ELECTRICAL CONTROL FOR MACHINES

7TH EDITION

DIANE LOBSIGER   PETER GIULIANI   KENNETH REXFORD

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Electrical Control for Machines, 7TH Edition

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Cover Image(s): ©hüseyin harmandağlı/iStock; ©ildogesto/shutterstock

Library of Congress Control Number: 2014939241

ISBN: 978-1-133-69338-3

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Printed in the United States of America
Print Number: 01 Print Year: 2014

We dedicate this book to our families. Without their love and support this book would not have been possible.

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FOREWORD

The seventh edition of *Electrical Controls for Machines* continues the tradition of this textbook as an introductory level to electrical machine controls. Significant changes have been made to this edition to update the text to reflect current trends in industry. As the electronics industry continues to change, it is imperative that the information obtained in this text accurately reflects these changes. The circuit diagrams and the descriptions of the circuits throughout the text have been updated to show a more modern representation of the control circuits.

This edition expands on the power and control circuitry required to operate electrical machinery. The bus system and the use of bus plugs are described as a means of power distribution throughout a factory. Transformers calculations and the sizing of transformers is included to assist the technician in understanding what values to expect (voltage and current) when troubleshooting equipment. Insulation classifications, conductor ampacity, and conductor color code is explained to assist the technician in identifying and selecting proper wiring for a given application. Finally, the trend toward 24 VDC as the standard control voltage for equipment is covered.

The introduction to PLCs has been modified to include updated information. The trend away from relay control to PLC control is discussed along with the advantages to using PLCs to control machinery. The need to still study relay circuits is explained as relays are still utilized on PLC equipment to switch loads. The study of relay circuits also provides a basic understanding of control circuits and knowledge that may be easily transferred to an understanding of PLC circuits. Clarification and expansion of important concepts are included such as PLC scan, addressing schemes, power supply functions, memory, I/O status, and peripheral devices. The use of Ethernet as a common protocol for control systems was also added in this edition.

Other updated technology included in this edition is the explanation of variable frequency drives. As the cost of electrical components continues to decline, the use of drives to control motors is continually becoming more affordable.

Several concepts have been explained in the new edition. One topic is the understanding of the normal state for switching devices. A thorough understanding of this concept is required to understand circuit diagrams and the proper operation of the devices. Another topic that is introduced is the concept of fail-safe designs. This practice is critical to the proper functionality of safety circuits, quality control systems, and processes by ensuring the integrity of switching devices.

The safety of workers and equipment is a number one priority in industrial settings. In this edition, an explanation of the risk assessment process and a safety relay circuit has been added. It is important to understand the need for safety rated devices and how they are integrated into a circuit so that unintentional changes to a safety circuit are not made. An explanation of Ground Fault Circuit Interrupters (GFCIs) is also included in this edition.

The globalization and integration of businesses has caused drastic changes to the way that industries function. It is very common for companies to purchase equipment from other regions of the world for use in their operations. It is also quite common for companies to relocate existing machinery to other regions of the world as production volumes fluctuate or as industry requirements change. This edition expands the content of the material to include international equipment specifications. Concerns related to relocating equipment to various regions of the world are also covered. In addition, the use of IEC617 symbols is included whenever a new device symbol is discussed. Questions have been added to the end of relevant chapters to include the conversion of circuits using JIC symbols to the equivalent circuits using IEC617 symbols.

It is imperative that someone troubleshooting equipment has a thorough understanding of the control circuit diagrams. To effectively work on the equipment and for the safety of workers and machinery, the troubleshooter must know how the circuit is supposed to function and what to expect when working on the system. Many modifications have been included in this edition to support the thorough understanding of the control drawings. Various cross-referencing schemes, parts lists, wiring methodology, and push-button layouts have been added to this edition. Some older material, although not readily utilized on new equipment, has been maintained in this edition. This decision was made to provide a comprehensive understanding of basic circuits and for the technician that will need to troubleshoot these devices on older equipment. Questions have been added at the end of each chapter to enhance the comprehension of the material covered in the text. In addition, the recommended web links at the end of every chapter have been updated to reflect accurate Web site addresses.

This text is designed for the student, maintenance technician, process engineer, and sales representative who need a clear and simple understanding of all elements of a complex manufacturing system. Therefore, this text can best be described as providing the reader with a practical understanding of electrical control principles. A prerequisite for the reader is knowledge of the basic theories of electricity and electrical circuits. To meet this prerequisite, a student should have taken a course in basic electricity. A practitioner (technician or engineer) should review a book on the principles of electrical theory and circuits.

The text is designed to be functional in either an educational or industrial environment. In education, no matter the level (vocational high school, two-year technical school, or four-year college), the entire contents should be examined and understood throughout the course. If the book is used as a reference, then appropriate chapters can be read as needed.

PREFACE

We need to teach the fundamentals of process and equipment control. Those mainly affected are the thousands of small builders and users, including the large manufacturer. Most selling organizations, both large and small, include many thousands of manufacturers' agents, distributors, sales engineers, and maintenance personnel. These are the people charged with the responsibility for selling machines and keeping the machines operating. The success or failure of installations may depend on the ability of these people to maintain and troubleshoot equipment properly. The personnel involved need to understand electrical components and their symbols. With this knowledge, they are in a better position to read and understand elementary circuit diagrams.

Six specific areas in which education is needed are (1) electrical and electronic components, (2) control techniques and circuits, (3) troubleshooting, (4) maintenance, (5) electrical standards, and (6) keeping current with changing technology.

1. *Components* are the building blocks of all systems. The core knowledge of the principles and application of each component in a system sets the groundwork for a complete understanding of all facets of a control system.
2. *Techniques and circuits* is the process of building the system from the components. Like building a house, without a concept and plan the structure will fail over time. Techniques and circuits are the lead to a successful plan.
3. *Troubleshooting* machine control circuits involves locating and properly identifying the nature and magnitude of a fault or error. This fault may be in the circuit design, physical wiring, or components and equipment used. The time required and the technique or system used to locate and identify the error are important. Of similar importance are the time and expense involved to put the machine back into normal operating condition.
4. *Preventive maintenance* would eliminate the need for most troubleshooting. Many machines are allowed to operate until they literally fall apart.
5. *Applicable standards* should be followed. If the intended result is the improvement of design and application to reduce downtime and promote safety, electrical standards can be extremely helpful. Where should the education start? The answer is at the beginning, and keep it simple. Even a basic concept, such as the relation between a component and its symbol, can be of benefit to the user.
6. *Keeping current with changing technology* means implementing a strategy for life-long learning. Today the Internet has become a medium for presenting information and expanding knowledge. To expand your knowledge, this text notes important Web sites that should be reviewed occasionally to keep up with latest technological changes.

In addition to the Web sites for specific technologies listed at the end of each chapter, the following Web sites are broad-based sites devoted to technical and training issues.

Standards Organizations

Electrical Inspectors Information: www.joetedesco.com

Institute of Electrical and Electronic Engineers (IEEE): www.ieee.org

International Brotherhood of Electrical Workers (IBEW): www.ibew.org

National Fire Protection Association (NFPA): www.nfpa.org

National Electrical Safety Foundation (NESF): www.nesf.org

National Joint Apprenticeship Training Committee (NJATC): www.njatc.org

National Electrical Contractors Association (NECA): www.necanet.org

National Electrical Manufacturers Association (NEMA): www.nema.org

Underwriters Laboratories Inc. (UL): www.ul.com

Council for the Harmonization of Electrotechnical Standardization of Nations of the Americas (CANENA): www.canena.org

Canadian Standards Association (CSA): www.csa.ca

Indexes of Technical Products

Process index: www.processindex.com

Norm's Industrial Electronics: www.compusmart.ab.ca/ndyrvik/

Process Mart: www.iprocessmart.com

Graybar Electric: www.graybar.com

Electronic Engineer's Master (EEM): www.eem.com

Omega Engineering: www.omega.com

On-Line Technical Publications

Control Engineering: www.controleng.com/

Motion: www.motion.org

Fluid Power Society—*Fluid Power Journal*: www.fluidpowerjournal.com

Allen Bradley—*View* Magazine: www.ab.com/viewanyware/the_view

Allen Bradley—*AB Journal*: www.ab.com/abjournal

ControNews and LogixNews: www.ab.com/controlnews/

Current Issues and News about Manufacturing: www.manufacturing.net

National Electrical code: www.nfpa.org/NEC/NEChome.org

Independent Web Sites Devoted to Automation Issues

PLC Tutor: www.plcs.net

NEC Information and Training: www.mikeholt.com

Brief Overview of the Chapters

Significant changes have been made to this edition to:

- Explain crucial components of industrial control systems in more depth
- Provide an introduction and general explanation of topics that are important to modern industrial machine control
- Delete obsolete information. Note that some material, although not readily utilized on new equipment, has been maintained. This decision was made to provide a comprehensive understanding of basic circuits and for the technician that will need to troubleshoot these devices.
- Update text to current trends in industry
- Update circuit diagrams to show a more modern representation of control circuits. The description of each circuit has also been updated.
- Questions have been added to Achievement Review section
- Recommended Web Links have been updated to reflect accurate Web site addresses
- Expand text content to international equipment specifications

Chapter 1 ("Transformers and Power Supplies") provides an overview of the power systems utilized on industrial equipment. New topics covered in this edition include:

- Bus system and bus plugs for power distribution

- Transformer calculations to determine turns ratio, voltage, and current values
- Sizing of transformers (moved from Appendix) with example calculations provided
- Concerns related to relocating equipment in various regions of the world
- Trend toward 24 VDC control
- Circuit diagrams
- Insulation classifications, conductor ampacity, and conductor color code
- Use of IEC617 symbols

Chapter 2 ("Fuses, Disconnect Switches, and Circuit Breakers") provides an overview of the means for disconnecting power to machinery. The construction and characteristics of different fuses are also covered. The use and operation of Ground Fault Circuit Interrupters (GFCIs) has been included in this edition.

Chapter 3 ("Control Units for Switching and Communication") introduces operator interface devices. Emphasis is given to pushbuttons, selector switches, and pilot lights. Significant changes have been made to this edition to clarify the normal state of switching devices to further comprehend the device symbols represented on electrical drawings. The operation of the devices has been expanded upon along with the different types of operating heads and switching configurations that are available. Series and parallel circuits have been explained and examples of control circuits have been included.

Chapter 4 ("Relays") describes the construction and operation of electrically operated relays. The relay is a functional device that can be used in many different control system operations, such as logical sequencing and control of motions. Some of the changes in this edition include the explanation of the normal states for relay contacts, the clarification and inclusion of timing diagrams for pneumatic timing circuits, the progression to PLC systems, and circuit modifications.

Chapter 5 ("Solenoids") is an introduction to the general operation of solenoids and solenoid-operated control valves. Some of the changes in this edition include the clarification and detailed explanation of solenoid/valve operations along with circuit modifications.

Chapter 6 ("Types of Control") covers the different types of control theories applied to controlling a process actuator. Each control method has unique characteristics that provide a reference for determining the expected controllability, which ultimately will affect the quality and productivity of the system. In this edition, the discussions involving different types of control are expanded. Additional examples are also provided.

Chapter 7 ("Motion Control Devices") is a comprehensive review of the control devices such as limit switches, proximity switches, and photoelectric transducers used in the control of moving actuators. The normal states for switching devices have been explained and circuit modifications have been incorporated into this edition.

Chapter 8 ("Pressure Control") is devoted to achieving an understanding of systems that require the precise control of pressures exerted by an actuator onto a process. The normal states for pressure switches and the implementation of pressure transducers have been explained in this edition. Circuit modifications have been also been made.

Chapter 9 ("Temperature Control") analyzes circuits and controllers used in industrial systems in which precise temperature control must be maintained within the process. In this edition, some clarifications to temperature control are provided along with modifications to circuits.

Chapter 10 ("Time Control") describes the operation and application of timers to timed, sequentially controlled events. Some changes to this edition include clarifications in regards to position sensing, the progression to timing control in PLCs, and circuit modifications.

Chapter 11 ("Count Control") covers counters and their applications in control sequences that depend on counted events. Some changes to this edition include clarifications in regards to counter operations and circuit modifications.

Chapter 12 ("Control Circuits") incorporates information learned in previous chapters to practical applications of electrical control circuits using ladder logic diagrams. Significant changes have been made in this edition to the control circuits and the supporting descriptions of the circuits throughout this chapter.

Chapter 13 ("Motors") provides insights into the theory and operation of AC and DC motors. Changes have been made in this edition to the order of the material and the content in this chapter. Some of the modifications include the analysis of a single loop DC motor and the addition of the Variable Frequency Drives section.

Chapter 14 ("Motor Starters") explains how motor starters are used to protect and control motors. Full-voltage and reduced-voltage magnetic types as well as solid state types are covered. Significant changes have been made in this edition to the control circuits and the supporting descriptions of the circuits throughout this chapter.

Chapter 15 ("Introduction to Programmable Control") is an introduction to the concepts associated with Programmable Logic Controllers. In this edition, numerous modifications have been made to this chapter. These changes include:

- Clarification of concepts from relay control that apply to PLCs
- Clarification of how the classification of devices change from a relay circuit to a PLC design
- Discussion in regards to the advantages of PLCs over relay circuits included
- Basic ladder logic fundamentals provided
- Explanation of different addressing schemes provided
- Clarification of PLC scan
- Clarification of PLC power supply functions
- Detailed explanation of PLC memory contents and I/O status as PLC scan is executed
- Updated information for peripheral and support devices
- Significant modifications to PLC circuits and their associated descriptions
- Introduction to fail-safe design practices

Chapter 16 ("Industrial Data Communications") explores the terminology, configuration, and issues of data communication within an industrial environment. A section on Ethernet is included in this edition.

Chapter 17 ("Quality Control") is a review of the devices and control concepts used to monitor and control product quality in a production process. In this edition, a section explaining the costs associated with the lack of a good quality control system and the need for fail-safe design practices has been added.

Chapter 18 ("Safety") presents the issues and technology that affect worker and equipment safety. In this edition, an explanation of the risk assessment process and a safety relay circuit has been added. Also, circuit modifications have been made throughout this chapter.

Chapter 19 ("Troubleshooting") provides the principles and techniques needed to isolate a problem associated with a control circuit. Changes have been made in this edition to the control circuits and the supporting descriptions of the circuits throughout this chapter.

Chapter 20 ("Designing Control Systems for Easy Maintenance") is devoted to the general requirements to be considered when designing and maintaining control circuits. Various cross-referencing schemes, parts lists, wiring methodology, and push-button layouts have been added to this edition. Also, changes have been made to the control circuits and the supporting descriptions of the circuits in this chapter.

Supplements

Lab Manual: A lab manual to accompany this text is also available. ISBN 9781285169057.

An online Instructor Companion Web site contains an Instructor Guide with answers to end of chapter review questions, testbanks, and Chapter presentations done in PowerPoint.

Accessing an Instructor Companion Web site from Single Sign On Front Door

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ACKNOWLEDGMENTS

The authors and Cengage Learning gratefully acknowledge the review panel for their suggestions in the development of this edition. Our thanks to:

Brett McCandless
Vincennes University
Vincennes, IN

Russ Davis
Delta College
University Center, MI

Denny Owen
Kennebec Valley Technical College
Fairfield, ME

Murry D. Stocking,
Ferris State University,
Big Rapids, MI

Bill Welborn,
Alamance CC,
Graham, NC

Mickey Giorgano,
Mississippi State University,
Mississippi State, MS

Technical guidance and illustrations were provided by the following companies. Appreciation is expressed to them for their cooperation and assistance.

Acme Electric—Acme Transformer Division, Lumberton, NC 28358 (www.acme-electric.com)

Allen-Bradley, a Rockwell International Co., Milwaukee, WI 53204 (www.ab.com)

Allen-Bradley, a Rockwell International Co., Highland Heights, OH 44143 (www.ab.com)

Automatic Timing and Controls Co., Inc., King of Prussia, PA 19406 (www.automatictiming.com)

Banner Engineering Corporation, Minneapolis, MN 55441

Barber-Colman Co., Loves Park, IL 61132-2940 (www.barber-colman.com)

Barksdale, Division of Crane Company, Los Angeles, CA 90058-0843 (www.barksdale.com)

Chromalox, Pittsburg, PA 15238 (www.chromalox.com)

Columbus Controls, Columbus, OH 43081 (www.columbuscontrols.com)

Detroit Coil Co., Ferndale, MI 48270

Divelbiss Corporation, Fredericktown, OH 43019 (www.divelbiss.com)

Eagle Signal Controls, Austin, TX

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Larry Flanery, Kendall Electric, Saginaw, MI

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McNaughton-McKay Electric Company (www.mc-mc.com)

Mercury Displacement Industries, Inc., Ewardsburg, MI 49112 (www.mdius.com)

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National Fire Protection Association, Quincy, MA 02269-9101 (www.nfpa.org)

POWERTEC Industrial Motors, Rock Hill, SC 29732 (www.powertecmotors.com)

Ronan Engineering Co., Woodland Hills, CA 91367 (www.ronan.com)

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Square D/Schneider Electric, Milwaukee, WI 53201 (www.squared.com)

Standish Industries, Lake Mills, WI 53551 (www.hitekelec.com)

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TECO-Westinghouse Motor Company, Pittsburgh, PA 15222 (www.teco-wmc.com)

XYMOX Technologies, Inc., Milwaukee, WI 53201 (www.xymoxtech.com

Yellow Springs Instrument Co., Inc., Industrial Division, Yellow Springs, OH 45387 (www.ysi.com)

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Diane received her Bachelor of Science degree in Electrical Engineering from Auburn University, Alabama. While attending graduate school, she was employed as a teachers' assistant and received an Honorable Mention—Outstanding Student-Teacher Award from Michigan State University. During this time, she was inducted into several honoraries including Eta Kappa Nu (EE Honorary), Tau Beta Pi (Engineering Honorary), Pi Mu Epsilon (Math Honorary), and Sigma Pi Sigma (Physics Honorary). Diane received her Master of Science degree in Electrical Engineering from Michigan State University, Michigan. She also obtained her Secondary Teaching Certification in Mathematics and Physics from Saginaw Valley State University located in University Center, Michigan.

Diane worked as a Senior Manufacturing Controls Engineer for 24 years at a manufacturing facility in Michigan. During this time, she gained a wealth of knowledge and extensive experience in the design, troubleshooting, specification writing, and the approval of machine controls systems. Her expertise includes relay control systems, programmable logic controllers (PLCs), human-machine interfaces (HMIs), servo systems, adjustable frequency drives, and fluid power systems.

Diane is married and has three children. She would like to thank her family for their continued love and support throughout her endeavors. Her life has been filled with opportunities, challenges, rewards, and blessings. The most fulfilling experiences have come from the opportunity to raise children, mentor college students, and work with young people throughout the community. She enjoys a wide variety of interests from sports to scrapbooking. In her free time, she can usually be found fishing at her cabin.

INTRODUCTION to Electrical Control—Development of Circuits

To understand electrical control circuits, it is necessary to examine three basic steps in developing a circuit.

The FIRST step is to know what work or function is to be performed. For example, a simple problem may be to light a lamp. The solution can be achieved by completing a path for electrical energy from a source such as a battery to a load such as a lamp. For convenience, a switch is used to open or close the path. When the switch is open, electrical energy is removed from the lamp, which is said to be *de-energized.* When the path of electrical energy is closed, the lamp is said to be *energized* and performs a function of illumination. See Figures 1 and 2, in which a battery is used as the source of electrical energy. These drawings are known as *pictorial* drawings because they show a picture of the actual components—battery, switch, and lamp.

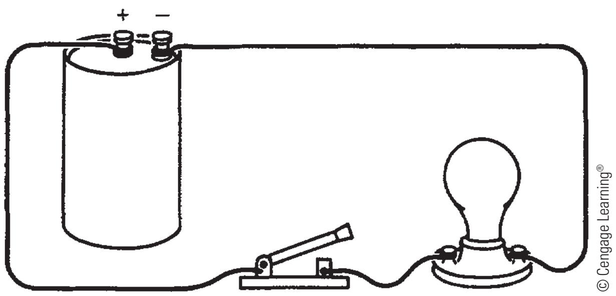

Figure 1 **With the switch open, the path is open and the lamp is de-energized.**

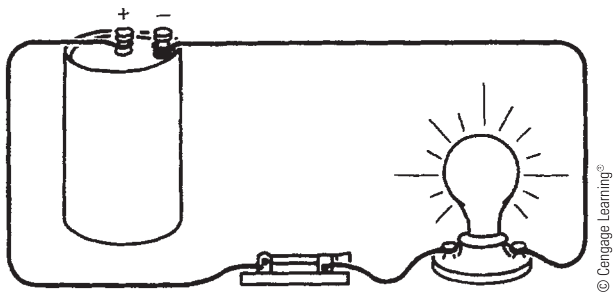

Figure 2 **With the switch closed, the path is closed and the lamp is energized.**

In industrial electrical control circuits, symbols are used to represent the components. Figures 3 and 4 show the use of symbols for the components (battery, switch, and lamp). These diagrams are referred to as *schematic* or *control circuit diagrams*.

Figures 3 and 4 can be redrawn in a slightly different form as shown in figure 5. The circuit performs exactly the same function since the lamp is energized, when the switch is closed. This type of drawing is called a *ladder* diagram. (The ladder-type diagram is used throughout the rest of the book.) In this drawing, the battery is shown as the source of electrical energy feeding the circuit, or the loads. In a ladder diagram, the voltage source is always depicted by two vertical lines (or sides of

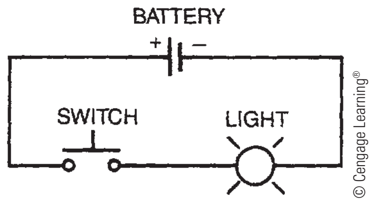

Figure 3 **Schematic showing the switch and path open and the light de-energized.**

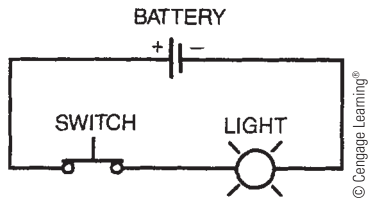

Figure 4 **Schematic showing the switch and path closed and the light energized.**

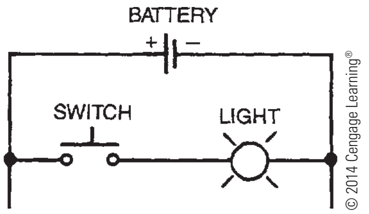

Figure 5 **Ladder diagram showing the source along the vertical lines and the load connected in a circuit drawn horizontally.**

the ladder). The circuit is then drawn horizontally with all switching devices shown in their normal or "at rest" condition being connected to the load. In this case, the switch is drawn as normally open and is connected to the light. Since the switch is open in this condition, there is no path for electricity to flow to the light. However, when the switch is closed, a path will be established between the light and the battery. Electricity will flow in the circuit and the light will illuminate. The vertical lines extend downward past the light and switch circuit indicating the potential to connect additional loads to the existing circuit.

Notice in Figure 5 that an important symbol has been introduced. The symbol is "conductors connected" and is shown separately in Figure 6. A similar symbol, which is not used here but appears many times in later diagrams, is "conductors not connected" and is shown in Figure 7.

The SECOND step is to know the operating conditions under which the starting, stopping, and controlling of the process is to take place. Practically all conditions fall into one or more general groups, as affected by:

- Position
- Time
- Pressure
- Temperature

Figure 6 **Symbols for conductors connected.**

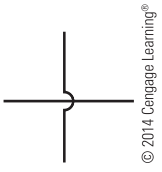

Figure 7 **Symbols for conductors not connected.**

In the chapters on components that follow, each of these conditions can generally be associated with certain components. In many cases, although the actual initiating of a cycle may be through the manually operated push-button switch, certain conditions must be met before the circuit can be closed. This cycle initiation could be one or any combination of the conditions previously listed.

The THIRD step in the development of a circuit is selecting the desired control conditions. There are many times that a circuit must be capable of operating under certain sets of conditions to produce the desired results. For example, a circuit may be required to operate a machine under manual, semiautomatic (single-cycle) or fully automatic (continuous-cycle) operation.

After a decision is made on which of these types of operation is to be used, a selection is made. For reasons of safety to both the machine and operating personnel, the machine must operate in the selected manner.

Review the three basic steps in developing the control circuit diagram.

1. Know what work or function is to be performed.
2. Know the conditions for starting, controlling, and stopping the process.
3. Arrange for selecting the desired control conditions: manual, semiautomatic, or automatic.

As the student progresses through the study of components, the symbol for each component will be prominently displayed. It is very important that the symbol becomes closely associated with the component. In Appendix A, all of the symbols used will be shown for review.

In understanding electrical control circuit diagrams, there are fundamental problems that should be recognized and overcome if progress is to be made. Some of these problems are:

- Starting with a circuit that is too large or too complicated.
- Failing to carry through a mental picture of the component into the electrical circuit.
- Failing to relate physical, mechanical, or environmental actions into devices that convert these actions into electrical signals.

- Failing to understand that an electrical circuit must perform the correct functions and not perform those actions that will result in damaged components, danger to the operator or machine, or a faulty product.

In addition, one of the biggest problems in reading circuits is gaining a clear understanding of a switch or contact condition. The condition must be properly presented in the ladder diagram, and the user must properly interpret its use in a process or on a machine. Diagrams will be shown in each of the component sections. As a new component is introduced, the symbol will be shown in the circuit. These circuits will show methods of obtaining specific actions through the use of electrical components. Ultimately all circuits designed for specific actions will need to be assembled into a complete circuit for the overall operation of a machine.

The important point here is to become acquainted with components and their use in the small circuits, and work with only one or a few components at a time.

1 CHAPTER

Transformers and Power Supplies

OBJECTIVES

After studying this chapter, you should be able to:

- Give two reasons for energizing machine control systems at 24 volts DC (VDC).
- Explain how to obtain 120 volts from a higher line voltage through the use of a transformer.
- Define *turns ratio* in a transformer.
- Identify the symbol for a dual-primary, single-secondary control transformer.
- Draw a connection diagram for a dual-primary, single-secondary control transformer to a higher voltage line and to a 120-volt control circuit.
- Define *regulation* in a transformer.
- Explain the method for calculating regulation in a transformer.
- Calculate the size of a transformer for a given load.
- Explain what causes temperature rise in a transformer.
- Explain the considerations to be taken into account when converting between 50 Hz and 60 Hz systems.
- Explain the basic operation of different types of power supplies.
- Explain the basic function of the uninterruptible power system.
- List the uses of uninterruptible power systems during undesirable power disturbances.

1.1 Control Transformers

In the electrical control circuits shown in "Introduction to Electrical Control—The Development of Circuits" (Figures 1 through 5), a battery is the source of electrical energy. It supplies a form of electrical energy known as *direct current* (DC). Most control circuits in industry today utilize DC to provide electrical energy for devices that control equipment. The DC voltage source on machinery is a power supply instead of a battery. The power supply is connected to a form of electrical energy called *alternating current* (AC). The power supply converts the incoming AC voltage to DC for use in the control circuit.

The main power that is supplied to industries in the United States is three phase (3ϕ), 480 volts alternating current (VAC), at a frequency of 60 Hertz (Hz). Some companies can run their facility from a 240 VAC system. However, the use of 480 VAC is most prominent.

The 480 VAC supply is typically distributed throughout a plant by the use of a bus system (see Figure 1-1). A bus system consists of copper bars that are capable of handling the large amount of current that is required to run many machines simultaneously. Bus plugs may be attached to the bus to provide a connection point from the power distribution system to the equipment (see Figure 1-2).

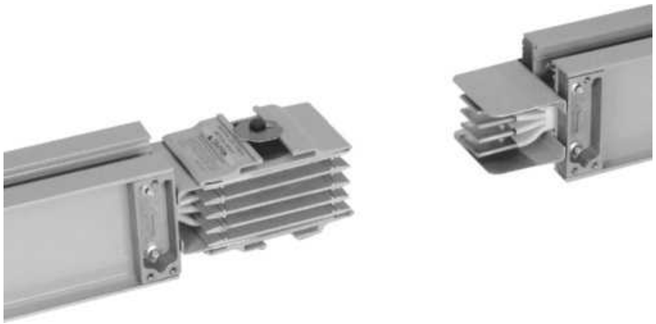

Figure 1-1 **Bus system.** *(Siemens Industry, Inc. provided the image. All rights reserved.)*

Figure 1-2 **Bus plug.** *(Siemens Industry, Inc. provided the image. All rights reserved.)*

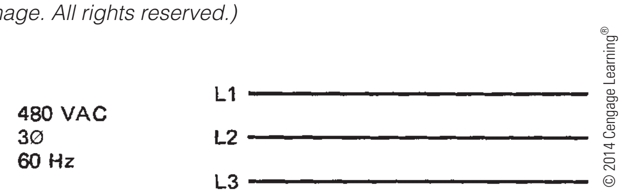

Figure 1-3 **Three-phase power line.**

These can be plug-in or bolt-on type. The plugs may be fused with a disconnect or they may contain a circuit breaker. The bus plugs must be locked out any time power must be disconnected to the incoming lines supplying the equipment. The power wiring is usually run from the bus plug to the electrical cabinet of the machine inside of the metallic conduit.

The electrical drawings for a piece of equipment will contain the wiring schematic for every electrical device connected to the equipment. The three-phase power source will be identified at the beginning of the drawings in the upper left-hand corner. The incoming wires are labeled L1, L2, and L3 and are shown as three parallel horizontal lines on the drawings (Figure 1-3).

Motors, heaters, and other devices that require 480 VAC for proper operation are connected as loads to the incoming power wiring circuit. Devices that operate at other voltage levels require the use of a transformer to convert the incoming 480 VAC to the proper voltage level.

Traditionally, most electrical control systems on machines were energized at 120 VAC. There were at least two good reasons for this: safety and the use of standard-design components. The transformer that converts the 480 VAC to 120 VAC for use in the control circuit is called the *control transformer*. Over the past decade, industry has moved away from the traditional 120 VAC design. New equipment generally uses 24 VDC as the primary control circuit voltage. This conversion to low level DC has made the equipment even safer for the operators who run the machines and for the personnel who services the equipment. As this trend continues, 120 VAC devices are becoming obsolete and low voltage DC devices are becoming more commonplace.

Even when the control devices on a machine are powered by DC circuits, the need for a 120 VAC control transformer still exists. The standard voltage for use in households throughout the United States is 120 VAC. Therefore, convenience receptacles included on the equipment will require this voltage level. These receptacles provide the power necessary to run peripheral devices for troubleshooting the equipment. They also can be used to operate devices such as lights, fans, tools, or computers.

In addition, some components still require the 120 VAC for proper operation. The power supply that supplies the 24 VDC control voltage for the machine is typically powered from the 120 VAC circuit. For these reasons, the 120 VAC control transformer will usually still be included on new equipment that is built for use in the United States.

The control transformer is single phase, requiring a connection to any two of the three power lines. The transformer used in industrial machine control consists of at least two separate coils wound on a laminated steel core. The line voltage is connected to one coil, called the *primary.* The control load is connected to the other coil, called the *secondary.* Where the voltage is reduced from the primary to the secondary, the transformer is called a *step-down transformer.* In a *step-up transformer*, the voltage is increased from the primary to the secondary.

The simplest arrangement uses only two coils. One coil is used for the primary, the other for the secondary. The voltage is directly proportional to the number of turns in each coil. This relationship may be shown by the equation:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \qquad \text{Eq 1.1}$$

where: V_p = primary voltage
V_s = secondary voltage
N_p = number of turns of wire on the primary coil
N_s = number of turns of wire on the secondary coil

The quantity N_p/N_s is referred to as the *turns ratio* for the transformer. This value is expressed as a ratio and is not simplified to a single value.

Example 1

Find the turns ratio for a transformer with a primary voltage of 240 VAC and a secondary voltage of 120 VAC.

Solution

Using Equation 1.1 $V_p/V_s = N_p/N_s$

Substituting V_p = 240 VAC and V_s = 120 VAC we obtain N_p/N_s = 240 VAC/120 VAC

Reducing this equation by dividing the numerator and the denominator by a common factor of 120, results in a final solution of $N_p/N_s = 2/1$

Note that the answer was left as a ratio of 2 / 1 (stated as 2 to 1) instead of an answer of 2.

The turns ratio is commonly written as a ratio $N_p : N_s$. For this problem, we would write the answer as 2:1 and state the answer as 2 to 1.

Example 2

A transformer has a turns ratio of 4:1. If the transformer is connected to a primary voltage of 480 VAC, what is the secondary voltage?

Solution

Using Equation 1.1 $V_p/V_s = N_p/N_s$
Substituting the given values of V_p = 480 VAC
$N_p/N_s = 4/1$
we obtain the equation
480 VAC/V_s = 4/1

Using cross multiplication to solve ratio equations results in

480 VAC × 1 = 4 × V_s

Solving for V_s by dividing both sides of the equation by 4 shows that

V_s = 480 VAC/4 = 120 VAC

It is possible for the line voltage in a plant to vary from approximately 460 VAC to 500 VAC. As the primary voltage varies, the secondary voltage will also vary accordingly. For example, if the line voltage in a plant were to drop from its normal 480 VAC to 460 VAC, the transformer in Example 2 would deliver 115 VAC to the secondary. Similarly, if a plant's power source voltage were to drop from its normal 240 VAC to 230 VAC, a transformer having a 2:1 ratio would deliver 115 VAC to the secondary.

Another useful equation for transformers involves the current in the primary and secondary circuits. The current is inversely proportional to the number of turns in each coil. This relationship may be shown by the equation:

$$\frac{N_p}{N_s} = \frac{I_s}{I_p} \qquad \text{Eq 1.2}$$

where: I_s = secondary current
I_p = primary current
N_p = number of turns of wire on the primary coil
N_s = number of turns of wire on the secondary coil

Combining Equations 1.1 and 1.2 results in the equation:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} = \frac{I_s}{I_p} \qquad \text{Eq 1.3}$$

Example 3

A transformer is connected to a 480 VAC line. The secondary voltage is 240 VAC. The load connected to the secondary draws 10 Amps.

a. What is the turns ratio of the transformer?
b. How much current flows in the primary circuit?

Solution

a. Using Equation 1.1 $V_p/V_s = N_p/N_s$

Substituting the given values of $V_p = 480$ VAC

$V_s = 240$ VAC

we obtain the equation

480 VAC/240 VAC $= N_p/N_s$

Reducing this equation by dividing the numerator and the denominator by a common factor of 240, results in a final solution of $N_p/N_s = 2/1$

b. Using Equation 1.3 $V_p/V_s = I_s/I_p$

Substituting the given values of $V_p = 480$ VAC

$V_s = 240$ VAC

$I_s = 10$ A

we obtain the equation

480 VAC/240 VAC = 10 A/I_p

Using cross multiplication to solve ratio equations results in

480 VAC × I_p = 240 VAC × 10 A

Dividing both sides by 480 VAC results in

I_p = (240 VAC × 10 A)/480 VAC = 5 A

Returning to Equation 1.3 $V_p/V_s = I_s/I_p$ and cross multiplying results in the relationship:

$$V_p \times I_p = V_s \times I_s \qquad \text{Eq 1.4}$$

The power delivered by a source or the power consumed by a load is equal to the voltage multiplied by the current. Therefore, Equation 1.4 shows that the power in the primary is equal to the power in the secondary circuit. This relationship will be true for ideal transformers where it can be assumed that there are no losses incurred in the system. Transformers are rated by this power relationship, which is expressed in volt-amps (VA). Larger transformers are rated in kVA where 1 kVA is equal to 1000 VA. Transformers are available in sizes from 50 VA to 10 kVA.

Multiple coil windings may be used on the primary and secondary sides of a transformer. The user may connect the coil windings in a manner that allows the transformer to provide the proper secondary voltage depending on the line voltage that is available. Multiple coil windings are usually provided on the primary side of the transformer to make it easier to connect to different power voltages. Special primary windings with multiple taps for 200 - 208 - 240 - 480 - 575 V and a 120 V secondary are available.

The most widely used control transformers have a dual-voltage primary of 240/480 VAC. They have an isolated secondary winding to provide 120 V for the load.

The symbol for the control transformer is shown in Figures 1-4 and 1-5. Two primary coils and one secondary coil are used. When the control transformer primary coils are connected to a 240-V power source, the two coils are connected in *parallel.* When the primary coils are connected to a 480-V power source, the coils are connected in *series.*

When two coils with the same number of turns (same voltage rating) are connected in parallel, the effective number of turns for determining the turns ratio remains the same as if only one coil were used. When two coils with the same number of turns are connected in series, the numbers of turns on each coil are added together.

When two separate coils are used on the primary side, the arrangement is called a *dual primary.* When two separate coils are used on the secondary side, it is called a *dual secondary.*

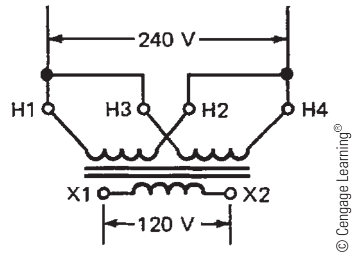

Figure 1-4 **Primary coils connected in parallel.**

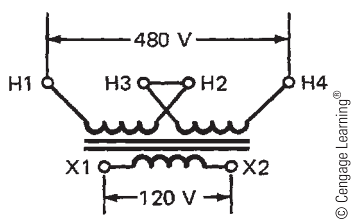

Figure 1-5 **Primary coils connected in series.**

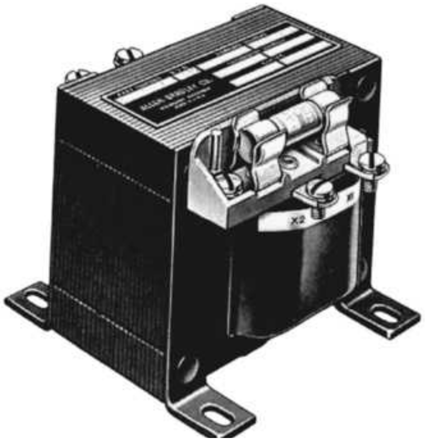

Figure 1-6 **Control-circuit transformer with built-in fuse block.** *(Courtesy of Rockwell Automation, Inc.)*

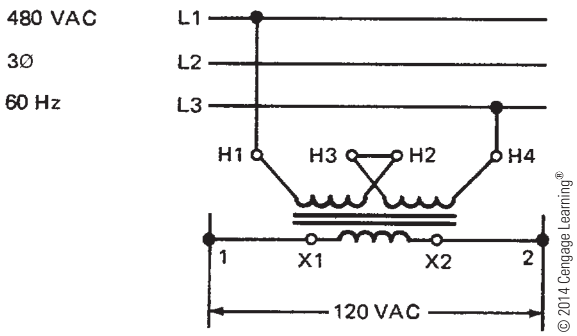

Figure 1-7 **Transformer connected to three-phase power line.**

The transformer is available either in an open type or in its own enclosure. At one time, the general practice was to use the open type and panel mount it in the control cabinet. With panel-mounted transformers, however, high allowable temperature rise may create unwanted high temperatures in the control cabinet. With this condition, the transformer in its own enclosure should be used, mounted on the outside of the cabinet.

The transformer either has screw-type terminals on the coil, or the leads are brought out to a terminal block. In some cases, fuses or circuit breakers are offered as an integral part of the transformer installation.

A typical transformer is shown in Figure 1-6. A diagram of a three-phase power supply and control transformer is shown in Figure 1-7. In that figure, the primary side of the transformer is connected to one phase (L1 to L3) of the three phase power source. The secondary is supplying 120 VAC to the vertical sides of the ladder-type control circuit diagram.

1.2 Transformer Regulation

Voltage *regulation* in transformers is the difference between the no-load voltage and the full-load voltage. This value is usually expressed in terms of a percent. It can be calculated as follows:

$$\frac{\text{No-load voltage} - \text{Full-load voltage}}{\text{Full-load voltage}} \times 100$$

Using an example in which the transformer delivers 100 V at no load and the voltage drops to 95 V at full load, the regulation would be calculated as follows:

$$\frac{100 - 95}{95} = \frac{5}{95} \times 100 = 5.26\%$$

It is generally desirable to have the regulation for a control transformer in the range of 2 to 3%.

1.3 Sizing a Transformer

Transformers are available in many different sizes. A transformer will be selected based on the primary voltage and frequency available, the secondary voltage required, and the capacity required in volt-amps (or kVA).

The transformer must be sized to handle the full load current for all of the devices that may be in operation at any given time. This process involves determining the current requirement for each load in the circuit individually. The overall current draw for the circuit may then be calculated by adding together the individual loads. Two calculations should be performed to determine the size of the transformer. Consideration should be given to the continuous or sealed current for all loads in the system. In addition, the inrush current characteristics of the coils on relays, contactors, motor starters, solenoids, etc. must be taken into account. This information is available from the manufacturer of the component. The procedure is as follows:

- Calculate the total maximum continuous or sealed current by adding the continuous current drawn by all the loads that will be in an energized condition at the same time. Multiply this figure by 5⁄4 (1.25).

- Calculate the total maximum inrush current by adding the inrush current of all the coils that will be energized together at any one time. Multiply this figure by 1⁄4 (.25).

Using the larger of the two figures you have just calculated, multiply this current by the control voltage. This product is the VA required by the transformer load. If the resulting figure drops below a commercially available transformer size, use the next larger size. For example, you may have calculated that the total VA required is 698. Then use a 750 VA transformer, which is commercially available.

Example 4

Calculate the kVA requirement for a transformer whose secondary will be connected to a 120 VAC circuit with the following loads (assume inrush calculation is not needed):

20 relays with a full load current (FLA) of .5 A each

10 pilot lights with a FLA of .2 A each

4 solenoids with a FLA of 1 A each

Solution

Calculate the total current required for all of the devices to operate simultaneously.

Device	FLA (A)
Relays	10
Pilot Lights	2
Solenoids	4
Total	16 A

Total current rating = $16 \times 1.25 = 20$ A
kVA rating = 120 VAC $\times$ 20 A = 2400 VA

Select the next highest available size. You would order a 2.5 kVA transformer.

1.4 Operating Transformers in Parallel

Single-phase transformers can be used in parallel only when their voltages are equal and impedances are approximately equal. If unequal voltages are used, a circulating current exists in the closed network between the two transformers that will cause excessive heating and result in a shorter life of the transformer. Impedance values of each transformer must be within 7.5% of one another. For example, if Transformer A has an impedance of 4%; Transformer B, which is to be connected parallel to A, must then have an impedance between 3.7% and 4.3%.

1.5 Temperature Rise in a Transformer

Temperature rise in a transformer is the amount by which the temperature of the windings and insulation exceeds the existing ambient or surrounding temperature. Temperature rise of a transformer is generally given on the transformer nameplate and should not be exceeded. Overloading of a transformer results in excessive temperature. This excessive temperature causes overheating, which results in rapid deterioration of the insulation and causes complete failure of the transformer coils.

Some of the lower kVA-rated transformers (below 1 kVA) that are rated at 60 Hz can be operated satisfactorily at 50 Hz. However, at higher kVA ratings 60-Hz rated transformers operating at 50 Hz will produce a greater heat rise. Therefore, it is not advisable to use higher kVA-rated transformers in 50-Hz power circuits.

1.6 50-Hz vs 60-Hz Operation

Globalization has had a significant impact on industry. It is now very common to purchase equipment produced in other countries or to build equipment for use in other countries. In addition, companies frequently transport existing equipment to other regions of the world as the production volumes or economic situations vary within their organizations. It is important to understand the governing codes and regulations, standards, and mains power supply available at the destination location for the machine to ensure the proper and safe operation of the equipment. Worldwide, the power distribution systems vary by the use of different voltages, frequencies, and grounding systems. Even the types of plugs and receptacles used for common household items vary in different regions of the world.

50 Hz is the standard frequency that is utilized in Europe, Asia, and many countries throughout the world. North America has standardized on the use of 60 Hz for its power distribution systems. When moving equipment, the ratings of each transformer must be evaluated. A transformer that is designed for use in a 60-Hz system may not be capable of withstanding the heat generated by use in a 50-Hz circuit. A transformer designed for 50-Hz operation will actually run cooler when placed in a 60-Hz system and would not be a concern in regards to heat generation. However, the nominal voltage of the primary circuit and the amount of variation of the voltage from the nominal value must also be taken into consideration. Remember that the turns ratio of the transformer dictates the amount of voltage available on the secondary of the transformer as the primary voltage is changed. Therefore, the correct voltage may not be available on the secondary to operate the loads on the equipment at a safe operating level. Also, if the voltage level varies significantly around the nominal value, special considerations may need to be implemented to maintain the voltage at a safe operating range for the devices. For these reasons, it is a common practice to replace all of the transformers on equipment when the machinery is relocated to different regions of the world.

Another item that is typically replaced on relocated equipment is the induction motors. Induction motors vary in speed based on the frequency of their supply voltage. A motor designed for use with a 50-Hz system will run faster when connected to a 60-Hz supply. Motors and the relationship between frequency and speed will be covered in more detail in Chapter 13.

1.7 Constant Voltage Regulators*

The constant voltage regulator (CVR) consists of a leakage reactance, a ferroresonant transformer with an additional pair of magnetic shunts, and a filtering winding. Together they develop a regulated, low-distortion sinusoidal output. The circuit is designed so that the segment of the core under the secondary winding (Figure 1-8) will saturate and ferroresonate with the AC capacitor once each half-cycle, limiting the output voltage to a fixed value. The primary-to-secondary leakage reactance and AC capacitor are tuned to achieve ferroresonant regulation of the output over a broad range of input voltage.

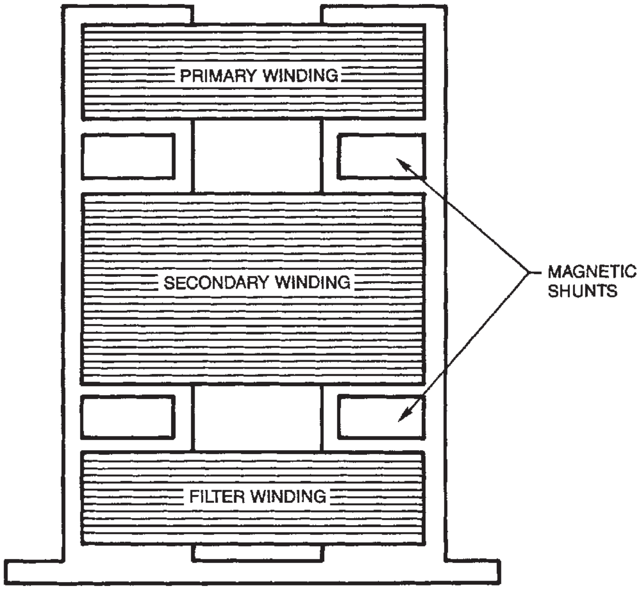

Figure 1-8 **Constant voltage regulator.** *(Courtesy of Acme Electric—Acme Transformer Division.)*

The second pair of magnetic shunts and filter winding is incorporated to soften the secondary core saturation effect, cancelling the harmonic voltages that are present in conventional CVRs. The filtering winding is connected in series with the AC capacitor (Figure 1-9). This forms an LC (inductance/capacitance) trap to filter out the low order of harmonics generated by ferroresonant action. A cutaway view of the Acme transformer coil is shown in Figure 1-10.

Ferroresonance (transformer) is a phenomenon usually characterized by overvoltages and very irregular wave shapes. It is associated with the excitation of one or more saturable inductors through capacitance in series with the inductor.

*Information courtesy of Acme Electric—Acme Transformer Division.

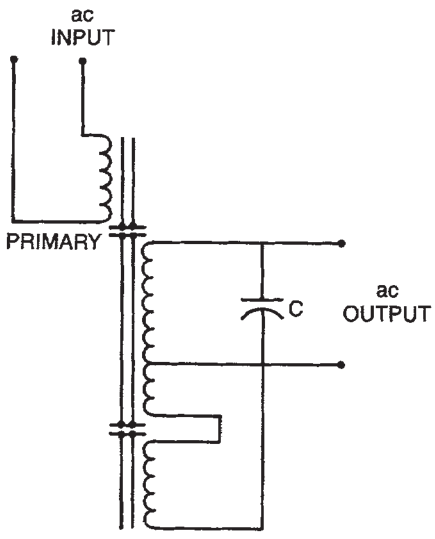

Figure 1-9 **Circuit for constant voltage regulator.** *(Courtesy of Acme Electric—Acme Transformer Division.)*

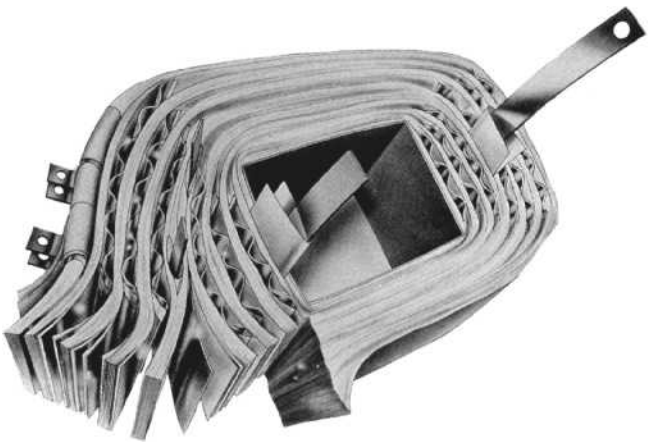

Figure 1-10 **Cutaway view of a CVR transformer coil.** *(Courtesy of Acme Electric—Acme Transformer Division.)*

1.8 Power Supplies for Control Voltage

The primary purpose of a power supply is to convert the incoming AC voltage to a DC voltage for use by the control circuit. The power supply is usually connected to the 120 VAC circuit on equipment used in the United States.

The simplest method to convert from AC to DC is by using an unregulated power supply. This unit will consist of a transformer, a rectifier, and a filter circuit. The transformer will change the incoming 120 VAC to a lower voltage level. The rectifier will then convert this lower level AC signal to a pulsating DC signal. The filtering circuit will smooth out (filter) the pulsating waveform to provide the DC voltage signal output. However, the output voltage of an unregulated power supply will vary as the load changes or as the incoming AC line voltage varies. If the system voltage drops to an unusually low level, components may begin to malfunction and drop out (de-energize).

A linear regulated power supply will generate a consistent output voltage that does not vary with the incoming voltage level or with the load applied to the system. A somewhat complex regulator circuit is used to maintain the voltage at the proper level. These power supplies provide excellent regulation with very little ripple on the output signal. However, they are inefficient and have a limited input range.

Switching regulated power supplies use complex circuitry to obtain a constant output voltage that is isolated from the incoming voltage supply. These power supplies convert the incoming AC voltage to a DC signal by rectifying the source voltage and filtering the signal. This DC signal is then switched at a high frequency to obtain a pulse width modulation (PWM) signal. The PWM signal is then sent through a transformer and rectified again to produce the DC output signal. This conversion from AC to DC to AC and finally back to DC essentially isolates the output power from variations in the utility supply. In addition, a sensing circuit can monitor the output voltage and adjust the PWM switching to maintain a consistent output voltage.

An uninterruptible power supply (UPS) will provide an emergency backup source of electricity in the event of a power outage.

All machine tool electrical control circuits shown in this text through Chapter 13 use the basic ladder-type diagram. The voltage source between the two vertical sides in these diagrams is 24 VDC. Therefore, the complete three-phase power circuit, transformer, and power supply symbols will not always be shown, though they will generally be shown on industrial schematics.

1.9 Uninterruptible Power Systems (UPS)*

Certain types of electrical equipment, such as programmable logic controllers and computers, are very sensitive when it comes to the quality of their power supply. Small voltage fluctuations or variations in frequency can cause serious malfunctions, and a total power outage can result in the loss of data stored in the memory.

When electric power is generated, it is both clean and stable but during transmission and distribution, it is subjected to a variety of detrimental influences. Electrical storms, noisy and largely varying loads, and accidents all lead to a less than perfect supply emerging from the utility power supply.

These supply problems can be overcome by connecting a UPS between the utility supply and sensitive load equipment. It will not only clean up any supply aberrations but will also maintain the critical load during a complete outage. The Liebert Corporation Uninterruptible Power System provides both power conditioning and supply backup (Figure 1-11). It takes the raw utility power and, using state-of-the-art solid-state power electronic technology, converts it into a DC form. A microprocessor-controlled inverter then reconverts the DC power into controlled AC that can be used to supply equipment. Due to this double conversion technique, from AC to DC to AC, the output power is essentially isolated from the utility supply so that the equipment will be oblivious to any utility supply variations.

Backup is provided by an internal battery that is automatically connected to the DC portion of the UPS when the input power fails. The standby battery can maintain the unit's fully rated load for 10 minutes, but this period will be longer if lighter loads are used. If the supply break exceeds the battery backup time, the UPS will shut down once the battery charge has been exhausted. However, the unit will sound an alarm to warn that this is about to occur to give adequate time to shut down the load in an orderly fashion.

Figure 1-11 **Uninterruptible power system.** *(Courtesy of Liebert Corporation.)*

This UPS will automatically restart when the utility supply returns, and the battery will quickly recharge to prepare for further use. A block diagram shows the arrangement of the various elements within this UPS (Figure 1-12).

1.10 Circuit Diagram

To troubleshoot or maintain a piece of equipment, it is crucial to understand the symbols that are shown on the electrical drawings.

A typical drawing is provided (Figure 1-13) to summarize many of the devices that were discussed in this chapter. Notice that line numbers are typically given on the drawing set to provide a means for cross-referencing devices to other places within the drawing set. The first number of

*Information courtesy of Liebert Corp.

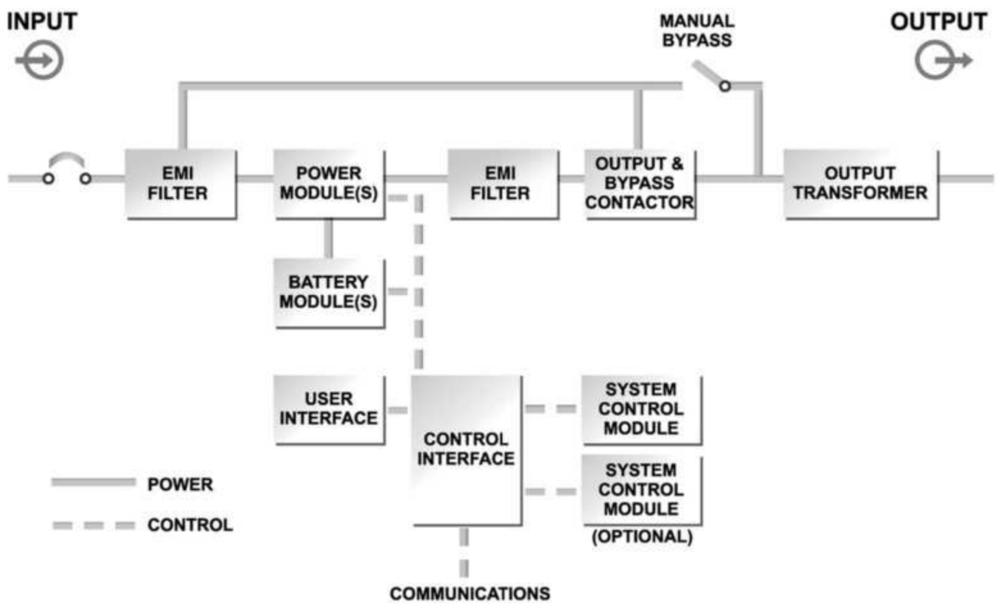

Figure 1-12 **Block diagram of various elements of the UPS.** *(Courtesy of Liebert Corporation.)*

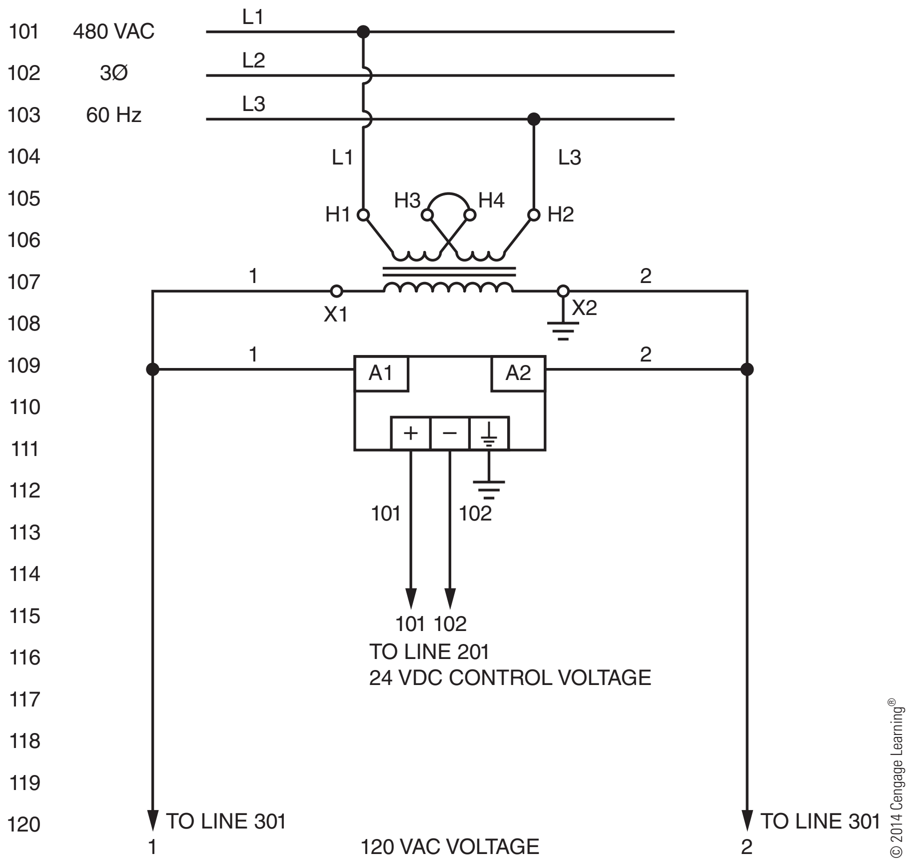

Figure 1-13 **Electrical schematic including wire numbers and line numbers.**

the line number is typically representative of the sheet number for the given drawing.

Notice also that wire numbers have been included in the drawing. All wires on a piece of equipment will be assigned a number. A label will be physically attached to both ends of the wire with the wire number printed on the labels. The wire numbers will agree with the wire number identified on the electrical drawing. The rule for assigning wire numbers is that the wire number will change every time the wire goes through a device. Therefore, several wires may have the same wire number if they are connected together to form a common node. This situation applies to wire numbers 1, 2, L1, and L3 in Figure 1-13.

1.11 Insulation Classifications

The Underwriters Laboratory (UL) is a global consumer safety company. The UL mark on a product signifies that the device has undergone extensive testing to ensure that it complies with its rigorous standards. This organization also publishes standards for safety and compliance. One such standard is UL83, which specifies the insulation requirements for 600 V wires used in electrical circuits. The National Electrical Manufacturers Association (NEMA) also classifies insulation systems according to the maximum temperature that is allowable for proper and safe operation. Other sources for requirements include the International Electrotechnical Commission (IEC) 60085 standard and the Japanese Industrial Standards (JIS) C4003. The important point to remember is the applicable standards for the location where a machine will operate must be consulted and complied with. The maximum allowable temperature for various types of insulation is consistent between these standards for the classes given in Figure 1-14.

It is imperative that the maximum temperature for a given type of wire is not exceeded or the insulation may melt or burn. Note also that the insulation classes listed in Figure 1-14 also apply to other devices such as motors and transformers.

Insulation Class	Maximum Temperature (Degree C)
A	105
B	130
F	155
H	180

Figure 1-14 **Insulation Classifications.**

1.12 Conductor Ampacity

The amount of current flowing through a wire also impacts the amount of heat generated in the wire. Therefore, ampacity tables are provided in electrical standards. The ampacity tables indicate the maximum amount of current allowed to flow through a given size of wire, for a given ambient temperature and insulation class of wire. The information presented in the tables must be derated to allow for different ambient temperatures or numbers of wires run together in a conduit or raceway. An example of an ampacity table for use on equipment in the United States is provided by the National Fire Protection Association (NFPA). Table 6 from NFPA79: Electrical Standard for Industrial Machinery is included in Appendix E.

1.13 Conductor Color Code

A consistent color coding scheme for conductors used on industrial equipment provides an additional level of safety for individuals working on the equipment. Compliance to these standards allows an electrician to quickly identify the amount and type of voltage that will be present when troubleshooting the equipment. Field devices may be wired using multi-conductor cable that will not comply with the color coding scheme. However, the color of conductors wired inside the main control cabinet should comply with the applicable standards for the region in which the machine resides. NFPA79: Electrical Standard for Industrial Machinery provides the color coding scheme for machinery in operation within the United States. The example wiring schematic shown in

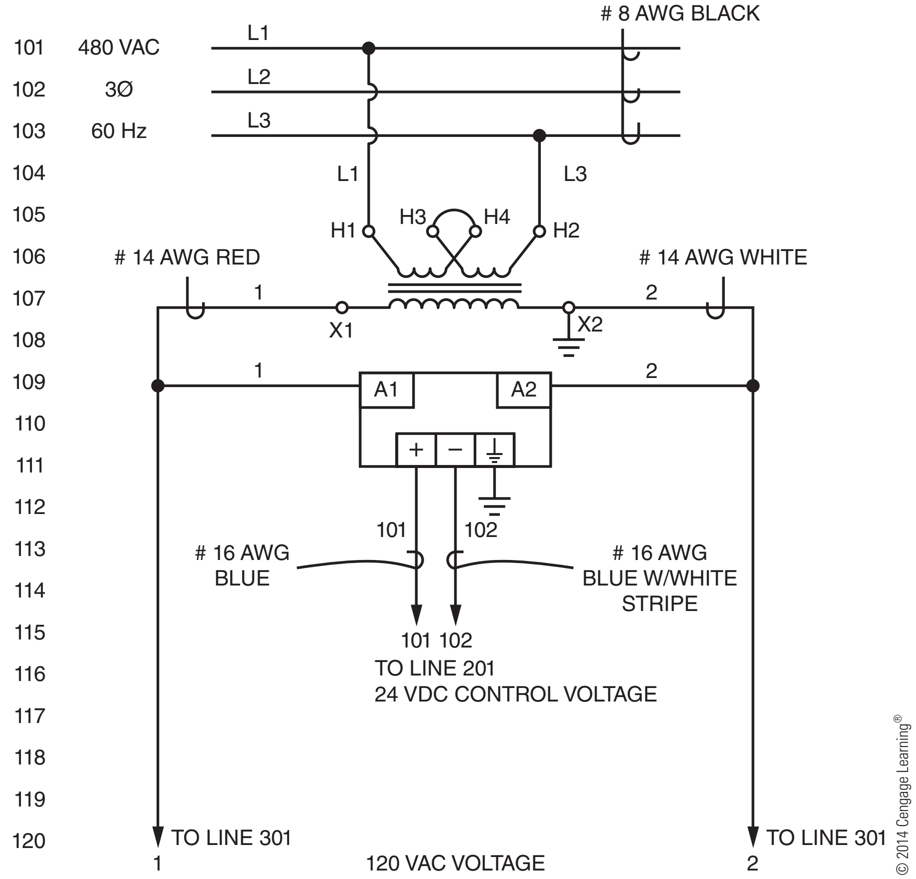

Figure 1-15 **Electrical schematic including wire size and color.**

Figure 1-13 may now be finalized as shown in Figure 1-15 to include the wire size and color for various conductors.

1.14 Electrical Symbols

The Joint International Committee (JIC) developed a set of symbols to be used in machine control drawings to standardize electrical drawings. The JIC symbols are shown in this text and are used in the electrical circuits shown throughout the chapters. European countries utilize symbols from the IEC 617 standard for use in electrical schematics. These symbols have been provided throughout the text whenever a new symbol is introduced. However, to avoid confusion, only the JIC symbols are used in circuit diagrams.

The European countries utilize a different format for their drawings along with a different standard sheet size. Drawings for North America utilize vertical lines to show power and common wires. Devices are then drawn horizontally between the power rails. Devices in European drawings are shown vertically in the drawings.

Recommended Web Links

Students are encouraged to view the following Web sites as a supplement to the concepts presented in this textbook. Review and analyze the array of products that are available for electrical control applications. Many of these sites offer technical information that can help in converting the principles to practical applications. To view catalogs, your PC may require Adobe Acrobat Reader software.

Transformers

1. The Osborne Transformer Co.
   www.osbornetransformer.com
   Review: Products and Applications
2. Sola/Hevi-Duty
   www.solahevidutysales.com
   Review: Products and Power Supplies
3. Acme Electric Corp.
   www.acmepowerdist.com
   Review: Technical Services and Transformers

Power Supplies and UPS

1. Majorpower.com
   www.majorpower.com
   Review: Products
2. APC
   www.apc.com
   Review: Products and Services
3. Liebert Corp.
   www.liebert.com
   Review: Products—Surge Suppressors, Power Conditioners, and UPS

Standards

1. Underwriters Laboratory
   www.ul.com

Achievement Review

1. What type of electrical energy is normally supplied to industries?
2. What are the two important reasons for using 24 VDC in machine control systems?
3. Why is 120 VAC still available on machine systems in the United States?
4. There is 480 VAC available in a given plant. To obtain 120 V, what turns ratio is required between the primary and secondary of the control transformer?
5. There is 460 VAC available in a given plant. To obtain 230 VAC, what turns ratio is required between the primary and secondary of the transformer?
6. A transformer has a turns ratio of 4:1. If the transformer is connected to a primary voltage of 360 VAC, what is the secondary voltage?
7. A transformer is connected to a 460 VAC line. The secondary voltage is 230 VAC. The load connected to the secondary draws 30 A.
   a. What is the turns ratio of the transformer?
   b. How much current flows in the primary circuit?
8. You find that under unusually heavy loads, the voltage in your plant drops to 456 V. What will be the resulting secondary voltage if you use a transformer with a 4:1 primary-to-secondary turns ratio?
9. Draw the symbol for a dual-primary, single-secondary control transformer. Show all lead designations.
10. Draw a complete circuit showing the primary of a dual-primary control transformer connected to a three-phase, 480-V power line, and the single secondary connected to a 120-V control system.
11. In a given transformer the voltage is reduced from the primary to the secondary. What is this transformer called?
    a. Current transformer
    b. Step-up transformer
    c. Step-down transformer
12. A transformer has a no-load voltage of 120 and a full-load voltage of 110. What is the percent regulation for this transformer?
13. Calculate the kVA requirement for a transformer whose secondary will be connected to a 230 VAC circuit with the following loads:
    a. 16 relays with FLA of .2A each (inrush 2A)
    b. 10 pilot lights with a FLA of .1A each (inrush 2A)
    c. 6 solenoids with a FLA of .5A each (inrush 5A)
14. What parts of a transformer generally contribute to temperature rise in the transformer?
    a. The enclosure
    b. Copper winding
    c. Iron core

15. What will generally result if you operate a transformer (1 kVA or larger) designed for 60 Hz on a 50-Hz supply?
16. What may happen to components that are energized in a control system if, owing to poor transformer regulation, the voltage drops to an unusually low level?
17. Draw a block diagram showing all the standard components that make up a UPS.
18. When using a UPS, what happens if the power is lost?
19. What factors will generally lead to a less than perfect supply emerging from the utility power system?
20. What problems can exist within a utility power supply that will make the use of an uninterruptible power supply advisable?

2
CHAPTER

Fuses, Disconnect Switches, and Circuit Breakers

OBJECTIVES

After studying this chapter, you should be able to:

- Describe basic fuse construction.
- List three different types of fuses and some of their uses.
- Identify four different types of circuit breakers and uses for each.
- Describe the steps to take when first setting up electrical control and power circuits.
- Explain why time-delay fuses are used with motor starter circuits.
- List the voltage and current ratings available for fuses and circuit breakers.
- Discuss the important factors to consider when selecting protective devices.
- Draw the symbols for important protective and disconnecting devices.
- Know what is meant by *interrupting capacity*.
- Understand the use of rejection-type fuses.
- Explain the two measures of the degree of current limitations provided by a fuse.
- Explain voltage and frequency surges caused by lightning or switching.
- Explain the operation of a GFCI circuit.

2.1 Protective Factors

Once the appropriate electrical power is determined for the control circuits, methods to protect the circuit components from current and temperature surges must be considered. There are two factors to be considered when providing control circuit protection:

1. A means of disconnecting electrical energy from the circuits.
2. Protection against sustained overloads and short circuits.

The power circuit can be disconnected by using a disconnect switch or nonautomatic circuit breaker (circuit interrupter). Protection is provided by adding adequate fusing to the disconnect switch, and thermal and/or magnetic trip units to the circuit interrupter.

The 120 VAC circuit is normally protected by a single fuse or circuit breaker. In some cases, two or more fuses may be used. This arrangement is covered in more detail in Chapter 19 “Troubleshooting.”

Figure 2-1 shows an example of a commercially available three-pole, fusible disconnect switch ganged with a handle.

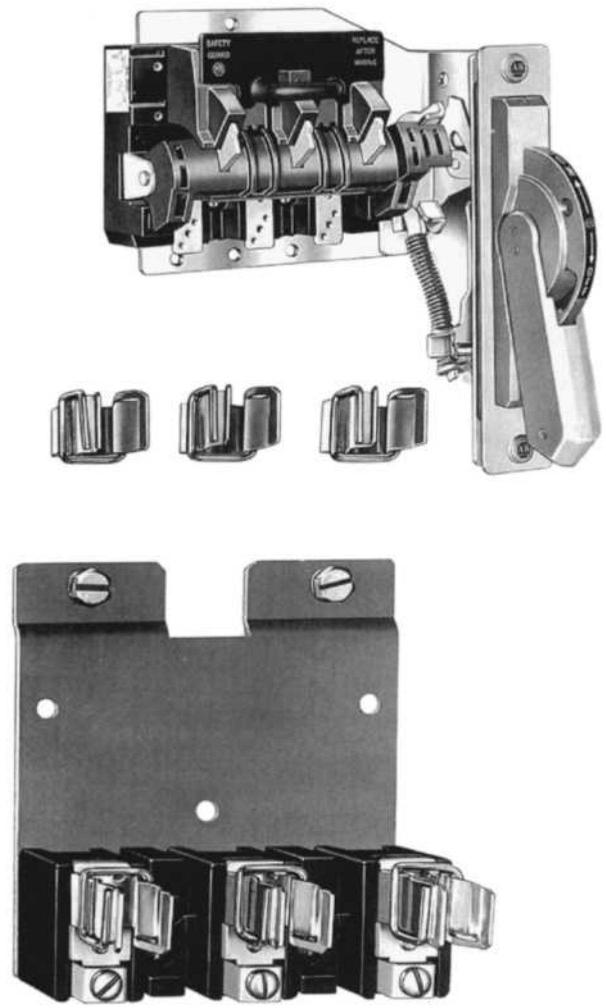

Figure 2-1 **Fusible disconnect switch.** *(Courtesy of Rockwell Automation, Inc.)*

2.2 Fuse Construction and Operation*

The typical fuse consists of an element surrounded by a filler and enclosed by the fuse body. The element is welded or soldered to the fuse contacts, blades, or ferrules (Figure 2-2).

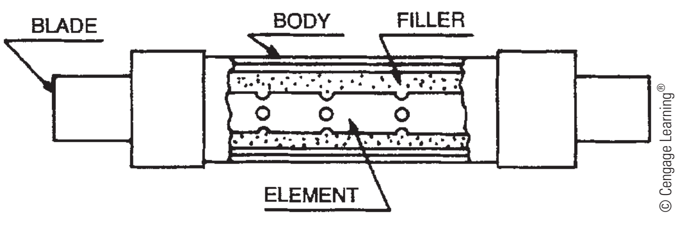

Figure 2-2 **Cross section through a typical fuse.**

The element is a calibrated conductor. Its configuration, mass, and the materials employed are varied to achieve the desired electrical and thermal characteristics. The element provides the current path through the fuse. It generates heat at a rate that depends on its resistance and the load current.

The heat generated by the element is absorbed by the filler and passed through the fuse body to the surrounding air. A filler such as quartz sand provides effective heat transfer and allows for the small-element cross section typical in modern fuses. The effective heat transfer allows the fuse to carry harmless overloads. The small-element cross section melts quickly under short-circuit conditions. The filler also aids fuse performance by absorbing arc energy when the fuse clears an overload or short circuit.

When a sustained overload occurs, the element generates heat at a faster rate than the heat can be passed to the filler. If the overload persists, the element will reach its melting point and open. Increasing the applied current heats the element faster and causes the fuse to open sooner. Thus, fuses have an inverse time-current characteristic; that is, the greater the overcurrent, the less time required for the fuse to open the circuit.

2.3 Fuse Types*

Fuses are available in numerous types; here are three common ones:

1. Standard one-time fuse (Figure 2-3)
2. Time-delay fuse (Figure 2-4)
3. Current-limiting non-time-delay fuse (Figure 2-5)

Standard voltage ratings for fuses are 125 V, 250 V, 300 V, 480 V, and 600 V. Higher-voltage fuses are available. Current ratings range from a fraction of an ampere (A) to 6000 A, in all voltage ratings.

The ability of a protective device (fuses or circuit breakers) to interrupt excessive current in an electrical circuit is important. All protective devices have a published *interrupting capacity*, which is defined as the highest current at rated voltage that a device can safely interrupt.

*Information courtesy of Ferraz Shawmut.

Figure 2-3 **One-time fuse—class K-5.** *(Courtesy of Ferraz Shawmut.)*

Figure 2-4 **Time-delay fuse—class RK-5.** *(Courtesy of Ferraz Shawmut.)*

Figure 2-5 **Current-limiting fuse—class RK-1.** *(Courtesy of Ferraz Shawmut.)*

It is therefore important when installing or replacing a protective device that at least three items be considered:

1. Voltage rating
2. Current rating
3. Interrupting capacity

Correct fuses must be used as replacements for continued safety in the protection of equipment. To help in this area, manufacturers provide a “rejection”-type fuse. It is called Class R (R for rejection). The ferrule sizes (0–60 A) have an annular groove in one ferrule. The blade sizes (61–600 A) have a slot in one blade. Replacement of this fuse with a fuse of lower voltage or lower interrupting rating is not possible provided that this fuse is used with rejection fuse blocks. The rejection fuse block is similar to the standard fuse block except physical changes are made in the block to accommodate the annular ring in the ferrule-type fuse and the slot in blade type.

The physical configuration of the rejection-type fuse is shown in Figures 2-4 and 2-5. The rejection-type fuse has a 200,000-A interrupting rating as contrasted to class K-5 with the standard fuse configuration, ferrule or blade, shown in Figure 2-3, with an interrupting capacity of 50,000 A.

To further understand the operation of fuses, a melting time–current data curve is shown in Figure 2-6. This curve is for a typical 100-A, 250-V, time-delay fuse. It shows an inverse time relationship between current and melting time; that is, the higher the current, the faster the melting time. For example, referring to this curve, it can be seen that at 1300 A, the melting time is 0.2 seconds. At 200 A, the melting time is 300 seconds. This characteristic is desirable because it parallels the characteristic of conductors, motors, transformers, and other electrical apparatus. This equipment can carry low-level overloads for relatively long times without damage. However, under high current conditions caused by short circuits, damage can occur quickly. Because of the inverse time characteristic, a properly applied fuse can provide effective protection over a broad current range from overloads to short circuits.

The standard one-time fuse (class K-5) link consists of a low-temperature-melting metal strip with several reduced area sections. On overloads that exceed the rating of the fuse, the narrow center section will melt, thus opening the circuit. The heat to

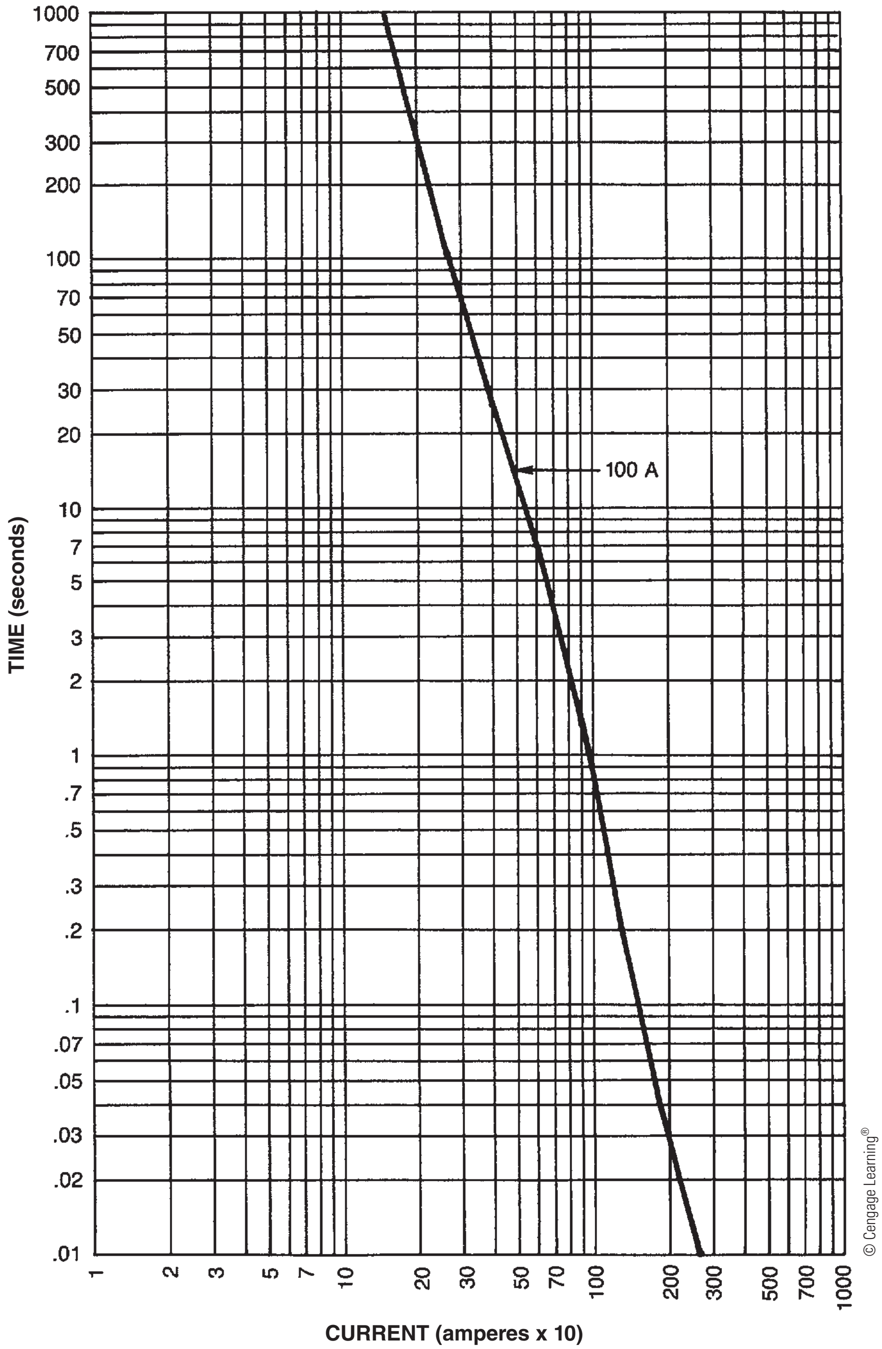

Figure 2-6 **Melting time–current data for a typical time-delay fuse—100 amperes.**

melt the strip comes from excessive current passed through the fuse. In case of short circuits, all the reduced cross-sectional areas will melt and vaporize simultaneously. The tube holding the strip (fuse link) must be of sufficient strength to withstand the internal pressure developed during this time.

The class K-5 fuses are suitable for the protection of mains, feeders, and branch circuits serving lighting, heating, and other nonmotor loads, provided that the interrupt capacity is adequate.

The time-delay fuses (class RK-5 and RK-1) were developed for use where a heavy overloading might exist for a short time and the fuse is not expected to open unless the overload persists. An example of a short overload is normal motor starting. These time-delay delay fuses are also suitable for general-purpose protection of transformers, service entrance equipment, feeder circuits, and branch circuits. The time-delay characteristic of an efficient fuse allows it to withstand normal surge conditions without compromising short-circuit protection.

Current-limiting time-delay fuses are used today in almost all fuse applications because in most electrical power systems, a fault can produce currents so great that much damage may result. The current-limiting fuse will limit both the magnitude and duration of the current flow under short-circuit conditions. This type of fuse will clear available fault currents in less than one half cycle, thus limiting the actual magnitude of the current flow. It is generally supplied as a rejection-type fuse. The replacement of these fuses with a fuse of another UL class is not possible.

The current-limiting fuse (class RK-1) is available as a non-time-delay fuse or a time-delay fuse with interrupting capacity of 200,000 A and higher. The non-time-delay fuse is suitable for the protection of capacitors, circuit breakers, load centers, panel boards, switch boards, and bus ducts in which high available short-circuit currents may exist. They are also available in time delay versions for motor loads with a high degree of current limitation for minimizing short-circuit current damage.

With the increased use of solid-state power devices, fuse designs have changed to match solid-state protection demands.

Solid-state devices operate at high current densities. Cooling is a prime consideration. Cycling conditions must be considered. The ability of solid-state devices to switch high currents at high speed subjects fuses to thermal and mechanical stresses. Solid-state devices have relatively short thermal time constants. A short-circuit current that may not harm an electromechanical device can cause catastrophic failure of a solid-state device in a very short time.

Most programmable controllers (covered in Chapter 15) use a semiconductor fuse with a blown-fuse indicator. There also may be add-on switches that can be used to energize an indicator light. This light can be used for remote indication. The trigger actuator may be a part of the fuse or a field-mounted blown-fuse indicator that would be wired in parallel with the fuse being monitored.

2.4 Peak Let-Thru Current (I_p) and Ampere Squared Seconds (I^2t)

Current limitation is one of the important benefits provided by modern fuses. Current-limiting fuses are capable of isolating a faulted circuit before the fault current has sufficient time to accelerate to its maximum value. This current-limiting action provides several benefits:

- It limits thermal and mechanical stresses created by the fault currents.
- The magnitude and duration of the voltage drop caused by the fault currents is reduced, improving overall power quality.
- Current-limiting fuses can be precisely coordinated to minimize unnecessary service interruption.

Peak let-thru current (I_p) and ampere squared seconds (I^2t) are two measures for the degree of current limitation provided by a fuse. Maximum allowable I_p and I^2t values are specified in UL standards for all UL-listed current-limiting fuses and by the fuse manufacturer for semiconductor and special purpose fuses.

Let-thru current is that current which passes by a fuse while the fuse is interrupting a fault within the fuse's current-limiting range (Figure 2-7). It is

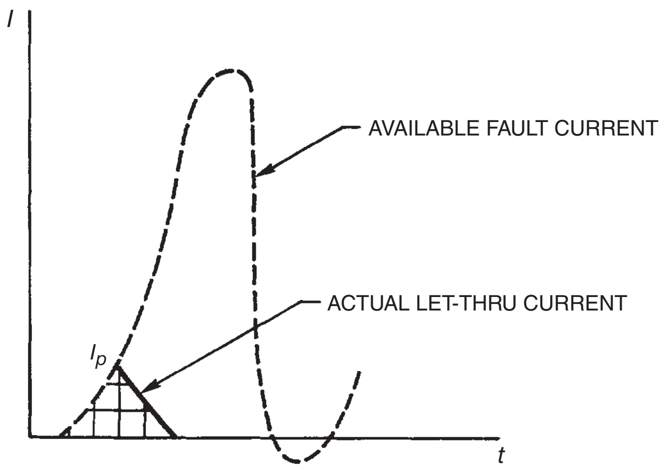

Figure 2-7 **Let-thru current is expressed as a peak instantaneous value (I_p).** *(Courtesy of Ferraz Shawmut.)*

expressed as a peak instantaneous value (I_p) in amperes. I^2t is a measure of the heat generated with current flow over time.

The I_p data is generally presented in the form of a graph. Key information is provided in the peak let-thru graph in Figure 2-8. As shown on the figure, the important components are:

1. The x-axis, labeled "Available Fault Current" in rms symmetrical amperes.
2. The y-axis, labeled "Instantaneous Peak Let-Thru Current" in amperes.
3. The line labeled "Maximum Peak Current Circuit Can Produce," which gives the worst-case peak current possible with no fuse in the circuit.
4. The "Fuse Characteristic Line," which is a plot of the peak let-thru currents that are passed by a given fuse at various available fault currents.

Figure 2-9 illustrates the use of the peak let-thru current graph. Assume that a 200 A, class J fuse is to be applied where the available fault current is 35,000 A rms. The graph shows that with 35,000 A rms available, the peak available current is 80,500 A (35,000 × 2.3) and that the fuse will limit the peak let-thru current to 12,000 A.

You may wonder why the peak available current is 2.3 times greater than the rms available current. In theory, the peak available fault current can be anywhere from 1.414 × (rms available) to

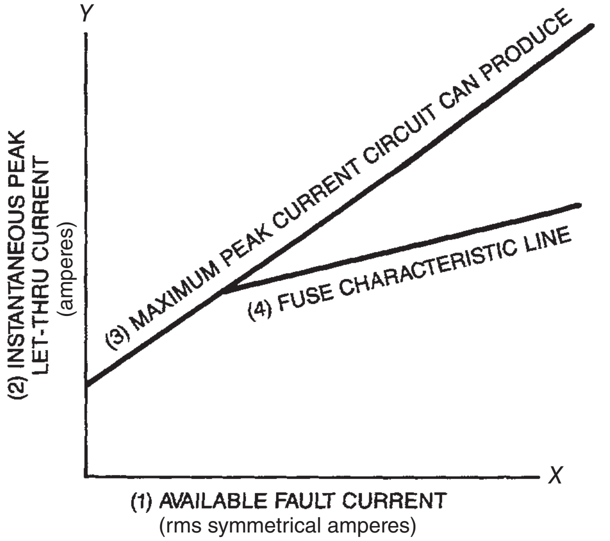

Figure 2-8 **I_p data—peak let-thru graph.** *(Courtesy of Ferraz Shawmut.)*

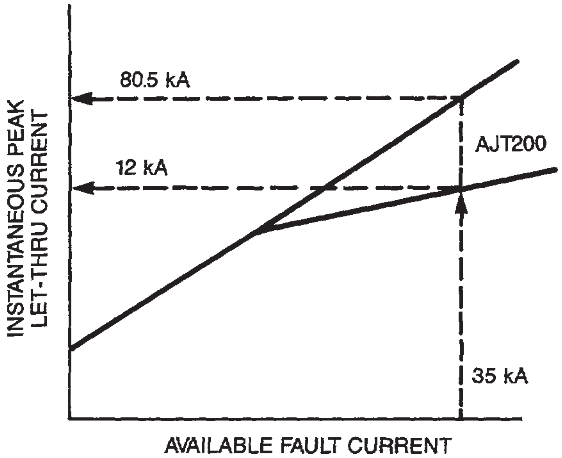

Figure 2-9 **Use of a peak let-thru graph.** *(Courtesy of Ferraz Shawmut.)*

2.828 × (rms available) in a circuit in which the impedance is all reactance with no resistance. In reality all circuits include some resistance, and the multiplier has been chosen as a practical unit.

The I_p value is relatively useful in determining the magnitude of the peak current available downstream of a fuse for general purpose circuits. If the fuse limits the current to a value less than the available fault current, then all the equipment downstream of the fuse may be selected to withstand this lower value, rather than the full available fault current. The level of protection for the equipment provided by the current-limiting fuse is not complete without considering the I_p and I^2t. I_p provides the peak current value, and I^2t provides a measurement of the amount of heat energy that the fuse passes during opening.

Two fuses can have the same I_p but different total clearing times (Figure 2-10). The fuse that clears by time A will provide greater component protection than the fuse that clears in time B.

Fuse I^2t depends on both I_p and total clearing time. The I^2t passed by a given fuse depends on the characteristics of the fuse and on the applied voltage. The I^2t passed by a given fuse will decrease as the application voltage decreases. Unless otherwise stated, published I^2t values are based on AC testing. The I^2t passed by a fuse in a DC application may be higher or lower than in an AC application. The voltage available fault current and time constant of the DC circuit are the determining factors.

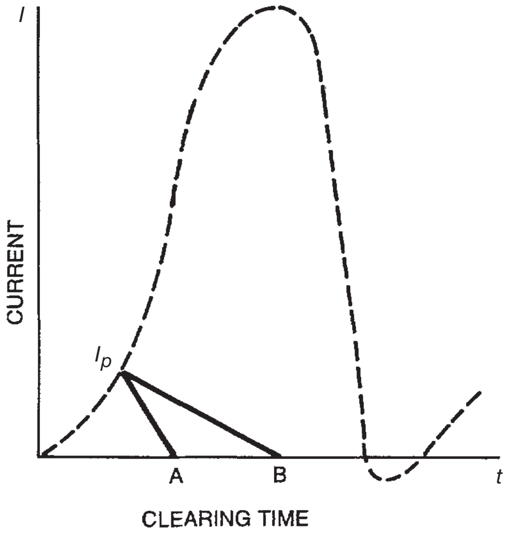

Figure 2-10 **Clearing time versus current.**
(Courtesy of Ferraz Shawmut.)

Fuse I^2t and I_p values can be used to determine the degree of protection provided for all circuit components under fault current conditions.

Manufacturers of diodes, thyristors, triacs, and cable publish I^2t withstand ratings for their products. The fuse chosen to protect these products should have a clearing I^2t that is lower than the withstand I^2t of the device being protected.

2.5 Voltage and Frequency Surges

Protecting electrical equipment against voltage surges caused by switching or lightning is very important. Even low surges that exceed the equipment insulation rating can cause the insulation to eventually weaken to the point of failure. For example, the insulation in motor windings can be stressed to the point that failure will result between windings and frame or between stator coils.

In case of a surge caused by lightning, the most severe damage occurs if there is a direct hit. Surge voltages from the lightning can also be caused by induction on the line. The voltage from a direct hit will be twenty to thirty times that caused by induction. In these cases it can be considered a high-voltage and high-frequency pulse.

A lightning arrester will limit the crest of the surge by breaking down and conducting to ground. After grounding, the arrester then returns to its initial condition of nonconducting.

Switching voltage surges are not as significant as lightning voltage surges. In most cases they will not exceed three times normal voltage. The highest overvoltage will be present when there is a ground fault in the system.

For switching voltage surges, the current-limiting fuse is used. The operating characteristic of this type of fuse is such as to interrupt in the first quarter of the cycle.

2.6 Circuit Breaker Types

The circuit breaker is available in four types:

1. Nonautomatic (circuit interrupter)
2. Thermal
3. Magnetic
4. Thermal magnetic

The *nonautomatic circuit breaker* (circuit interrupter) is used for load switching and isolation. Adding a *thermal trip unit* to the nonautomatic circuit breaker, by using a bimetallic element in each pole of the breaker, provides automatic tripping. This unit then carries the load current. When the conductors carry a current in excess of the normal load, the breaker thermal element increases in temperature as it carries the same current. This temperature increase deflects the thermal element and trips the breaker. Since the tripping action depends on temperature rise, a time lag is present. Therefore, the tripping action is not affected by momentary overloads.

To clear a circuit in case of a short circuit, a more rapid opening system is required. To achieve such a system, a *magnetic trip unit* is added either to the nonautomatic breaker or to the breaker with the thermal trip unit. The magnetic trip unit operates through a magnet that trips the breaker instantaneously on short-circuit current.

A combination of thermal and magnetic trip units is desirable. The thermal element provides inverse time tripping on overloads. The magnetic trip provides instantaneous trip on short circuits. *Molded-case* circuit breakers are available from 100 A to 2500 A. The voltage ratings are 240 V, 480 V, and 600 V with the interrupting capacity in some circuit breakers to 100,000 A. Figure 2-11 is a cutaway view of a molded-case circuit breaker.

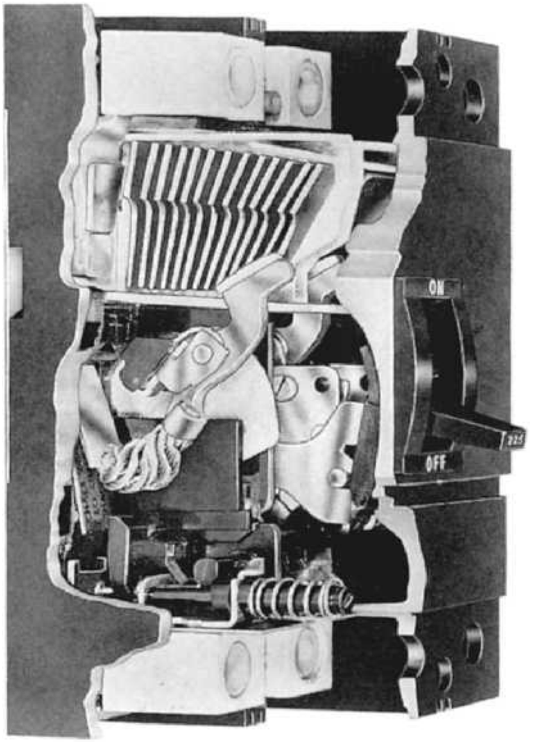

Figure 2-11 **Cutaway view of a molded-case circuit breaker.** *(Courtesy of Square D/Schneider Electric.)*

Figure 2-12 **Molded-case circuit breaker.** *(Courtesy of Rockwell Automation, Inc.)*

The fused disconnect switch and the circuit breaker are available in many types of enclosures. They can also be obtained as open types for panel mounting. Remote operators can be mounted on the door of the control cabinet and interlock mechanically with the door. The operator may also be mounted in a "dead" or stationary portion of the cabinet. The door is mechanically interlocked with the breaker trip switch. This allows the breaker to be locked open or closed with the cabinet door open.

Figure 2-12 shows a typical molded-case circuit breaker design. It incorporates, in frame ratings 150 A to 1600 A, interrupting capacities as high as 100 kA at 480 V AC (200 kA at 240 V AC) in physical sizes normally associated with standard interrupting capacity breakers.

The L-frame circuit breaker provides higher interrupting capacities and improved current-limiting capabilities compared to previous standard line circuit breakers.

Thermal magnetic and electronic trip unit designs are available. This circuit breaker is available with a fixed, thermal-adjustable magnetic trip unit that provides inverse time and instantaneous tripping. Also available is the electronic trip unit, including current-sensing circuits that provide an inverse time-delay tripping action for overload condition and either short delay or instantaneous tripping for protection against short-circuit conditions.

A push-to-trip button located on each trip unit provides a local means of manually exercising the trip mechanism.

High-strength glass-polyester bases and covers have excellent dielectric qualities and are inherently fungus proof. Cover design reduces the possibility of accidental contact with live terminals.

2.7 Programmable Motor Protection

The unit shown in Figure 2-13 is a multifunction, motor-protective relay that monitors three-phase AC current and makes separate trip and alarm decisions based on preprogrammed motor current and temperature conditions. This unit's motor protection algorithm is based on proven positive

Figure 2-13 **Motor-protective relay.** *(Courtesy of TECO-Westinghouse Electric Corporation.)*

and negative (unbalance) sequence current sampling and true rms calculations. (An algorithm is a special set of rules or instructions that perform a specific operation.)

By programming this unit with the motor's electrical characteristics (such as full-load current and locked-rotor current), the unit's algorithm will automatically tailor the optimal protection curve to the motor being monitored. No guesswork or approximation is needed in selecting a given protection curve because this unit matches the protection from an infinite family of curves to each specific motor.

Application-related motor-load problems are further addressed through the use of such functions as jam, underload, and ground fault protection.

A few of the many protective features of this unit are:

- Instantaneous overcurrent trip level and start delay
- Instantaneous overcurrent disable setting
- Locked-rotor current
- Maximum allowable stall time
- Ultimate trip current level
- I^2t alarm level
- Zero-sequence ground fault trip level with start and run delays

2.8 Electrical Metering and Voltage Protection

The unit shown in Figure 2-14 is a microprocessor-based monitoring and protective device. It provides complete electrical metering and affords system voltage protection. In one compact, standard package this unit provides an alternative to individually mounted and wired ammeters, voltmeters, ammeter and voltmeter switches, wattmeters, watthour meters, and more. Its protection features include:

- *Phase loss*. Voltage phase loss occurs if less than 50% of the nominal line voltage is detected. Current phase loss occurs if the smallest phase current is less than 1/16 of the largest phase current. (It updates itself twice per second and all other protection functions once per second.)
- *Phase unbalance*. It occurs if the maximum deviation between any two phases exceeds the amount of unbalance as a percent of nominal line voltage preset by dual in-line package (DIP) switches. Range: 5% to 40% (5% increments).
- *Phase reversal*. It occurs if any two phases become reversed for more than 1 second.
- *Overvoltage*. DIP switch setting as a percent of nominal line voltage. Range: 105% to140% (5% increments).

Figure 2-14 **Electric metering and voltage protection.** *(Courtesy of TECO-Westinghouse Electric Corporation.)*

- *Undervoltage*. DIP switch setting as a percent of nominal line voltage. Range: 95% to 60% (5% increments).
- *Delay*. It allows existence of overvoltage, undervoltage, or voltage unbalance before an alarm or trip occurs. Range: 0 to 8 seconds (1 second increments).

2.9 Selecting Protective Devices

The important factors to consider when selecting protective devices are:

- Size (current rating)
- Whether a time lag is required
- Interrupting capacity
- Ambient temperature where the device is to be located
- Voltage rating
- Number of poles
- Mounting requirements
- Type of operator
- Enclosure, if required

If the line voltage and load in a circuit are known, the size and voltage rating of the protective device can be determined. The conductor size to feed the load must be properly determined. Tables are available to supply this information (refer to Appendix E).

The actual sizing of the protective device should come from sources such as the National Fire Protection Association (NFPA), the National Electrical Code (NEC), and the NFPA-79 Electrical Standard for Industrial Machinery. Local electrical code requirements should also be consulted. The manufacturers of protective devices can also be helpful in obtaining this information.

The problem in providing a time-lag element depends on the nature of the load. If inductive devices such as motors, motor starters, solenoids, and contactors are involved, some time lag is generally needed. Here again, the manufacturers of protective devices can help.

In selecting a protective device, you should know the available short-circuit current in your plant. The first information needed is the impedance of the transformer supplying power. This information can be read from the unit's nameplate or obtained from the manufacturer of the unit. *Impedance* is the current-limiting characteristic of a transformer and is expressed as a percent.

The impedance is used to determine the interrupting capacity of a circuit breaker or fuse employed to protect the primary of a transformer.

Example 1

Determine the minimum circuit breaker trip rating and interrupting capacity for a 10-kVA, single-phase transformer with 4% impedance. It is to be operated from a 480-VAC, 60-Hz source.

Solution:

Normal full-load current =

$$\frac{\text{Nameplate volt-amperes}}{\text{Line voltage}} = \frac{10,000}{480} = 20.8 \text{ A}$$

Maximum short-circuit amperes =

$$\frac{\text{Full-load amperes}}{4\%} = \frac{20.8}{0.04} = 520 \text{ A}$$

The breaker or fuse would have a minimum interrupting rating of 520 A at 480 VAC.

Example 2

Determine the interrupting capacity in amperes required of a circuit breaker or fuse for a 75-kVA, three-phase transformer with a primary of 480 VAC delta and secondary of 208Y/120 VAC. The transformer impedance (Z) is 5%.

Solution

If the secondary circuit is shorted, the following capacities are required:

Normal full-load current =

$$\frac{\text{Volt-amperes}}{3 \times \text{Line voltage}} = \frac{75,000 \text{ VA}}{3 \times 480} = 52 \text{ A}$$

Maximum short-circuit line current =

$$\frac{\text{Full-load amperes}}{5\%} = \frac{52}{0.05} = 1040 \text{ A}$$

The breaker or fuse would have a minimum interrupting rating of 1040 A at 480 VAC.

The ambient temperature in the location where the protective device is to be located is important. Overload protection devices can be thermally operated. Therefore, an increase in the ambient temperature can affect the trip setting of the device. In some cases, ambient temperature compensation is provided by the manufacturer in the design of the device.

Standard pole arrangements for most disconnecting devices and protective devices are two poles for single-phase lines and three poles for three-phase lines. One- and four-pole devices are also available. The multiple-pole (multipole) devices are generally ganged together with a single common operator.

Symbols for various protective and disconnecting devices are shown in Figure 2-15. By using symbols, these components can be added to power source and control source diagrams.

Figure 2-16 illustrates a complete diagram: a three-phase power source, disconnect and protection, and control transformer with protection added in the secondary circuit.

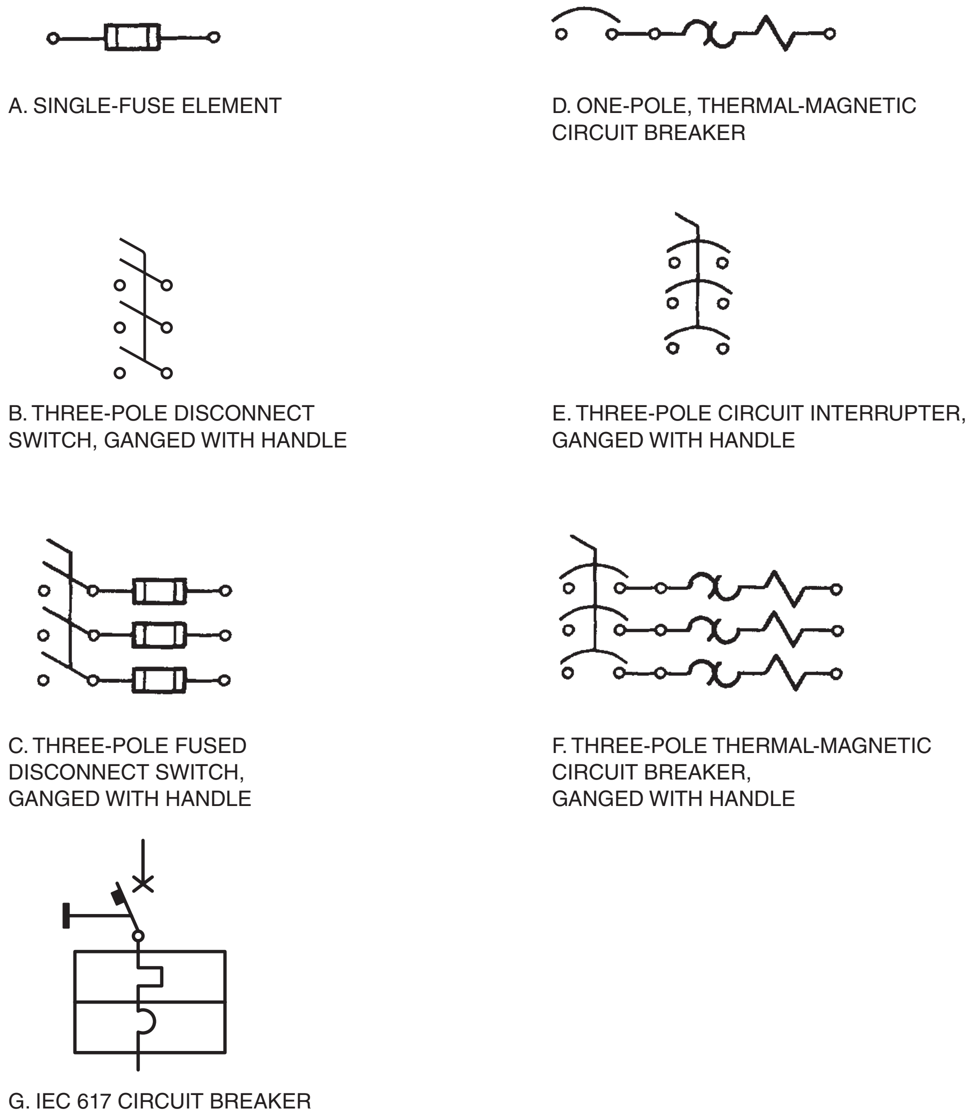

Figure 2-15 **Symbols for protective devices.**

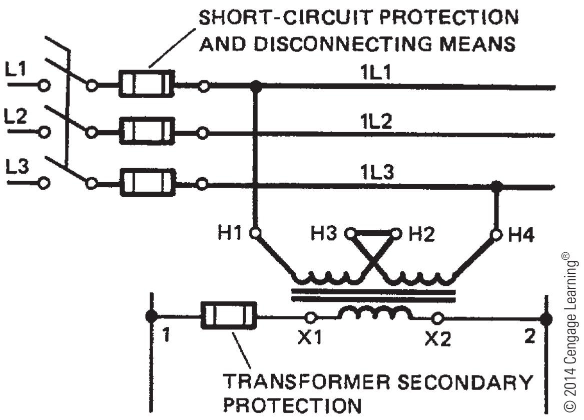

Figure 2-16 **Power and control protection. Conductors carrying load current at line voltage are denoted by heavy lines.**

2.10 Ground Fault Circuit Interrupter*

The main purpose of a fuse is to protect wiring from overheating when excessive current flows through the wire. The fuse will open to disconnect the flow of current in the circuit. A ground fault circuit interrupter (GFCI) will also safely open an electrical circuit. However, the main purpose of a GFCI is to protect a person from electrical shock.

In residential dwellings, GFCIs are required in potentially wet locations such as a bathroom, kitchen, garage, and basement. For industrial applications, GFCIs are used for receptacles that are installed external to the main control enclosure where the potential exists for any exposure to liquids such as water, oil, coolant, etc. In addition, any receptacles or cord sets used for portable equipment should have GFCI circuit protection.

GFCI circuits monitor the current flow to and from the electrical devices that are connected to the circuit. For normal operation, the incoming current is equal to the return current. If the amount of current differs by more than 5 mA (.005 A), the circuit will be interrupted quickly (25 msec) to avoid electrocution. For example, suppose a hot wire inside a tool is making contact with the metal casing. The case is now energized. Touching the case would then cause current to flow through you to ground (Figure 2-17). The additional current path causes the incoming current to no longer equal the return current. The GFCI circuit would quickly detect the difference in current and disconnect the circuit.

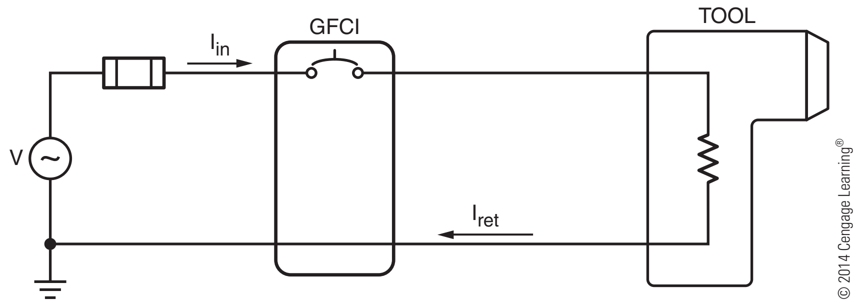

Figure 2-17A **GFCI Circuit Normal Operation ($I_{in} = I_{ret}$)**

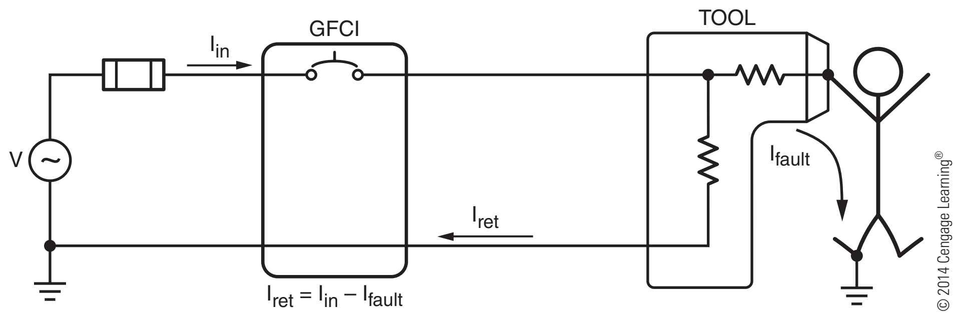

Figure 2-17B **GFCI Circuit – Fault Detected ($I_{in} \neq I_{ret}$)**

*Courtesy of the U.S. Department of Labor, http://www.dol.gov

Recommended Web Links

Students are encouraged to view the following Web sites as a supplement to the concepts presented in this textbook. Review and analyze the array of products that are available for electrical control applications. Many of these sites offer technical information that will help in converting the principles to practical applications. To view catalogs, your PC may require Adobe Acrobat Reader software.

Fuses

1. Littelfuse
   www.littelfuse.com
   Review: Education, Technical Resources, Technical Articles

Disconnect Switches

1. Hubbell Ltd.
   www.hubbell.co.uk/fuse.htm
   Review: Fused and Nonfused Disconnect Switches
2. Advance Controls, Inc.
   www.acicontrols.com
   Review: Disconnect Switches

Circuit Breakers

1. IDEC Corp.
   www.idec.com
   Review: Industrial Components, Circuit Breakers

Achievement Review

1. What two factors must be provided for in any electrical power or control system?
2. Under what conditions would you use the time-delay fuse? Give an example.
3. What are the four types of circuit breakers?
4. Under what conditions would you want to use the magnetic trip feature in a circuit breaker?
5. List at least five important factors to consider when selecting a protective device.
6. Are more than two poles available on disconnecting devices? If so, how many?
7. Draw the symbol for each of the following:
   a. Single-fuse element
   b. Three-pole fused disconnect switch, ganged with handle
   c. Three-pole circuit interrupter, ganged with handle
   d. Three-pole, thermal-magnetic circuit breaker, ganged with handle
8. What is meant by the interrupting capacity of a fuse?
9. What does quartz sand filler in a fuse provide?
   a. Increased voltage rating
   b. Effective heat transfer
   c. An inexpensive filler
10. Why is the inverse time characteristic of a fuse important?
    a. The fuse cost is reduced.
    b. It increases the interrupting capacity.
    c. It parallels the characteristics of conductors, motors, transformers, and other electrical apparatus.
11. What are two measures of the degree of current limitations provided by a fuse?
12. How are I^2t values of a fuse derived?
13. Under what condition will the highest overvoltage occur from a surge caused by switching?
14. Explain how a lightning arrester protects electrical equipment for a surge current caused by lightning.
15. Determine the interrupting capacity in amperes required of a circuit breaker or fuse for a 15-kVA, single-phase transformer with 4% impedance, to be operated from a 480-V, 60-Hz source.

3
CHAPTER

Control Units for Switching and Communication

OBJECTIVES

After studying this chapter, you should be able to:

- Describe two methods of mounting push-button switch units.
- List four types of operators for the push-button switch.
- Explain why different colors are used for push-button switch operators.
- Draw the symbols for push-button switch units with (1) flush or extended head, (2) mushroom head, and (3) maintained contact attachment.
- List several arrangements available for selector switches.
- Draw the symbol for the selector switch.
- Draw the symbol for the foot switch.
- Discuss the advantages of push-to-test pilot lights.
- Draw the symbol and detailed circuit for the push-to-test pilot light.
- Explain the meaning of the letter in the pilot light.
- Draw basic circuits using selector switches, push-buttons, and pilot lights.
- Discuss the use of annunciators to obtain process information.
- Explain the use of the LED.
- Discuss how the environment may affect the design of a membrane switch.

3.1 Oil-Tight Units

Almost all push-button switches, selector switches, and pilot lights offered to industry today are oil-tight units. Since this text is concerned with industrial electrical control, only oil-tight types of units are discussed.

3.2 Push-Button Switches

Switches generally consist of two parts: the contact unit and the operator. This composition allows for many combinations that cover almost every application required.

The *normal* state of a switch is an important concept to understand. The symbol used to identify a device on an electrical drawing will show the component in its normal state. Therefore, to comprehend how a circuit functions, a thorough understanding of this concept must be mastered.

The normal state of a switch shows the contact configuration when the device is NOT being actuated (being acted upon by an external force). A discrete device can only have two states—*on* or *off*. Since a switch is a discrete device, each individual contact will either be *normally open* (NO) or *normally closed* (NC).

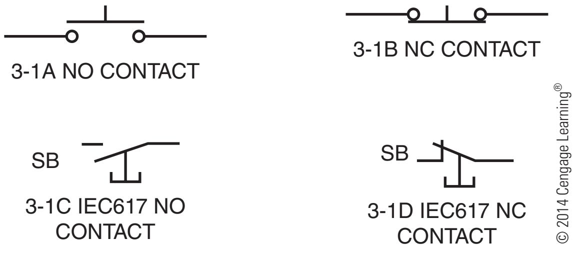

Figure 3-1 **Electrical symbols for push buttons.**

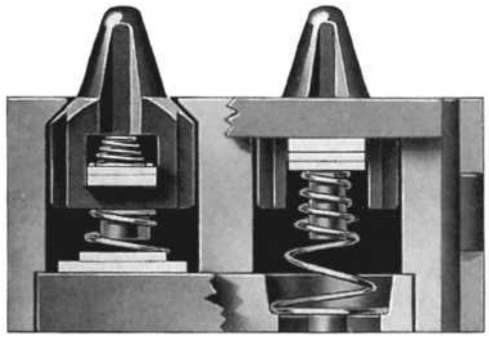

Figure 3-2 **Standard double-circuit contact block.** *(Courtesy of Eaton Corporation.)*

When the push-button is pressed (actuated) every contact associated with the device will transition states. The NO contact will close and the NC contact will open. When the push-button is released the contacts will return to their normal state. It is important to distinguish between a contact transitioning and the normal state of the contact. For example, an NO contact will close when the device is *actuated* but the contact will not become an NC contact. Likewise, an NC contact will open when the device is actuated but the contact will not become an NO contact.

The circuit symbols for a push-button device are shown in Figure 3-1. Remember that for electricity to flow in a circuit there must be a complete path throughout the circuit (commonly referred to as having continuity). Therefore, when the switch is not being actuated (or pressed), Figure 3-1A shows the NO contact as being an open in the circuit. Electricity cannot pass through the push-button device. When the push-button is pressed the contact will close and provide a path for electricity to flow.

Figure 3-1B shows the circuit symbol for a NC contact. This contact configuration allows a path for continuity in its normal state. However, when the push-button is pressed this contact will open and stop the flow of electricity through the push-button device.

Figure 3-2 shows a typical contact block. In the deactivated condition, the spring is released and the contacts are in their normal state of operation. When the push-button is pressed the spring compresses and the contacts transition states. When the push-button is released, the spring will push on the actuating bar and return the contacts to their normal state.

Push-buttons may be purchased with different contact configurations. The number and type of contacts will be determined by the part number of the device. Additional contact blocks may typically be purchased to add on to existing contact assemblies. One contact block will consist of one NO contact, one NC contact, or a combination of both contacts. Figure 3-3 shows typical contact blocks. The maximum number of contact blocks that may exist on a device will vary by manufacturer and the actual component. Product specifications should be verified when modifying existing assemblies.

Figure 3-3 **Contact blocks.** *(Courtesy of Square D/Schneider Electric.)*

The contacts will generally be rated for use in an AC or DC circuit. The inrush current and the continuous current ratings for the contacts will depend on whether the device is connected to an AC or a DC circuit. The product specifications for the device should be consulted when installing a new design or when replacing a component with another device.

In some cases, the contact block is *base-mounted* in the push-button enclosure. Thus, the units can be prewired before the cover with the operators is put in place. This method also eliminates cabling conductors to the cover.

The typical method is *panel mounting*. The base of the operator, with the contact block attached, is mounted through an opening in the cover or door of an enclosure. The push-button is then secured in its place by a threaded ring installed from the front of the panel. The ring is part of the operator assembly. Later in the text it will be shown that this arrangement has the advantage of providing a space for a terminal block installation in the base of the enclosure. Thus, all connecting circuits can be terminated at an easily accessible checkpoint.

There are slight differences in the way manufacturers machine mounting holes. Also, push-button devices are available in different sizes. The standard sizes are 30 mm for NEMA devices and 16 mm or 22 mm for IEC components. Therefore, modifications may be required when substituting one unit for another.

Figure 3-4 shows a cutaway section of a typical operator. Many types of operators are available to suit almost any application. They include:

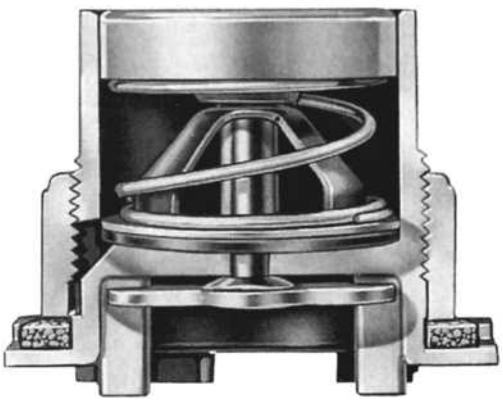

Figure 3-4 **Standard-duty, flush button operator.** *(Courtesy of Eaton Corporation.)*

- Recessed button (Figure 3-5A)
- Mushroom head (Figure 3-5B)
- Illuminated push-pull (Figure 3-5C)
- Keylock (Figure 3-5D)

Flush head operators are used to start a motion or energize a circuit. Because of the flush (or recessed) head on the operator, the switch cannot be accidentally pressed; thus requiring an intentional action to initiate any motion.

Figure 3-5A **Recessed button push-button unit.** *(Courtesy of General Electric Company, General Purpose Control, Bloomington, IL.)*

Figure 3-5B **Mushroom head push-button unit.** *(Courtesy of General Electric Company, General Purpose Control, Bloomington, IL.)*

Figure 3-5C **Illuminated push-pull unit.** *(Courtesy of General Electric Company, General Purpose Control, Bloomington, IL.)*

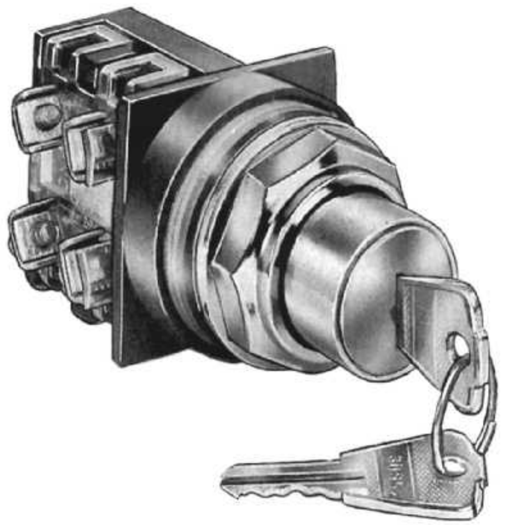

Figure 3-5D **Cylinder lock push-button unit.** *(Courtesy of General Electric Company, General Purpose Control, Bloomington, IL.)*

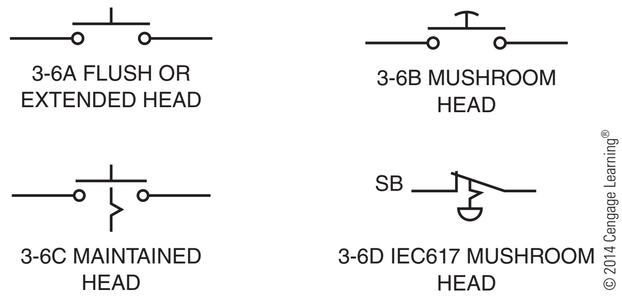

Figure 3-6 **Symbols for push-button units with various operator heads (shown NO).**

Extended head operators are used to stop a motion or de-energize a circuit. The stop button on a piece of equipment should be readily available to stop the machine. Therefore, mushroom type operators may be used to perform emergency stop functions. The placement of extended or mushroom head push-buttons should be taken into consideration to avoid nuisance or unintentional stopping of the equipment. However, this placement should not jeopardize the ability of the person running the machine to have easy access to the device in the event of an emergency.

Illuminated push-buttons will turn on a light when the button is pressed to provide a clear indication that the button is pressed or the circuit has been activated. The push-pull push-button does not utilize a spring to return the contacts to their normal state when the push-button is released. Instead, a maintained or detented type of operation is utilized. When this type of push-button is pressed the operator will remain in the pressed position until the push-button is physical pulled back out to its normal operating position. A twisting motion instead of a pulling force may be used to return the operating head to its normal state. This style of operator is referred to as a push-pull twist release.

Figure 3-6 shows the symbol used to identify the different types of operating heads. All contact configurations are shown with one NO contact to avoid any confusion.

A keylock push-button may be used to prevent the operation of the device by untrained personnel. The key must be inserted into the device to operate the push-button.

Color designation is an important factor in push-button switch operators. It not only provides an attractive panel but, more importantly, it lends itself to safety. Quick identification is important. Certain functions become associated with a specific color. Standards have been developed that specify certain colors for particular functions. For example, in the machine tool industry, the colors red, yellow, and black are assigned the following functions:

Red: Stop, Emergency Stop

Yellow: Return, Emergency Return

Black: Start Motors, Cycle Start, Initiate Motion

Figure 3-7 shows the symbol for a push-button with multiple contact blocks. In this example, one mushroom head operator is used to switch three contacts (two NC and one NO). The contacts are shown as connected to the same device through the use of a dashed line. Also, note the use of wording added to the drawing to provide

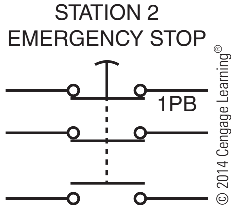

Figure 3-7 **Push-button with multiple contacts.**