer's standard adapters made for this purpose.

(H) Exposed conduit shall be securely fastened in place on maximum ____________ foot intervals. Hangers, supports, or fasteners shall be provided at each elbow and at the end of each straight run terminating at a box or cabinet. Only couplings and fittings designed specifically for the type of conduit procured shall be used. The conduit shall be supported by corrosion-resistant straps and/or clamps.

(I) Conduit systems shall be installed in accordance with the current NEC to provide a continuous bond throughout the system in a neat, workmanlike manner.

Wire and Cables

(A) All wire and cable shall meet all applicable specifications and standards and shall conform with the current edition of the NEC. Insulated wire shall have information including but not limited to gauge, voltage rating, insulation type, temperature rating, sheath type, permissible location, and manufacturer's name, as applicable to the type, permanently marked on the outer covering at regular intervals not exceeding 4 feet. Cable shall have information including but not limited to type, style, voltage rating, number of conductors, ground conductors, maximum voltage, UL listing, and sunlight resistance, as applicable to the type, permanently marked on the outer covering at regular intervals not exceeding 4 feet. Wire and cable shall be delivered in complete coils or reels with identifying tags stating the gauge and type of insulation.

(B) Wire and cable shall be suitably protected from weather and other damage during storage and handling, and shall be in pristine condition after installation.

(C) Conductors shall be soft-drawn copper conforming to ASTM B3 for solid wire and ASTM B8 for stranded wire. Stranded wire shall be No. 6 American Wire Gauge (AWG) and larger, and solid wire shall be No. 8 AWG and smaller.

(D) Wire and cable shall be factory color-coded with a separate color for each phase and a neutral color used consistently throughout the system, as required by the current NEC.

(E) All conductors shall be rated for 600 volts, unless otherwise specified or shown on the drawings, or for electronic or communication use.

(F) Conductors for lighting, receptacles, and power branch circuits, feeders, and subfeeders size No. 1/0 AWG and smaller shall be Type THHW flame retardant, moisture- and heat-resistant, thermoplastic insulated.

(G) Conductors for feeders and subfeeders size No. 1/0 AWG and larger shall be type RHW flame retardant, moisture-resistant, thermoset insulated.

(H) Branch circuits containing all electric heating elements such as electric duct coils, baseboard radiation, and cabinet unit heaters shall be Type THHN flame retardant, heat-resistant, thermoplastic insulated with a maximum operating temperature of 90 degrees C (194 degrees F).

(I) Underground feeder and branch circuit wire for direct burial in earth or in conduit shall be Type UF for use in wet or dry locations.

(J) Wire and cable shall be as manufactured by ____________ or approved equal.

Wire Connections

(A) Joints in branch circuits shall be made only where such circuits divide as indicated on the drawings and shall consist of one through circuit to which the branch from the circuit shall be spliced. Joints in branch circuits shall not be made by fixture hangers. No splices shall be made in conductors except at outlet, junction, or splice boxes.

(B) All joints or splices for No. 10 AWG conductors or smaller shall be made with UL-approved wire nuts or compression-type connectors.

(C) All joints or splices for No. 8 AWG or larger conductors shall be made with a mechanical compression connector. After the conductors have been made mechanically and electrically secure, the entire joint or splice shall be covered with 3M Scotch brand No. 33 tape, or approved equal, to make the insulation value at the joint or splice equal to the insulation value of the conductors. The connectors shall be UL approved.

Junction and Pull Boxes

(A) The Electrical Contractor shall furnish and install all junction and pull boxes to provide access points for pulling and feeding conductors into a raceway system. They shall be used in conduit runs where the number of bends between outlets exceeds the maximum number permitted by the current NEC. Junction and pull boxes shall be located as shown on the drawings in the sizes indicated in the junction and pull box schedule.

(B) Junction and pull boxes and their covers shall be formed from sheet steel and shall have widths, heights, and depths as shown on the drawings or junction and pull box schedules and shall be finished in gray enamel paint. Boxes without hinged covers shall include covers with attached screws.

(C) Junction and pull boxes shall be in industry standard sizes as manufactured by ____________, or approved equivalent.

Outlet Boxes

(A) Outlet boxes with the correct fitting for the application shall be located at each conductor splice point, at each outlet, switch point, or junction point, and at each pull point for the connection of conduit and other raceways. They shall also be located at all transitions from conduit to open cables. All outlet boxes for concealed wiring shall be made from galvanized- or cadmium-plated sheet steel, and they shall have a depth of at least 1.5 inches, whether single or ganged. The boxes shall be large enough size to accommodate the number of wiring devices and conductors as specified in the fill schedule of the current NEC. The depths, clamps, and number of knockouts shall be as specified in the outlet box schedule.

(B) Rectangular 3- by 2-inch metal boxes shall be used for installing single switches or duplex receptacles, as specified or shown on the drawings. Two compatible boxes may be ganged together to accept two switches or two duplex receptacles at a single location or as specified or shown on the drawings.

(C) Square 4- by 4-inch or $4^{11}/_{16}$- by $4^{11}/_{16}$-inch metal boxes shall be used for installing two switches or two duplex receptacles at a single location or as specified or shown on the drawings.

(D) Octagonal 4- by 4-inch metal boxes shall be used for containing and protecting wire connections for ceiling- or wall-mounted luminaires as specified or shown on the drawings. The Electrical Contractor shall furnish all required telescoping metal braces, hickeys, covers, and miscellaneous hardware, as required.

(E) Round ceiling metal pan boxes with diameters of $3^{1}/_{4}$ inches shall be used for containing and protecting wire connections for ceiling- or wall-mounted luminaires as specified or shown on the drawings. The Electrical Contractor shall furnish all hickeys, covers, clamps, and miscellaneous clamps, as required.

(F) Telephone and communications boxes shall be as specified or shown on the drawings.

(G) Outlet boxes shall be in industry standard sizes as manufactured by __________, or approved equivalent.

Wiring Devices

(A) The wiring devices listed below by manufacturer and catalog number indicate the quality and specification grade required. In the judgment of the Electrical Contractor, wiring devices manufactured in the same style and dimensions that comply with the same tests and codes may be used without approval by the Architect/Engineer. In cases where a device is specified with only one manufacturer and catalog or part number and without the phrase "or equivalent," substitutions shall be made only with the approval of the Architect/Engineer.

1. *Wall-Mounted Switches.* Where more than one flush wall switch is indicated in the same location, the switches shall be mounted in gangs under a common wallplate.

	Device	Manufacturer and Catalog No.
a.	Single-pole switch, 20A/120V	____________________
b.	Three-way switch, 20A/120V	____________________
c.	Four-way switch, 20A/120V	____________________

2. *Wall-Mounted Receptacles,* unless otherwise specified, shall be duplex.

	Device	Manufacturer and Catalog No.
a.	Receptacle, 20A/125V	____________________
b.	Receptacle, 20A/250V	____________________
c.	Receptacle, 20 A/120V, GFCI	____________________
d.	Receptacle, 30 A/120V, GFCI	____________________
e.	Receptacle, 20A/120V, isolated ground	____________________

(B) The following wiring devices are specified by only one manufacturer and catalog number; substitutions may be made only with the approval of the Architect/Engineer.

- **a.** Dimmer switches
- **b.** Pilot-light switches
- **c.** Switch/receptacles

d. Timer switches

e. Motion sensors

(C) The Electrical Contractor shall furnish and install appropriate wallplates for all receptacles, switches, control devices, communications, and telephone outlets. The wallplates shall be made of ___________ with a ___________ finish, and shall be in the color specified on the wallplate schedule. Special markings shall be as indicated on the drawings or in the specifications.

(D) Where wiring devices are installed in outlet boxes exposed to weather, the boxes, wallplates, and covers shall be approved by the Architect/Engineer for those locations.

Electrical Identification

(A) The Electrical Contractor shall maintain accurate records of all deviations in work as installed from work specified on the drawings or in the specifications. On completion of the project, two (2) complete sets of marked-up prints showing these deviations shall be delivered to the Architect/Engineer.

SERVICE AND DISTRIBUTION

General

(A) The Electrical Contractor shall furnish and install an electric service entrance, related distribution equipment, and an approved grounding system as shown on the drawings, and schedules shall comply with the current NEC, local and state building and electric codes, and Electric Utility specifications.

(B) The Electrical Contractor shall furnish and install all required conduit, cable, and watthour meter and base provided by the Electric Utility and all equipment required by the Electric Utility for secondary service from the point of attachment to the main service panel. The Electric Utility will furnish and install the primary service cable from the nearest distribution transformer to the service end box and make all splices to the secondary electrical system of the project. The Electrical Utility will also provide a watthour meter and base appropriate for the amperage rating of the electrical system. The Electrical Contractor shall provide all documentation required by the Electric Utility and complete all forms and pay all fees required for licenses required by the local building/electrical inspector.

(C) The Electrical Contractor shall furnish and install a proper electrical ground as shown on the drawing that makes the approved connections to suitable metallic cold water piping and a properly driven approved ground rod or rods as specified by the NEC or local electric codes, whichever is more stringent.

(D) The conduit used for the service entrance shall be rigid, galvanized steel conduit unless otherwise indicated on the drawings.

(E) The conductors for the service entrance shall be copper Type RHW-2 or THW-2 rated at 194 degrees F (90 degrees C), unless otherwise noted.

Overhead Service Connection

(A) The Electric Utility will install, own, and maintain the overhead service lateral to supply service equipment rated at 600 amperes or less. In those cases where the service lateral exceeds one hundred (100) feet, the Electrical Contractor may be required to contribute toward the cost of the excess in accordance with the Electric Utility's rate schedule. The Electric Utility retains responsibility for the connection at the weatherhead.

(B) The Electric Utility reserves the right to designate the location at which its service drop will be attached to the owner's building. This point will normally be not less than fifteen (15) feet or more than twenty-one (21) feet above final grade. Where the Owner's structure is too low to permit the installation of the service bracket at the minimum fifteen (15) feet above the final grade, the Electric Utility may, if local ordinances and field conditions permit, approve the attachment at a lower point provided the minimum heights for the lowest service drop conductor in the Electric Utility's schedule can be obtained with the drop attached at normal height on the Electric Utility's poles.

(C) All service drops must be directly accessible by ladder in contact with the ground.

(D) The Electrical Contractor shall furnish and install a $^1/_2$-inch steel eye-bolt with a 1-inch minimum inside-diameter eye or approved screw eye-lag securely bolted with a backing plate and supported by a sound structural member at a point 6 inches minimum or 10 inches maximum below the weatherhead.

(E) The Electrical Contractor shall locate the service head above and within 10 inches of the point of attachment of the Electric Utility's service drop. A minimum of 36 inches of slack for service up to and including 400 amperes shall be provided in each of the service entrance conductors, at the service head, for connection to the service drop.

(F) The Electrical Contractor shall mount the watthour meter and base plumb and level at the distance above the finished grade specified or shown on the drawings. For 200-ampere service the service entrance cable shall be 20-inch galvanized steel pipe threaded into the meter base. Raintight threaded flange conduit connectors shall be located as shown on the drawings, and the metal conduit shall be strapped to the supporting wall with conduit straps not more than 54 inches apart.

Underground Service Connection

(A) Where the Electric Utility's distribution facilities are in a zoned underground or network area, it will install, own, and maintain, at its own expense, the necessary cable system from the underground distribution line which is part of its distribution system to the Owner's point of service connection.

(B) The Electrical Contractor shall contact the Electric Utility and determine the cable and conduit to be installed by the Electric Utility and the limits of its installation, ownership, and maintenance responsibilities. The Electrical Contractor shall also determine the Electric Utility's recommended position for a service end box, as necessary, where the splice is to be made.

(C) The Electrical Contractor shall furnish the matching cable and conduit necessary to extend the service lateral from the service end box to the main disconnect inside the project building, as indicated in the drawings and specifications. The Owner shall maintain at his or her own expense the required service lateral from this point to his or her main disconnect.

(D) Unless otherwise specified, the service lateral shall be three insulated conductors buried in a trench 2 to 4 feet deep below finished grade and a minimum of 4 inches wide.

(E) The Electrical Contractor shall mount the watthour meter and base plumb and level at the distance above the finished grade specified or shown on the drawings. For 200-ampere service, the service entrance conduit shall be 2-inch galvanized steel pipe threaded into the meter base. Raintight threaded flange conduit connectors shall be located as shown on the drawings, and the metal conduit shall be strapped to the supporting wall with conduit straps not more than 54 inches apart.

Service Entrance

(A) The Electrical Contractor shall provide a service entrance system as shown on the drawings and described in the specifications. The Electrical Contractor shall calculate and verify the electrical demand requirements for the building prior to the installation of electric service.

(B) The electrical systems shall be a 120-volt, 60-Hertz, single-phase, three-wire service.

Grounding

(A) Unless otherwise specified or determined by local building code, the Electrical Contractor shall measure ground resistance with an approved Megger ground-resistance tester to determine the requirement for more than one ground rod as specified in the current NEC.

(B) In addition to the ground rod(s), the Electrical Contractor shall make approved connections to one other earth ground, a metal cold water pipe or as approved by the NEC. In no case shall a gas pipe be used as an earth ground. The grounding wire shall be at least No. 6 AWG copper protected by PVC conduit if exposed above ground at any outside location. All ground clamps shall be approved for the intended purpose.

(C) If a second ground rod is specified, it shall be separated at least 6 feet from the first, assuming vertical orientation of the rods.

Branch-Circuit Panelboards/Loadcenters

(A) Lighting and appliance branch-circuit panelboards (loadcenters) shall be made from cold-rolled steel and shall be finish painted in the manufacturer's colors. It shall consist of three main parts: front cover, inner cover, and backpan built to accept molded branch circuit breakers rated for 240 volts or less.

(B) The branch-circuit panelboard shall be equipped with parallel hot buses with sufficient stabs to accept the number and type of circuit breakers specified for the project and have room to spare for later expansion. The back pan shall contain a rail for effective clamping of all circuit breakers. The parallel neutral/ground buses shall be made from solid, rectangular copper alloy with screw-type wire terminals. The backpan shall be large enough to provide adequate gutter space around the busbars for the anticipated wire fill. It shall have sufficient knockouts for the number and position of cables specified. The front cover shall be provided with a secure latch and concealed hinges.

(C) The branch-circuit panelboard shall be UL listed for indoor applications, bear the UL label, and meet NEMA and ANSI requirements. It shall also conform to the current NEC for switchboards and panelboards and the insertion of overcurrent devices.

(D) The branch-circuit panelboard shall be NEMA Type 1, as manufactured by ____________ or approved equivalent, and shall be fully assembled with all hot and neutral/ground buses, gutter posts, tie bar, and other ancillary fittings. It shall be durably marked in accordance with the current NEC.

(E) The Electrical Contractor shall make every reasonable effort to balance the load to the satisfaction of the Electric Utility. The Electrical Contractor shall complete the panelboard directory on the inner face of the front cover legibly to identify all circuits in a permanent manner, as approved by the Owner.

Overcurrent Protective Devices

(A) The Electrical Contractor shall furnish and install, where indicated on the drawing or as required by the current NEC, main and branch circuit breakers. The breakers shall be capable of manual operation and opening all poles simultaneously. The tripping mechanism shall operate thermally, magnetically, or both, shall open instantaneously on short circuits, and have a time delay on overcurrent. The circuit breakers shall be of the type shown on the drawings or called out in the protective device schedule.

(B) The circuit breakers shall be Class CTL manufactured by ____________ or approved equivalent.

GENERAL

Lighting

(A) The Electrical Contractor shall furnish, install, and wire all permanent luminaires as shown on the drawings or as listed in the luminaire schedule and shall install all required lamps, lenses, reflectors, protective covers, and decorative components.

(B) Luminaires shall be of the types, and sizes, with the specified lamping, in the wattage ratings, shown on the drawings or as listed in the luminaire schedule. The Electrical Contractor may furnish luminaires that meet current commercial electrical and mechanical standards for quality and the specified illumination requirements as listed in the luminaire schedule from the product selections of different manufacturers. However, at the Architect/Engineer's request, the Electrical Contractor shall submit for approval one sample of each luminaire specified.

(C) If a luminaire is specified only by a single manufacturer and model number for reasons of appearance, style, or specialized function, and that product is not available commercially, the Electrical Contractor may make a reasonable substitution only with the approval of the Architect/Engineer.

(D) The material and workmanship of the luminaires shall be quality products in accordance with commercial standards. By mutual agreement with the Electrical Contractor, the Owner reserves the right to request replacements for any luminaire furnished that is damaged, defective, or poorly finished or otherwise fails to meet the accepted commercial quality standards for that grade of product, provided that the Electrical Contractor is notified prior to the installation of said luminaire.

(E) The Electrical Contractor shall assemble custom-made luminaires furnished disassembled by others following approved assembly instructions and/or shop drawings, and install and wire them where and as specified.

(F) The Electrical Contractor shall coordinate the furnishing and installation of luminaires with the completion of the project to avoid interference with the work of other trades, unless otherwise required by the specifications. The Electrical Contractor shall keep all luminaires delivered to the job site in their protective cartons or packages to protect them from dust or damage prior to installation.

Lamps

(A) All luminaires shall be lamped as indicated on the lighting fixture schedule. All lamps shall be new and unused and shall have the style, shapes, special properties, wattage ratings, and spectral colors specified. Lamps installed shall not exceed the wattage ratings recommended by the luminaire manufacturer. All fluorescent lamps shall be matched with the appropriate electronic or magnetic ballasts, as recommended by the luminaire manufacturer. Lamps shall be purchased from recognized commercial manufacturers or vendors.

(B) At the time of the acceptance of the building, the Electrical Contractor shall have all luminaires lamped, cleaned, and assembled with all reflectors, domes, or light shields, and be prepared to demonstrate their proper operation to the satisfaction of the Architect/Engineer and Owner.

BIBLIOGRAPHY

Black & Decker staff, *The Complete Guide to Home Wiring,* Creative Publishing, Minnetonka, Minn., 2001.

Cauldwell, Rex, *Wiring a House,* The Taunton Press, Newtown, Conn., 1996.

Fink, Donald G., and Beaty, H. Wayne, *Standard Handbook for Electrical Engineers,* McGraw-Hill, New York, 2000.

Hickey, Robert B., *Electrical Engineers's Portable Handbook,* McGraw-Hill, New York, 1999.

McPartland, Joseph F., and McPartland, Brian J., *National Electrical Code Handbook,* McGraw-Hill, New York, 1999.

National Fire Protection Association, *National Electrical Code, NFPA 70,* NFPA, Boston, 2002.

Sclater, Neil, *Electronics Technology Handbook,* McGraw-Hill, New York, 1999.

Sclater, Neil, and Chironis, Nicholas P., *Mechanisms and Mechanical Devices Sourcebook,* 3d ed., McGraw-Hill, New York, 2001.

Walsh, Ronald A., *Electromechanical Design Handbook,* McGraw-Hill, New York, 1990.

REFERENCES ON WIRING DEVICES, CABLING SYSTEMS, AND LAMPS AND BALLASTS

Cooper Bussmann, *Circuit Protection Solutions,* Cooper Bussmann, Inc., St. Louis, 2001.

Cooper Industries, *Arrow Hart Wiring Devices Catalog 40,* Cooper Industries, Inc., Syracuse, N.Y., 2000.

Leviton, *Structured Cabling Systems, T-500,* Leviton Voice & Data Division, Bothell, Wash., 2000.

Leviton, *Wiring Devices for Industrial Commercial and Residential Construction and Maintenance, D501,* Leviton Manufacturing Co., Little Neck, N.Y., 2000.

Osram Sylvania, *Lamp and Ballast Catalog,* Osram Sylvania, Inc., Danvers, Mass., 2000.

Telematic, *Application Note TAN 1004, Surge Protection for Intrinsically Safe Systems,* MTL Incorporated, Hampton, N.H., 1996.

INDEX

AC generators, 14, 45–50
  bus-voltage, generation of, 48–49, *48*
  frequency generation of, 47
  rotors for, *46*, 47–48
  schematic symbols for, *14,* 16
  synchronization of, 49–50
AC motors:
  polyphase, 14, 16, 96, 346, 351–352, 359–362
    induction, 346, 351–352, 359–362
      squirrel cage rotor, 346, 351–352, 360
      wound-rotor, 346, 351, 360
    principles, 351–352
    rotors, 346, 351–352, 360
    schematic symbols for, *14,* 16
    speed-torque curve, 360, *361*
    stators, 360–361
    synchronous, 346, 352
      DC-excited, 352
      nonexcited, 352
    synchronous speed, 98, 352, 360–362
    torque, 360–361
  single-phase, 14, 16, 345–346, 351–360
    armatures, 352
    capacitor-start (CS), 346, 352–354, *354–356,* 359–360
AC motors, single-phase (*Cont.*):
    commutator, 352, 358
    curves, speed-torque, 355–356
    induction, 346, 351–352
    premanent-split-capacitor (PSC), 346, 352, *354*, 355–356, *356*
    repulsion-start/induction run, 346, 358–360
    rotors, 345–346, 351–352, 357–358
      squirrel-cage, 346, 351–352, 357
      wound, 345, 351, 358
    running and starting loads, 360
    schematic symbols for, *14,* 16
    shaded-pole (nonsynchronous) 346, 352, 357–358, *358*
    shading coils, 357–358
    speed-torque curves, 353, 355 *355–356*
    split-phase, resistance-start (SP), 346, 352–353, *354–355*, 359–360
    squirrel cage, 346
    starting versus running watts, 359–360
    synchronous, 346, 352
    synchronous speed, 355–356
AC motors, single-phase (*Cont.*):
    torque, 353–356
    two-capacitor start/one-capacitor run, 346, 352, 356–357, *357*
    universal AC/DC, 346, 358–360
    windings, 353–358
    wound rotor, 346
  (*See also* Motors, general)
AC motor starters, 363–366
  across-the-line, 363–364, *363–364*
  autotransformer, 364–365, *365*
  primary resistor, 365
  semiconductor, 366, *366*
American National Standards Institute (ANSI) (*see* Standards organizations)
Armatures, 46, 359, 367, 369, 372, 374
Automation systems, residential, 322, 333–334
  smart home, 333–334
Autotransformers (*see* Transformers, low-voltage)
Auto zigzag grounding transformers (*see* Transformers, low-voltage)

Backpanels (*see* Loadcenters)
Ballasts, 283, 287–288, 316–317, 320

Numbers in *italics* denote a figure or illustration.

- Ballasts (*Cont.*):
  - electronic, 283, 317
  - fluorescent lamps, for, 283, 287, *288*
  - high-intensity discharge lamps, for, 287
  - hybrid, 283
  - magnetic, 283, 320
- Bases for watthour meters, 135, 137–144
- Batteries, 14, 15, 19, 20, 359, 384–387
  - graphic symbols for, *14*, 15, 19, *20*
  - rechargeable storage, 359, 384–387
- Boxes, electrical (*see* Electrical boxes)
- Branch-circuit wiring diagrams (*see* Wiring, electrical and communications)
- Brushless DC motors (*see* DC motors)
- Brush-type motors (*see* AC motors; DC motors)
- Buck-boost autotransformers (*see* Transformers, low-voltage)
- Bulb shapes (*see* Lamps, electric)
- Bus bars, 113
- Bus voltage generation, 48–49

- Cable grips, wire mesh, 232, 238
- Cables, electrical:
  - burial of, 122–126, 265–267
    - direct, 122–126, 265–267
    - low-voltage, 266–267, *267*
    - 120-V, UF, *265*
  - BX (*see* flexible armored *below*)
  - coding and identification, 180–182
  - communications, 185, 342–344
    - coaxial, 185, 343
    - color code of telephone, 185
    - telephone, 185
  - direct burial, 124
    - type MC/MI, 124, 184, *184*
    - type UF, 124, 181, *182*, 183
    - type USE, 124, 183
  - fiberoptic, 332
  - flexible armored (AC, BX, or Greenfield), 181, *184*
    - NEC requirements for, 184
  - Greenfield (*see* flexible armored *above*)
  - large appliance, 183
  - metal-clad, type MC/MI, 181, 184, *184*
    - NEC requirements for, 184
  - nonmetallic, type NM (Romex), 181, *182*, 183
    - NEC requirements for, 183
- Cables, electrical (*Cont.*):
  - overhead distribution and clearance, 131–132, *132*
    - NEC requirements for, 131
  - power transmission systems, 52
  - service-entrance, 124, 135–142, 181–183
    - NEC requirements for, 182–183
    - type SE, style R, *135–139*, 182–183, *182*
    - type SE, style U, 181–183, *182*
    - type USE, 124, 183
  - Romex (*see* nonmetallic, type NM *above*)
  - service lateral, 140, *140*
  - structured (*see* Structured wiring systems)
  - TIA cable categories, 325, 342, 344
  - transmission, 52
  - underground distribution, for, 123–130
    - type MC/MI, 24, 124, 181, 184, *184*
    - type SE, *135–141,* 136–138
    - type UF, 124
    - type USE, 124, 140–142, *140–141*
    - trench for direct burial, 124–125, *125*
  - underground feeder (UF), 181, *182*, 183
    - NEC requirements for, 183
  - underground/underwater, for, 52
- CAD (*see* Computer-aided design)
- Capacitor motors (*see* AC motors)
- Capacitors, 14–15, 19–20, 68, 95–98, 356–357, 374, 405
  - electrical motors, in, 356–357, 374
  - function in electrical systems, 95–98, *98*
  - graphic symbols, *14*, 15, 19, *20*
  - high-frequency, 405
  - power, primary and secondary, 96–97
  - power factor correction in, 68, 95–97
  - switched, 97–98, *98*
  - very high frequency, 405
- Chromaticity, 316, 317
- Circline fluorescent lamps (*see* Lamps, electric, fluorescent)
- Circuit breakers, 14–17, 58, 84–87, 101, 111, 113, 154–159, 225–226
  - classification, 85
  - distribution, 58, 111
- Circuit breakers (*Cont.*):
  - GFCI type, 101, 225–226
  - graphic symbols for, *14*, 15–16, *17*
  - high-voltage, 58, 84–87
    - construction, 86
    - general, 84–85
    - power system, 58, 85–86
      - air-blast, 85–86
      - gas, 86
      - magnetic-air, 86
      - oil, 85–86
      - vacuum, 86
    - ratings, 86–87
  - miniature, molded, 85, 101, 154–159, 225–226
    - GFCI-type, 101, 158–159, 225–226
    - NEC requirements for, 158–159
    - thermal, 154–157, *154*
    - thermal-magnetic, 154–157, *156*
  - substation, 113
- Circuit drawings (*see* Electrical drawings)
- Circuit reclosers (*see* Reclosers)
- Circuit switchers, 58, 87–89
  - blade type, 87- 89, *88*
  - operation of, 87–89
- Coils, 58, 357
  - shading, 357
  - transformer, 58
    - primary (input), 58
    - secondary (output), 58
- Cold-cathode fluorescent lamps (*see* Lamps, electric, fluorescent)
- Color rendering index (CRI), 289–291, 317
- Color temperature, light spectrum, 270–271
- Commutators, 352, 358–359, 367, 371–372, 375
- Compact fluorescent lamps (*see* Lamps, electrical, fluorescent)
- Compound-wound motors (*see* DC motors)
- Computer-aided design, 4–5, 7
  - cost estimation, 4–5
  - drawing (*see* Electrical drawings)
  - material lists, 4
  - plotters, 7
  - software, 4–5
- Computer-aided drawings (*see* Electrical drawings)
- Condensers (*see* Synchronous condensers)
- Conductors (*see* Cables, electrical; Wires, insulated)

- Conduit, 174, 140–141, 186–204, 263–264, 310
  - bodies and fittings, 174, 187–204
    - bodies and covers (with dimensions), 187–190, *188–190*
    - connectors, couplings, and fittings (with dimensions), 190–204, *191–204*
    - NEC requirements for, 187, 190,
  - metallic, 140, *141,* 185–186, 263–264
  - nonmetallic, 140–141, *140–141,* 186–187, 264
  - NEC requirements for, 186–187, 263–264
  - outdoor use, for, 263–264
- Connections, three-phase, 50, 71–74, 130–132
  - delta, 50, *50,* 121
  - delta-delta, 70, *71*
  - delta-wye, 70–72,
  - four-wire delta system, 72, *72*
  - four-wire wye system, 73
  - overhead distribution, 130–132, *132*
  - Scott or T connection, 73–74, *73*
  - wye, 50, *50,* 120–121, *120*
  - wye-delta, 70–72, *71*
  - wye-wye, 70, *71*
- Connection systems, 120–122
  - delta connected 121–122, *121*
  - wye connected, 120–121, *120*
- Connectors, 191–195, 197–204
  - armored cable, for, *204*
  - dimensional data for, 191–195, 197–204
  - EMT, *191–195, 200, 203*
  - flexible metal conduit, for, 201–203
  - liquidtight, *197–198*
  - nylon, *199–200*
- Contactor state graphic symbols for, *17*, 18
- Control and protective devices, 113
- Converters, 58, 98–101
  - AC-to-DC, 59
  - phase, 58, 98–101
    - rotary, 58, 98–100, *99*
    - static, 58, 100–101
- Correlated color temperature (CCT), 286, 289–291, 317
- Cost estimation software (*see* Software, computer)
- Current transformers (CTs) (*see* Transformers, low-voltage)
- Daisy-chain topology (*see* Wiring, electrical and communications)
- DC high-voltage transmission, 55–56
- DC motors:
  - armature, 367, 374
  - characteristics, 367–373
  - commutator, 374–375
  - comparison of characteristics, 370–371
  - compound-wound, 346, *368,* 370, *371*
    - cumulative, 370
    - differential, 370
  - permanent-magnet, 346, 371–373
    - brushless, 346, 371–373, *372*
    - brush-type, 371, *372*
  - principles, 366–367
  - rotor, 367, 373
  - schematic symbols for, *14,* 16
  - series-wound, 346, *368–369*, 369–370
  - shunt-wound, 346, 367–368, *368*
  - speed-load and torque-load curves, 367–369, *368–369, 371*
  - starting, 373–374
  - stator field, 367
  - torque, 367
- Delta connections (*see* Connections, three-phase)
- Delta-wye connections (*see* Connections, three-phase)
- Digital data storage, 4
  - CD-ROMs, 4
  - computer disks, 4
  - servers, 4
- Dimmers and fan controls, 174, 216–219, 308–309
  - applications for lighting, 308
  - digital controls, 309, 216
  - fan-speed controllers, 216–219, *218*
  - fluorescent lamp, for, 216–219, *218*
  - incandescent lamp, for, 216–219, *218*
  - rotary, 216, 217
  - single-pole, 309
  - slide action, 216, 218
  - specifications for, 217–219
  - toggle, 219
  - touch-pad/digital, 2, 219, 309
- Distribution substations, 110–114
  - diagram of, *110*
  - equipment, 113
  - power routes, 113–114
  - switching arrangements, 111–113, *112*
- Distribution systems, 114–132
  - connection systems, 120–122
    - delta-connected, 121–122, *121*
    - wye-connected, 120–121, *120*
  - feeders, 114–115, *115*
  - local, 119–120
    - common power service, 119–120, *119*
  - loop, *116*, 117
  - monitoring of, 118
  - multiple parallel circuit pattern, 117
  - overhead connections for, 130–132
    - cable and clearance, 131, *132*
  - primary, 114–117, *115, 116*
    - routes, 113–114
  - radial, 116–117, *116*
  - secondary, 117–118
  - underground cables for, 123–130, *125*, *127–129*
    - bending space for conductors, 130
    - cable burial instructions, 124
    - digging the cable trench, 124–125
    - direct-burial conductors, 124
    - duct installation, 129–130
    - ducts and duct banks, 128–129, *129*,
    - manholes, 126–128, *127–128*
    - minimum cover requirements, 125–126, *125*
    - NEC installation requirements, 123–125
  - underground systems, 122–123
    - residential (URD), 122
- Distribution transformers (*see* Transformers, distribution)
- Drawings, electrical (*see* Electrical drawings)
- Ducts and duct banks (*see* Underground distribution cables)

- Edison, Thomas, 37
- Electrical boxes, 174, 204–211, 263
  - enclosures, driptight and watertight, 263
  - junction and pull, 174, 205
  - NEC requirements for, 174, 205, 210–211
  - outlet, 205–211, *206–209*
- Electrical CAD software, 4
- Electrical cost-estimation software, 6–7
- Electrical design, planning for, 1–36

- Electrical drawings:
  - computer-aided (CAD), 4–6
    - benefits of, 5
    - software for, 4, 6
  - conventions, 7–8
  - detail, 28, *29*
  - distribution feeder, *115*
  - electronic graphic symbols, 18–21, 20
  - floor plan,wiring, *23*
  - graphic symbols for, 5, 11–21, 296, App. A
    - connection and interconnection, *12*, 13, App. A
    - electronic schematics, 18–21
    - schematics, 14–18, *14, 17*
  - line widths and styles, 9–11, *10*
  - objectives of, 2–3
  - plotters, CAD ink-jet for drawing, 7–8
    - characterristics of, 8
  - preparation, 3–4
  - product and work standards, 30–32
  - projects, for, 22–30, 48, 145, 168, 245–262, 388, 390, 392
    - detail, 28–29, *29*
    - electrical schematics, 26–28, *28*, 72, *72,* 144–145 *145–146,* 167, *168,* 363–365, *363–365,* 388, *390*
    - one-line diagrams, 24–26, *25,* 48, *48*, 115, *115*
    - power riser diagrams, 26, *27,* 138, *139*, 388, *392*
    - shop, 29–30
    - wiring diagrams, 22–24, *23*, 245–262, *247–260*
  - reproduction of, 9
  - revision blocks, 9
  - schedules, 21–22
  - sizes and conventions, 3, 7–9
    - title blocks, 7–8
  - style guides, 5
- Electrical graphic symbols (*see* Electrical drawings)
- Electrical grounding (grounds), 14–15, 19–20, 134, 138–149, 161–170
  - bonding electrode system, 166
  - electrode (rod) systems, 162–170, *165, 168–170*
  - equipment, 162
  - graphic symbols for, *14*, 15, 19, *20*
  - installing conductors, 166–167
    - conductors, 166
  - NEC requirements for, 134, 138–149, 161–168
- Electrical grounding (*Cont.*):
  - rod installation, 164
  - rod/plate characteristics, 164–165
  - testing (resistance), 167, *168*
  - wiring system, 162
- Electrical loads:
  - balancing, 152–153
  - calculation of, 149–151
  - determining capacity for standby/emergency systems, 395–396
  - table of wattage values, 150
  - wye- and delta-connected, 50, *50*
- Electrical power, 37–132, 270
  - AC generators, 45–49
    - AC frequency generation, 47
    - AC generator rotors, 47–48, *46*
    - bus voltage generation, 48–49, *48*
  - AC transmission systems, 51–52
    - undergouund/underwater, 52
  - capacitors, primary and secondary, 96–97
  - distribution, 109–132
  - energy for generation, 39–42, *40*
  - factor, 93–98
    - correction of, 95–96, *95*
    - defined, 94
    - meter, 98
  - generating stations, 45
  - generation and transmission, 37–56
  - generator synchronization, 49–50
  - North American power grid, 42–43
  - single versus three-phase, 43–44, *44*
  - stations, 37–41, 48–49, 98
    - auxiliary quipment, 49
    - Edison's Pearl Street DC, 37
    - fossil fuel (coal, gas, oil), 39–41
    - hydroelectric, 40
    - Niagara Falls hydroelectric AC, 37
    - nuclear, 39–41
    - regulators, 98
    - renewable, 39–41
    - single-line diagram for, *48*
  - supplies, 340, 380, 384–392
    - battery-powered, 384–386, *386–387*
    - emergency systems, for, 384
    - engine-generator, 380, 384, 388–395, *389–392*
- Electrical power, supplies (*Cont.*):
    - fire alarm, for, 340
    - standby systems, for, 380, 384–387, *386–387*, *389–392*
    - uninterruptible (UPS), 380, 386–387, *387*
  - system equipment, 57–108
  - systems, 109–111, *110*
- Electrical product and work standards, 30–32
- Electrical service, 132–142, 149–151, 170–171
  - cable, 135–137, *135–141*, 140–142,
    - NEC requirements for, 141
  - clearance dimensions, *132*
  - drop (triplex), 134–135
  - entrance, 133–134, 136, 139–140
    - connections, 136–138, *137–139*
    - drip loop, 136, *136*
    - drop (triplex), 134–136, *135–136*
  - glossary of terms, 170–171
  - grounding (*see* Electrical grounding)
  - ground testing (*see* Electrical grounding)
  - head (weatherhead), 136–138
  - lateral, 140
  - load calculation/determination, 149–151
  - loadcenters (*see* Loadcenters)
  - overhead, 132, 134–139
    - connections, *132*, 136–138, *136, 137*
    - grounding, 138–139, *138–139*
    - NEC requirements for, 138–139
  - temporary, 167–170, *169–170*
    - NEC requirements for, 167–168
  - transformers (*see* Transformers, distribution)
  - underground, 133, 139–141, *140–141*
    - connections and grounding, 140–141, *141*
    - laterals, 140, *140, 141*
    - NEC requirements for, 140–141
  - wattage for lighting and appliances, 150–151
- Electrical specifications, 32–36, App. B
  - definition of, 32
  - emergency/standby power, for general and special conditions and provisions, 35–36

Electrical specifications (*Cont.*):
  master, 32–35, App. B
  organization, typical, 33–35
  preparing a written, 35
  sections of, 34–35
  supplementary general and special conditions, 36
  word usage, 33
Electrical surges (*see* Surge protection)
Electronic graphic symbols, 18–21, *20*
Electrostatic discharge, 410–411
Emergency and standby systems, 380–397
  determining load capacity, 395–396
  emergency systems, 380–382, 384–385, 387, 396–397
    NEC requirements for, 380–384
    power sources and functions 384, 387
  glossary of terms, 396
  lighting for safe exit, 384
  power sources for, 384–396
    battery-powered standby supplies, 384–386, *386–387*
    emergency functions, 387
    rechargeable storage batteries for, 384–385
    separate electrical service, 384
    standby engine-generator sets, 380, 384, 388–395, *389–392*
      engine-generator farms, 393–394
      fuels for, 394–395
    uninterruptible (UPS), 380, 386–387, *387*
  references to standards for, 397
  specifications for, 395
  standby systems, 380, 382–383
    legally required, 380, 382–383
    NEC requirements for, 380, 382–383
    optional, 380, 383
Emergency systems (*see* Emergency and standby systems)
Enclosures, driptight and watertight (*see* Electrical boxes)
Energy sources for electricity generation, 39–42, *40*
Engine-generator sets, 380, 384, 388–395, *389–392*
  engine-generator farms, 393–394
  fuels for, 394–395
Fan-speed controls (*see* Dimmers and fan controls)
Fire alarm systems, 322, 338–341
  code requirements, 338
  controls for activation, 338
  equipment, classes and styles, 340
  general, 322
  installation guidance, 341
  power supplies (sources), secondary, 338, 340
  signaling system, 339, *339*
  system classifications, 338–340, *339*
    houshold, 339
    protected-premises, 339–340
  warning devices, audible or visual, 338
Fluorescent lamps (*see* Lamps, electric, fluorescent),
Frame sizes of motors (*see* Motors, general)
Fuses (60 A or less), 14–15, 19–20, 159–161, 401, 410–411
  cartridge, 159, 161
  Edison bases, 159, 160
  electronic circuit, one-time-only (OTO), 159, 401, 410–411
  graphic symbols for, *14*, 15, 19, *20*
  NEC requirements for, 159
  S and T series, 159–161, *160*
  SL and TL series, 159, 161
  W series, 159–160, *160*

Generators, AC (*see* AC generators)
Generator synchronization, 49
Ground-fault circuit interrupters (GFCI), 101, 168, 225–228, 244, 259–260, 264, 308–312
  circuit breakers with, 101, 225–226
  NEC requirements for, 225–226, 244, 309–312
  operation of, 225–226, *226*
  protection outdoors with, 264, 308
  receptacles with, 227–228, *227*, 259–260, 310

Hall-effect devices (HEDs), 371–372
Halogen lamps (*see* Lamps, electric, tungsten-halogen)
High intensity discharge (HID) lamps (*see* Lamps, electrical, high-intensity discharge)
Home-run topology (*see* Wiring, electrical and communications)
Illuminating Engineering Society of North America (IESNA) (*see* Standards organizations)
Incandescent lamps (*see* Lamps, electrical, incandescent)
Inductors/windings, 14, 15, 19, 20, 406
  graphic symbols for, *14*, 15, 19, *20*
Infrared-emitting lamps (*see* Lamps, electrical, specialized)
Institute of Electrical and Electronic Engineers (IEEE) (*see* Standards organizations)
Integrated circuits (*see* Semiconductor devices)
International Commission on Illumination (CIE), 297
Interrupter switches (*see* Switches, interrupter)
Isolated-ground receptacles (*see* Receptacles and plugs)

Kilovarmeters (*see* Meters, electrical)

Lamps, electric:
  characteristics, table of typical, 291–294
  fluorescent, 14–15, 101, 280–288, 293, 300–302
    ballast circuits for, 283, 287, *288*
    bulb and base shapes, *281*, 281
    characteristics of, 282, 293
    compact (CFLs), 101, 283–286, *284*, 300–301
    emission colors, 286–287
    graphic symbols for, *14*, 15
    luminaires, 287, *288*
    standard, *280,* 280–282, 293
  high-intensity discharge (HID), 270, 273, 287–291, 293–294, 302
    ballast circuits for, 287
    characteristics of, 293–294
    high-pressure sodium (HPS), 290–291, *291*, 294, 302
    mercury-vapor (MV), 288–289 *289*, 293–294, 302
    metal halide (MH), 289–290, *290*, 294, 302
  incandescent, 271–278, 292, 298, 300
    bases, 275, *275*
    bulb shapes, 273–274, *271*, *273*

Lamps, electric,
  incandescent (*Cont.*):
    characteristics, 292
    filaments, 275–277, *277*
    finish and color, 274–275
    labeling, 277
    tubular (T), 278
  specialized, 273–274, 278–279, 292, 293, 373
    infrared (IR), 273, 279
    projector and reflector (PAR), *273*, 273–274, 278–279, 298
      characteristics, 292–293
    reflector (R), 273–274, *273*, 279, 298
      characteristics (R and ER), 292–293
      elliptical (ER), 279
    tubular (T) bulb, 273–274, *273*, 278
  tungsten-halogen, 270, 273, 277–278, 291, 293, 298, 302
Lateral (*see* Electrical service)
Lighting, electrical, 270, 294–296, 304–306, 308–320
  calculations for room, 304–306
    zonal-cavity (lumen) method, 305–306
  controls, 308–309
    dimmers, 308–309
  design of residential, 294–296
  fixtures (*see* Luminaires and lighting systems)
  glossary of terms, 315–320
  illumination data for home lighting, 303–304
  lighting requirements for homes, 304
  outdoor, 270, 309–315
    bonding of metal pool parts, 311–312, *311*
    floodlighting, 312–314, *313*
    low-voltage, 270, 314–315, *315*
    NEC rules for, 309–312
    pool and fountain, 309–310
    rules for lighting devices near water, 310
    rules for receptacles near water, 310
    underground wiring near water, 310
    underwater lighting fixtures, 310–312, *311*
  plan, wiring diagram, 295, *296*
  residential room, 270, 306–309
    basement, 308
    bathroom, 307
    bedroom, 307
    dining room, 306
Lighting, electrical,
  residential room (*Cont.*):
    family room, 306
    kitchen, 307
    laundry room, 308
    NEC rules for closets, 307
  types of, 296–297
    accent, 296
    ambient, 296
    task, 297
Loadcenters (main service panels), 134, 144–154, 401
  backpan/panelboard, 147–149, *148*
  electrical schematic, 144–145, *145–146*
  enclosure, 146–147, *147, 148, 153*
  load balancing, 152–153
  load calculation, 149–151
    typical wattage values, 150
  NEC classification of, 144, 147
  NEC requirements for, 144, 148–149
  sizing 151–152
  typical wattage for lighting and appliances, 150
  wiring, subpanel to main panel, 152 *153*
Low-voltage lighting (*see* Lighting, electrical)
Luminaires and lighting systems, 270, 297–304, 310
  architectural, 300–301
  devices near water, rules for, 310
  low-voltage lighting, 314–315, *315*
  NEC requirements, 307, 309
  outdoor floodlighting, 312–314, *313*
  recessed luminaire, 298, *299*
  schedule, 295
  selection of, 301–303
  underwater, 310–311, *311*

Main service panels (*see* Loadcenters)
Manholes (*see* Underground distribution cables)
Metal-oxide varistors (MOVs), 401–411, *406*
Meters, electrical, 14, 16, 81, 97–98, 137–141
  ammeter, 81
  graphic symbols for, *14*, 16
  kilovar, 97, *98*
  Megger, 167, *168*
  power-factor, 98
  voltmeter, 81
  watthour meters, 137–141, *137–139*
  wattmeter, 81
Modular telephone plugs (*see* Telephone systems)
Motion sensors (*see* Sensors)
Motors, general, 14, 16, 345–351, 374–377
  classification, 345–347, *346*
  frame sizes, NEMA, 347–350, *348*, 375
  glossary of terms, 347, 374–377
  graphic symbols for, *14*, 16
  nameplate information, 350–351, *351*
  (*See also* AC motors; DC motors)

Nameplates, motors (*see* Motors, general)
National Electrical Code (NEC) (*see* Standards organizations)
National Electrical Manufacturers Association (NEMA)
  (*see* Standards organizations)
North American power grid, 42–43

Occupancy sensors (*see* Sensors, security systems)
Overhead electrical service (*see* Electrical service)

Pad-mounted transformers (*see* Transformers, distribution)
Panelboards (*see* Loadcenters)
Phase converters (*see* Converters, phase)
Plotters, CAD drawing, 7
Plugs (*see* Receptacles and plugs)
Pole-mounted transformers (*see* Transformers, distribution)
Polyphase motors (*see* AC motors, polyphase)
Potential transformers (*see* Transformers, low-voltage)
Power, electrical (*see* Electrical power)
Power factor (*see* Electrical power, factor)
Power semiconductor devices (*see* Semiconductor devices, power)
Power supplies (*see* Electrical power)
Primary distribution systems (*see* Distribution systems)

Reactors, nuclear, 39–41
Regulators, voltage (*see* Voltage, regulators)
Receptacles and plugs, 174–175, 221–225, 227–240, 243–246, 253–262
  GFCI, 221 227–228, *227*

Receptacles and plugs (*Cont.*):
  isolated-ground, 221, 228–229, *229*, 407, *408*
  locking, 175, 221, 230–231, 235–236
    duplex, *235*
    single, *235*, *236*
  NEMA configurations for, *222*, App. A
  pin-and-sleeve devices, 221, 231–232, *237*
  plugs for receptacles, 221–223, 230–232, *233–235*
  straight-blade, non-locking, 174, 221–225, 227, 229, 233–235, 253–256, 407–408
    duplex, 174, 223–225, *224, 227, 227, 229,* 253–254, *256, 408, 409*
  profiles, 221–222, *222*
    quad, *233*
    single, *233–235*
  surge-protective, 221, 229, *235*, 405, 407–408, *408*
  wiring of, 243–246, 253–262, *256–261*
Reclosers, 89–90
Relays, graphic symbols for, 20, *21*
Resistors, graphic symbols for, 20, *21*
Romex cable (*see* Cables, electrical)
Rotary converters (*see* Converters)
Rotors, 350–352, 360–362, 367, 372, 376

Schedules (*see* Electrical drawings)
Schematic diagrams (*see* Electrical drawings)
Secondary distribution systems (*see* Distribution systems)
Security sensors, residential/commercial (*see* Sensors)
Security systems, residential/commercial, 334–336
Semiconductor devices, 19–21, 101–108, 359, 401, 405–406, 409–412
  integrated circuits (ICs), graphic symbol for, 19–21, *20*
  power, 101–108
    diodes:
      graphic symbol for, 19, *20*
      rectifier, 102–103
    rectifier bridges:
      full-wave, center-tapped, 103–104
      full-wave bridge, 103–104, *103*
      graphic symbol for, *20,* 21
      half-wave, 103–104
Semiconductor devices, power (*Cont.*):
    thyristors:
      graphic symbols for, *20,* 21
      silicon controlled rectifiers (SCR), 101, 106–107, *107*, 359
      silicon controlled switches, 108
      triacs, 101, 107–108, *108*, 359
    transistors:
      bipolar junction, 104
      Darlington pairs, 105
      graphic symbols for, *20,* 21
      MOSFETs, 105–106, *106*, 410
  signal level, 19–21
    diodes, graphic symbols for, 19, *20,* 21
      light-emitting, *20*
      rectifiers, *20*
      zener, *20,*
    transistors, graphic symbols for, *20,* 21
  surge-protective, 101, 401, 405–406, 409–412
    MOVs, 401, 405–406, *406*, 409–411
    TVSs, 401, 405, *406*, 409–410, 412
Sensors, 101, 174, 219–221, 336–338
  fire alarm, 338
  motion/occupancy, 101, 174, 219–221
    passive infrared (PIR), 219–221, *220*
    ultrasonic, 219–220
  security systems, 336–338
    advanced, 337–338
    residential/commercial, 336–337
Service entrance (*see* Electrical service, entrance)
Single versus three-phase power, 43–44, *44*
Software, computer:
  computer-aided drawing, 4–6
  cost estimation, 6–7
Solid-state circuitry, 101
Specifications, electrical (*see* Electrical specifications)
Standards, product and work, 30–32
Standards organizations:
  American National Standards Institute (ANSI)/Institute of Electrical and Electronic Engineers (IEEE), 2, 30, 114, 213, 223, 315, 401–404, 407–408, 411–413, App. A
Standards organizations (*Cont.*):
  Canadian Standards Association (CSA), 190, 213, 223, 350
  Federal Communications Commimssion (FCC) 323
  Illuminating Engineering Society of North America (IESNA), 303–304, 307
  National Electrical Code (NEC)(NFPA 70), 30, 60, 123–125, 134, 138–149, 158–159, 161–168, 174, 176–177, 179–180, 182–184, 186–187, 190, 204–205, 210–212, 225–226, 228–229, 239, 243–246, 248, 253, 263–264, 304, 307, 309–312, 322–323, 333, 380–384, 400, 404, 407–408, 412–413
  National Electrical Installation Standards (NEIS), 30–31
  National Electrical Manufacturers Association (NEMA), 2, 213, 221–223, 225–226, 230, 238–239, 347–350, 369, 407–408
  National Electrical Safety Code (NESC), 30
  National Fire Protection Association (NFPA), 30–31, 338
  Telecommunications Industry Association (TIA), 325
  Underwriters' Laboratories Inc. (UL), 82–83, 182, 190, 213, 223–224, 226, 239, 302, 320, 323, 350, 400, 404, 407–408, 411–413
Standby systems (*see* Emergency and standby systems)
Star topology (*see* Wiring, electrical and communications)
Stator, 372, 377
Structured wiring systems, 328–333, 343–344
  distribution center, 329
  distribution modules, 329, 343
  multimedia, 330–332
    benefits, 331–332
    outlets for, 330
  network configurations, 330–331
  wire and cable in, 330, 343
  (*See also* Wiring, electrical and communications)
Substations (*see* Distribution substations)

- Substation transformers (*see* Transformers, distribution)
- Surge protection, 377, 400–412
  - categories, 401–404, *402*
  - electrical surges, 399–400
  - electrostatic discharge (ESD), 411
  - glossary of terms, 377, 411–412
  - protective devices, (SPDs), 400, 401, 404–406, 410–412
    - electronic circuit fuses-one-time-only (OTO), 401, 410–411
    - hybrid networks, 405, *406*
    - metal oxide varistors (MOVs), 401, 405–406, *406*, 409–411
    - meter socket adapters, 404
    - panel-mount SPDs, 404
    - power-line conditioners, 404
    - plug-in (strip) SPDs, 405, 407–408, *409*
    - specifications for, 406–409
    - surge adapters, 406
    - surge-protective receptacles (isolated grounding), 405
    - surge strips, 405
    - surge voltage protectors (SVPs), 410
    - transient voltage suppressors (TVSs), 401, 405, *406*, 409–410, 412
    - transient voltage surge suppressors (TVSSs), 400, 404, 412
  - standards for:
    - ANSI/IEEE, 401–404, 407–408, 411–413
    - NEC, 412–413
    - UL, 404, 407–408, 412–413
  - test waveforms, 403–404, *403*
- Surge protective devices (SPDs) (*see* Surge protection)
- Surge voltage protectors (SVPs) (*see* Surge protection)
- Switchers, circuit (*see* Circuit switchers)
- Switches, 14, 16–17, 20–21, 58, 174, 211–216, 243–255, 353–354, 357
  - AC manual motor starting, 216
  - centrifugal motor starting, 353–354, 357
  - graphic symbols for, *14*, 16–17, *20*, 21
  - interrupter, 58, 90–91
    - horn gap, 91
    - side-break, 90
- Switches, interrupter (*Cont.*):
    - single-pole, 90
    - vertical break, 90
  - NEC requirements for, 212
  - wall-mounted, 174, 211–216, 243–255
    - duplex, 212–213, *213–214*
    - four-way, 212–213, *214*, 247, *247*
    - lamp dimmers and fan controls *(see* Dimmers and fan controls*)*
    - pilot-light, 214–215, *214*
    - programmable, 215–216
    - single-pole, 212–213, *213–214*, 246–247, *247*
    - switch/receptacle combinations, 215, *214*
    - three-way, 212–213, *214*, 247, *247*
    - time-delay, 215
    - timer, 215
    - wiring of, 243–255, *248–255*
- Synchronous condensers, 96–98
- Synchronous motors (*see* AC motors; DC motors; Motors, general)
- Symbols, graphic (*see* Electrical drawings)
- Symbols, electronic (*see* Electronic graphic symbols)

- Telecommunications systems, 332–333, 341–344
  - coaxial cable for, 185
  - glossary of terms, 341–344
  - NEC requirements for, 322, 333
  - wiring rules for, 322, 332–333
- Telephone systems, 185, 321–328, 342–344
  - cable, 185
  - deregulation of, 322
  - FCC standards for, 323
  - jacks, 322, 324, 325, 343
    - demarcation points, 322
    - modular, 324, *325*
  - plugs, modular, RJ style, 324, *324*, 343
  - station wire (*see* wires, cables, and cords *below*)
  - unshielded twisted pair, 327
  - wired technology, 323–327, *323–326*
  - wires, cables, and cords, 185, 325–327
    - (*See also* Wires (conductors), insulated)
- Temporary electrical service (*see* Electrical service)
- Tesla, Nicola, 38
- Topology of wiring systems (*see* Wiring, electrical and communications)
- Torque, 374, 376–377
- Transformers, distribution, 66–77, 119, 134–135, 140
  - connections of three-phase to, 70–73
    - secondaries, 72–73, *72*
    - single phase, 70, *71*
  - four-wire delta and wye systems, 72–73
    - delta system, 72, *72*
    - wye system, *72*, 73
  - Scott or T connection, 73–74, *73*
  - single-phase, 66–73, 119, 134–135, 140
    - connection to form three-phase,
      - delta-delta, 70, *71*
      - delta-wye, 70–73
      - wye-delta, 70–73, *71*
      - wye-wye, 70, *71*
    - overhead, pole-type, 67–69, *68*, *119*, 134–135, *135*
    - pad-mounted, 67, 69–70, *69*, *119*, 140, *140*
    - step-down, 67, *67*, 68
    - submersible, 67, 70
  - substation, 60, *61*
  - tap changing, 66
  - three-phase, 75–77
    - overhead, 75, *76*
    - pad-mounted, 75, *77*
- Transformers, general, 14, 16, 20–21, 58–70, 74–77, 82–84
  - characteristics, 60–62
  - classification, 59–60
  - coils, 58
    - primary (input), 58
    - secondary(output), 58
  - connection in parallel, 75–77, *77*
  - construction, 63–64
  - cooling, 64–65
  - core-type, 63, *63*
  - efficiency, 64
  - glossary of terms 83–84
  - graphic symbols for, *14*, 16, *20*, 21
  - insulation, dry-or liquid, 59
  - losses, 64
  - NEC requirements for, 60
  - overcurrent protection for, 82–83
  - parallel operation of, 75–77, *77*
  - power rating, 62–63
  - shell-type, 63, *63*
  - single-phase, 66–70, *67–69*
  - three-phase, 74–75

- Transformers, low-voltage, 59, 60–66–68, 74–75, 79–83, 113
  - autotransformers, 59, 65–66, *65,* 68, 79–80, *79, 80*
    - buck-boost, 59, 79–80, *79, 80*
  - auto zigzag grounding, 59, 78–79, *78*
  - current (CT), 59, 81–82, 113
  - distribution (*see* Transformers, distribution)
  - instrument, 80–82
    - current, 81–82*, 81*
    - voltage, 81*, 81*
  - NEC requirements for, 60, 82–83
  - overcurrent protection for, 82–83
  - polyphase, 59
  - potential (voltage) (VT), 81
  - power rating, 62–63
  - single-phase, 59, *67*
  - step-down, 59, 62, *67*
  - step-up, 59, 62, 67
  - substation, 59–60, *61*
  - switching, 59
  - tap changing, 66
  - three-phase, 74–75
  - voltage potential (VT) 59, 81, *81*, 113
  - windings, 62–63
  - wound-core, 64
  - zigzag, auto grounding*,* 59*, 78*
- Transformers, substation (*see* Transformers, distribution)
- Transient voltage suppressors (TVSs) (*see* Surge protection)
- Transient voltage surge suppressors (TVSSs) (*see* Surge protection)
- Transmission systems, 42–43, 51–52, 55–56, 58
  - AC, 51
  - cable in, 52
  - computers in, 43
  - DC, 42, 55–56, 58
    - high-voltage, 55–56, 58
    - links, 42
  - electronic devices and controls in, 43
  - North American power grid, 42–43
  - towers (*see* Transmission towers, poles, and frames)
  - voltage levels in, 43
- Transmission towers, poles, and frames, 52–56
  - aluminum structural, 53
  - basic kinds of, 53
  - conductors for, 54
- Transmission towers, poles, and frames (*Cont.*):
  - criteria for installation, 53
  - guyed towers, 53, 55
  - H-frame structures, wood, 55, *56*
  - optimum selection of, 53
  - poles, steel, wood, and concrete, 53, 55
  - steel, 53–55
    - semiflexible self-supporting towers, 53–54
    - structural towers 53–54, *54*
    - tubular poles, 53, 55
  - suspension towers, 53
  - tubular steel poles, 55

- Underground distribution cables, 123–130
  - bending space for, 130
  - burial instructions for, 124
  - digging the trench for, 124–125
  - ducts and duct banks for, 126–130
    - installation of, 129–130, *129*
  - manholes for, 126–128, *127–128*
  - minimum cover requirements for, 125–126, *125*
  - NEC installation requirements for, 123–124
  - (*See also* Cables, electrical)
- Underground electrical service (*see* Electrical service, underground)
- Underwater lighting (*see* Lighting, electrical)
- Underwriters' Laboratories (UL) (*see* Standards organizations)
- Uninterruptible power supplies (UPS), 380, 386–387, *387*
- Universal motors (*see* AC motors)

- Varmeter, 98
  - (*See also* Meters, electrical)
- Voltage, 44, 58, 91–93, 98, 114
  - pad-mounted, 91–92, *92*
  - regulators, 58, 91–93, 98, 114
  - sinewaves, 3-phase, *44*
  - step-voltage, 91–93, *93*
  - transformers (*see* Transformers, low-voltage)

- Watthour meter bases, 142–143, *135, 137–143*
- Watthour meters (*see* Meters, electrical
- Weatherhead (*see* Electrical service, head)
- Westinghouse, George, 38
- Wires (conductors), insulated, 175–181, 186–187, 190, 210–211, 326
  - ampacities of, 175–176, 178–180
    - allowable values, 178–180
  - capacities, in metal electrical boxes, 210–211
  - cross sections, 175, *175*
  - four-pair, 326
    - color coding of 326, *326*
  - gauge*,* American wire (AWG), 175, *175*
  - insulation materials, 176–177, 180, *181*
    - code identification on common wires, 176–177, 180
  - NEC requirements, 176–177, 179–180, 182–184, 186–187, 190
  - telephone wires, 185, 325–327
    - four twisted pair, eight-wire, band-striped, 185, 326–327, *326*
      - band color code, 185, 327
    - three twisted pair, six-wire, 185, 327
      - solid color code, 185, 327
    - TIA wire and cable categories, 325, 342, 344
    - two nontwisted pair, four-wire (quad, station wire), 185, 327–327 *326*
      - solid color code, 185, 326–327
  - temperature ratings, 176
- Wiring, electrical and communications, 210–211, 243–267, 310–311, 325–328, 342–343
  - bonding of metal pool parts, 311
  - branch circuit, 243–245, 264–267
    - NEC requirements for, 243–245
    - outdoor, low voltage, 243–245, 265–267, *267*
    - outdoor, 120-V, 243–245, 264–265, *265*
  - devices, wall-mounted, 245–262
    - connections, 260–262
    - diagrams for, 245–262
      - receptacles, 253–262, *257–261*
      - switches, 246–252, *248–255*

Wiring, electrical and communications (*Cont.*):
  lighting devices near water, rules for, 310
  outlet boxs, 210–211
    metal box conductor capacities, 211
  pigtailing, 256
  protection of, 243, 262–264
    GFCIs, by, 243, 264
    outdoor, for, 262–264

Wiring, electrical and communications (*Cont.*):
  receptacles, wall-mounted, 243–246, 253–262, *257–261*
    GFCI, 243, 259–260, *260*, 264
    near water, rules for, 310
  structured (*see* Structured wiring systems)
  subpanel to main panel, *153*
  switches, wall mounted, 243–252, *248–255*

Wiring, electrical and communications (*Cont.*):
  telecommunications, rules for, 322, 332–333
  topology, system, 322, 327–328, 342–343
    daisy chain, 327–328, *328,* 342
    home run/star, 327–328, *328*, 343
  underground, near water, 310

About the Authors

Neil Sclater was an engineer in the military/aerospace industry before turning to editing and writing professionally on electromechanical and electronic subjects. After working as a staff editor for several engineering magazines, he became an editorial consultant. His technical articles have been published in more than a dozen different publications. In addition to revising this book, he is the author or co-author of nine other McGraw-Hill Professional reference books. He holds degrees from Brown and Northeastern universities.

The late John E. Traister was employed in the electrical construction industry as an electrician and electrical contractor for more than 35 years. He was the author of nine books on different topics for McGraw-Hill, including the First Edition of the *Handbook of Electrical Design Details* and McGraw-Hill's *Illustrated Index to the National Electrical Code®*.