6TH EDITION

INDUSTRIAL MOTOR CONTROL

Stephen L. Herman

INDUSTRIAL MOTOR CONTROL

Sixth Edition

Stephen L. Herman

DELMAR
CENGAGE Learning™

Australia • Brazil • Japan • Korea • Mexico • Singapore • Spain • United Kingdom • United States

DELMAR
CENGAGE Learning™

Industrial Motor Control,
6th Edition
Stephen L. Herman

Vice President, Career and Professional Editorial: Dave Garza

Director of Learning Solutions: Sandy Clark

Managing Editor: Larry Main

Senior Product Manager: John Fisher

Senior Editorial Assistant: Dawn Daugherty

Vice President, Career and Professional Marketing: Jennifer McAvey

Marketing Manager: Deborah S. Yarnell

Marketing Manager: Jimmy Stephens

Marketing Coordinator: Mark Pierro

Production Director: Wendy Troeger

Production Manager: Mark Bernard

Content Project Manager: Christopher Chien

Art Director: David Arsenault

Technology Project Manager: Christopher Catalina

Production Technology Analyst: Thomas Stover

Printed in Canada
1 2 3 4 5 XX 10 09 08

Library of Congress Control Number: 2008935164

ISBN-13: 978-1-4354-4239-9
ISBN-10: 1-4354-4239-3

Delmar
5 Maxwell Drive
Clifton Park, NY 12065-2919
USA

Cengage Learning is a leading provider of customized learning solutions with office locations around the globe, including Singapore, the United Kingdom, Australia, Mexico, Brazil and Japan. Locate your local office at:
international.cengage.com/region

Cengage Learning products are represented in Canada by Nelson Education, Ltd.

For your lifelong learning solutions, visit **delmar.cengage.com**
Visit our corporate website at **cengage.com.**

Notice to the Reader

Publisher does not warrant or guarantee any of the products described herein or perform any independent analysis in connection with any of the product information contained herein. Publisher does not assume, and expressly disclaims, any obligation to obtain and include information other than that provided to it by the manufacturer. The reader is expressly warned to consider and adopt all safety precautions that might be indicated by the activities described herein and to avoid all potential hazards. By following the instructions contained herein, the reader willingly assumes all risks in connection with such instructions. The publisher makes no representations or warranties of any kind, including but not limited to, the warranties of fitness for particular purpose or merchantability, nor are any such representations implied with respect to the material set forth herein, and the publisher takes no responsibility with respect to such material. The publisher shall not be liable for any special, consequential, or exemplary damages resulting, in whole or part, from the readers' use of, or reliance upon, this material.

CONTENTS

This page intentionally left blank

PREFACE

The amount of knowledge an electrician must possess to be able to install and troubleshoot control systems in today's industry has increased dramatically in recent years. A continuous influx of improved control components allows engineers and electricians to design and install even more sophisticated and complex control systems. *Industrial Motor Control* presents the solid-state devices common in an industrial environment. This is intended to help the student understand how many of the control components operate, such as solid-state relays, rectifiers, SCR drives for direct current motors, variable frequency drives for alternating current motors, and the inputs and outputs of programmable controllers. Although most electricians do not troubleshoot circuits on a component level, a basic knowledge of how these electronic devices operate is necessary in understanding how various control components perform their functions.

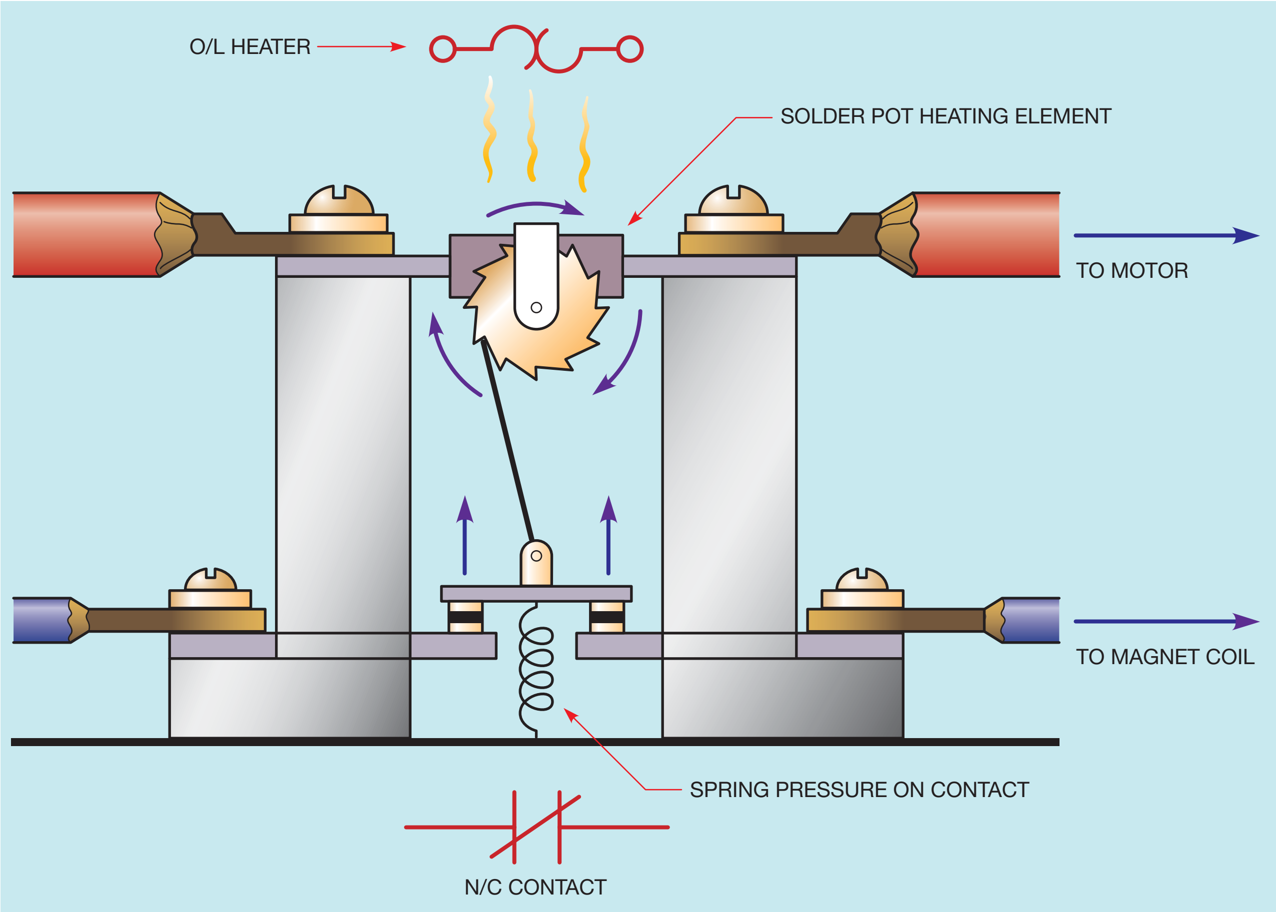
The influx of programmable logic controllers into industry has bridged the gap between the responsibilities of the electrician and the instrumentation technician. Many industries now insist that electricians and instrumentation technicians be cross-trained so they can work more closely together. *Industrial Motor Control* helps fulfill this requirement. Many of the common control devices found throughout industry are also discussed from a basic instrumentation standpoint by providing information on analog sensing of pressure, flow, temperature, and liquid level.

The sixth edition of *Industrial Motor Control* is the most comprehensive revision since the text was first published over twenty years ago. The chapter on motor installation has been updated to reflect changes in the 2008 *National Electrical Code®*, and a new unit that instructs students in basic troubleshooting techniques has been included. The chapters have been rearranged to present the information in a different order. This rearrangement was done to reflect recommendations made by instructors that use the text.

Industrial Motor Control presents many examples of control logic and gives the student step-by-step instructions on how these circuits operate. There are examples of how ladder diagrams can be converted into wiring diagrams. This is the basis for understanding how to connect control circuits in the field. The concept of how motor control schematics are numbered is thoroughly discussed. Students are also given a set of conditions that a circuit must meet, and then that circuit is developed in a step-by-step procedure. Learning to design control circuits is a very effective means of learning how circuit logic works. It is impossible to effectively troubleshoot a control circuit if you don't understand the logic of what the circuit is intended to do.

Industrial Motor Control is based on the results of extensive research into content, organization, and effective learning styles. Short chapters help the student to completely understand the content before progressing to the next subject, and they permit the instructor to choose the order of presentation. Each chapter contains extensive illustrations, which have been designed for maximum learning. Color is used to help the student understand exactly what is being conveyed in a particular illustration.

Industrial Motor Control, Sixth Edition, is a complete learning package that includes this comprehensive textbook, a hands-on Lab Manual, an Interactive Companion on CD, an *Instructor's Guide,* and an *Instructor's e-resource*. The Lab Manual offers practical hands-on circuits to be wired by the student. Each of the labs uses standard components that most electrical labora tories either have on hand or can obtain without difficulty. The Lab Manual lets students learn by doing.



Sample Illustration

New for the Sixth Edition

- Rearrangement of chapters to reflect the recommendations made by instructors that used the text.
- A new chapter on troubleshooting techniques.
- The chapter on motor installation has been updated in accord with the 2008 *National Electrical Code*®.
- Many of the chapters have been rewritten in an effort to make the material more understandable for beginning students.
- Many of the drawings and illustrations have been updated and improved.

The Interactive Companion CD, which can be found in a sleeve on the inside back cover of this textbook, includes applications and explanations of the concepts developed in the textbook. This exciting CD includes outstanding graphics, animations, and video segments and provides students with reinforcement of important concepts. The text of the licensing agreement for this software, along with instructions for installing and operating it, can be found on the pages following the index.

The *Instructor's Guide* includes the learning objectives from the textbook for the instructor's convenience, as well as a bank of test questions, and the answers to all of the test questions and textbook Chapter Review Questions.

The new *Instructor's e.resource* is an invaluable addition to the Industrial Motor Control package. It includes PowerPoint slides for each unit (a total of nearly 500), nearly 1,000 Computerized Test Bank questions, and an image library containing hundreds of full-color images in electronic format.

Content Highlights

- The most commonly used solid-state devices are thoroughly described, in terms of both operation and typical application.

- Information on analog devices that sense pressure, flow, and temperature has been added to help bridge the gap between the industrial electrician and the instrumentation technician.
- DC and AC motor theory is included so students will understand the effects of control circuits on motor characteristics.
- The text covers the operating characteristics of stepping motors when connected to either DC or AC voltage.
- Detailed instructions are given for connecting motors in the field, including the size of conductors, overload relays, and fuses or circuit breakers. All calculations are taken from the *National Electrical Code*®.
- The principles of digital logic are described in sufficient detail for students to understand programmable controllers and prepare basic programs.
- A step-by-step testing procedure for electronic components is provided in the Appendix.
- Starting methods for hermetically sealed single-phase motors includes the hot-wire relay, solid-state starting relay, current relay, and potential relay.
- Extensive coverage on overload relays and methods of protecting large horsepower motors.
- Extensive coverage of variable frequency drives.
- Extensive coverage of solid-state control devices in addition to electromagnetic devices.
- Basic electronics is not a prerequisite for studying this text. Sufficient solid-state theory is presented to enable the student to understand and apply the concepts discussed.

About the Author

Stephen L. Herman has been both a teacher of industrial electricity and an industrial electrician for many years. He obtained formal training at Catawba Valley Technical College in Hickory, North Carolina, and at numerous seminars and manufacturers' schools. He also attended Stephen F. Austin University in Nacogdoches, Texas, and earned an Associates Degree in Electrical Technology from Lee College in Baytown, Texas. He was employed as an electrical installation and maintenance instructor at Randolph Technical College in Asheboro, North Carolina, for nine years. Mr. Herman then returned to industry for a period of time before becoming the lead instructor for the Electrical Technology Program at Lee College in Baytown, Texas. He retired from Lee College with twenty years of service and presently lives with his wife in Pittsburg, Texas. Mr. Herman is a recipient of the Excellence in Teaching Award presented by the Halliburton Education Foundation.

Acknowledgments

The following individuals provided detailed critiques of the manuscript and offered valuable suggestions for improvement of the sixth edition of this text:

Salvador Aranda
Savannah Technical College
5717 White Bluff Road
Savannah, GA 31405-5521

Richard Cutbirth
Electrical JATC
620 Legion Way
Las Vegas, NV 89110

Harry Katz
South Texas Electrical JATC
1223 East Euclid
San Antonio, TX 78212

Rick Hecklinger
Toledo Electrical JATC
803 Lime City Road
Rossford, OH 43460

Ivan Nickerson
North Platte Community College
1101 Halligan Drive
North Platte, NE 69101

Alan Bowden
Central Westmoreland Area Vocational School
Arona Road
New Stanton, PA 15672

The following companies provided the photographs used in this text:

Allen-Bradley Company
1201 South Second Street
Milwaukee, WI 53204

Automatic Switch Company
50-A Hanover Road
Florham Park, NJ 07932

Eaton Corporation
Cutler-Hammer Products
4201 North 27th Street
Milwaukee, WI 53216

Eagle Signal Controls
A Division of Gulf & Western Manufacturing Company
736 Federal Street
Davenport, IA 52803

Emerson Electric Company
Industrial Controls Division
3300 South Standard Street
Santa Ana, CA 92702

Furnas Electric Company
1007 McKee Street
Batavia, IL 60510

GE Fanuc Automation North America, Inc.
P.O. Box 8106
Charlottesville, VA 22906

General Electric Company
101 Merritt 7, P.O. Box 5900
Norwalk, CT 06856

Hevi-Duty Electric
A Division of General Signal Corporation
P.O. Box 268, Highway 17 South
Goldsboro, NC 27530

International Rectifier
Semiconductor Division
233 Kansas
El Segundo, CA 90245

McDonnell & Miller, ITT
3500 N. Spaulding Avenue
Chicago, IL 60618

McGraw-Edison Company
Electric Machinery
800 Central Avenue
Minneapolis, MN 55413

Micro Switch
A Honeywell Division
11 West Spring Street
Freeport, IL 61032

RCA
Solid State Division
Route 202
Somerville, NJ 08876

Ramsey Controls, Inc.
335 Route 17
Mahwah, NJ 07430

Reliance Electric
24701 Euclid Avenue
Cleveland, OH 44117

Sparling Instruments, Co. Inc.
4097 North Temple City Boulevard
El Monte, CA 91734

Square D Company
P.O. Box 472
Milwaukee, WI 53201

The Superior Electric Company
Bristol, CT 06010

Struthers-Dunn, Inc.
Systems Division
4140 Utica Ridge Road
P.O. Box 1327
Bettendorf, IA 52722-1327

Tektronix, Inc.
P.O. Box 500
Beaverton, OR 97077

Telemecanique, Inc.
2525 S. Clearbrook Drive
Arlington Heights, IL 60005

Turck Inc.
3000 Campus Drive
Plymouth, MN 55441

U.S. Electrical Motors Division
Emerson Electric Company
125 Old Gate Lane
Milford, CT 06460

Vactec, Inc.
10900 Page Boulevard
St. Louis, MO 63132

Warner Electric Brake & Clutch Company
449 Gardner Street
South Beloit, IL 61080

The following individuals provided detailed review comments and suggestions for this edition of the text:

Bob Keller
Dayton Electrical JATC
Green County Career Center
Xenia, OH 45385

Madison Burnett
Assistant Training Director/Instructor
Electrical JATC of Southern Nevada
Las Vegas, Nevada 89110

Richard Paredes
Training Instructor
IBEW Local Union 164
Jersey City, NJ

This page intentionally left blank

CHAPTER 1

GENERAL PRINCIPLES OF MOTOR CONTROL

OBJECTIVES

After studying this chapter, the student will be able to:

- State the purpose and general principles of motor control.
- Discuss the differences between manual and automatic motor control.
- Discuss considerations when installing motors or control equipment.
- Discuss the basic functions of a control system.
- Discuss surge protection for control systems.

The term "motor control" can have very broad meanings. It can mean anything from a simple toggle switch intended to turn a motor on or off (Figure 1–1) to an extremely complex system intended to control several motors, with literally hundreds of sensing devices that govern the operation of the circuit. The electrician working in industry should be able to install different types of motors and the controls necessary to control and protect them and also to troubleshoot systems when they fail.

Installation of Motors and Control Equipment

When installing electric motors and equipment, several factors should be considered. When a machine is installed, the motor, machine, and controls are all interrelated and must be considered as a unit. Some machines will have the motor or motors and control equipment mounted on the machine itself when it is delivered from the manufacturer, and the electrician's job in this case is generally to make a simple power connection to the machine. A machine of this type is shown in Figure 1–2. Other types of machines require separately mounted motors that are connected by belts, gears, or chains. Some machines also require the connection of pilot sensing devices such as photo switches, limit switches, pressure switches, and so on. Regardless of how easy or complex the connection is, several factors must be considered.

Power Source

One of the main considerations when installing a machine is the power source. Does the machine require single-phase or three-phase power to operate?

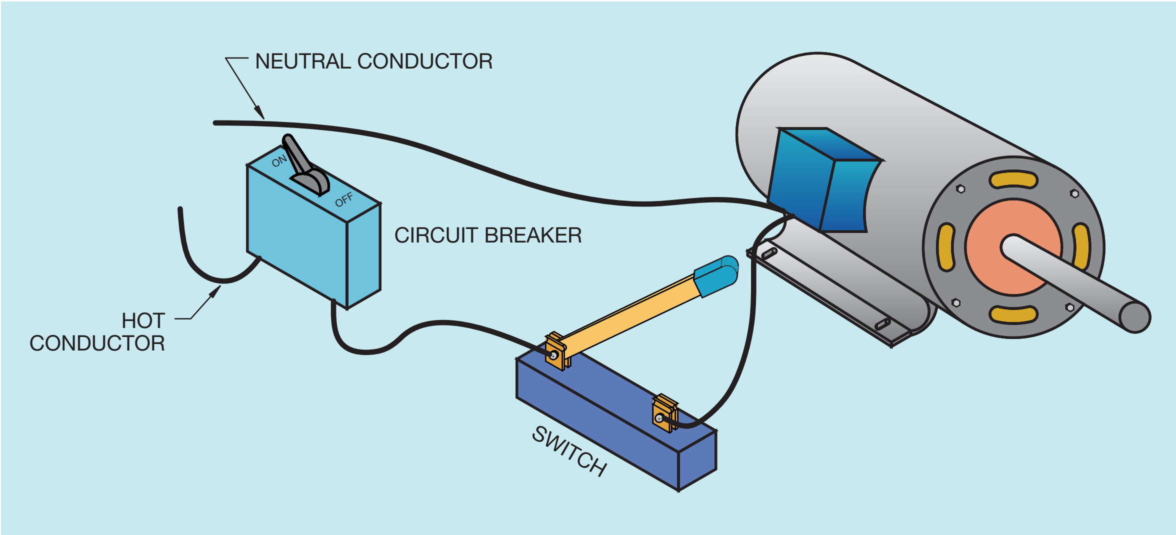


Figure 1–1 Motor controlled by a simple toggle switch. (Source: Delmar/Cengage Learning.)

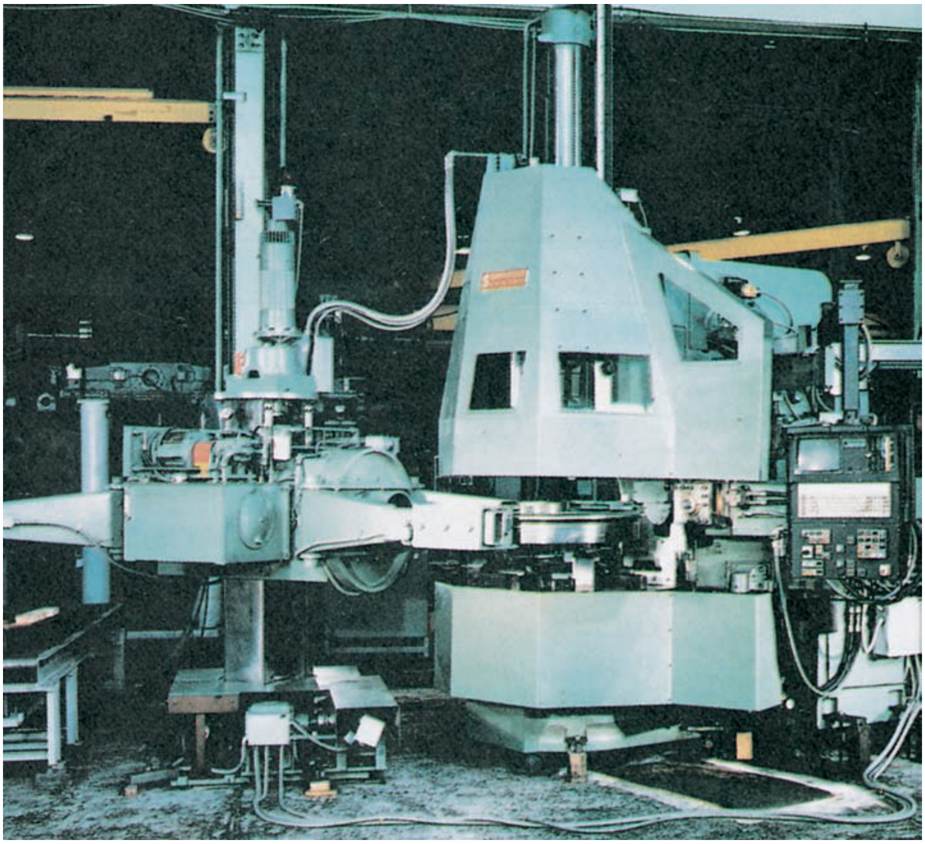


Figure 1–2 This machine was delivered with self-contained motors and controls. (Courtesy of Simmons Machine Tool Co.)

What is the horsepower of the motor or motors to be connected? What is the amount of in-rush current that can be expected when the motor starts? Will the motor require some type of reduced voltage starter to limit in-rush current? Is the existing power supply capable of handling the power requirement of the machine or will it be necessary to install a new power system?

The availability of power can vary greatly from one area of the country to another. Power companies that supply power to heavily industrialized areas can generally permit larger motors to be started across-the-line than companies that supply power to areas that have light industrial needs. In some areas, the power company may permit a motor of several thousand horsepower to be started across-the-line, but in other areas the power company may require a reduced voltage starter for motors rated no more than one hundred horsepower.

Motor Connections

When connecting motors, several factors should be considered, such as: horsepower, service factor (SF), marked temperature rise, voltage, full load current rating, and National Electrical Manufacturers Association (NEMA) Code letter. This information is found on the motor nameplate. The conductor size, fuse or circuit breaker size, and overload size are generally determined using the National Electrical Code (NEC®) and/or local codes. It should be noted that local codes generally supersede the National Electrical Code and should be followed when they apply. Motor installation based on the NEC® will be covered in this text.

Motor Type

The type of motor best suited to operate a particular piece of equipment can be different for different types of machines. Machines that employ gears generally require a motor that can start at reduced speed and increase speed gradually. Wound rotor induction motors or squirrel cage motors controlled by variable frequency drives are generally excellent choices for this requirement. Machines that require a long starting period, such as machines that operate large inertia loads such as flywheels or centrifuges, require a motor with high starting torque and relatively low starting current. Squirrel cage motors with a type A rotor or synchronous motors are a good choice for these types of loads. Synchronous motors have an advantage in that they can provide power factor correction for themselves or other inductive loads connected to the same power line.

Squirrel cage motors controlled by variable frequency drives or direct current motors can be employed to power machines that require variable speed. Squirrel cage induction motors are used to power most of the machines throughout industry. These motors are rugged and have a proven record of service unsurpassed by any other type of power source.

Controller Type

The type of controller can vary depending on the requirements of the motor. Motor starters can be divided into two major classifications: NEMA (National Electrical Manufacturers Association) and IEC (International Electrotechnical Commission). NEMA is an American organization that rates electrical components. NEMA starter sizes range from 00 through 8. A NEMA size 00 starter is rated to control a 2 horsepower motor connected to a 460 volt three-phase power supply. A size 8 starter will control a 900 horsepower motor connected to a 460 volt three-phase power source. IEC starter sizes range from size A through size Z. Size A starters are rated to control a 3 horsepower motor connected to a 460 volt three-phase source. Size Z starters are rated to control a 900 horsepower motor connected to a 460 volt source. It should be noted that the contact size for an IEC starter is smaller than for a NEMA starter of the same rating. It is common practice when using IEC starters to increase the listed size by one or two sizes to compensate for the difference in contact size.

Environment

Another consideration is the type of environment in which the motor and control system operates. Can the controls be housed in a general purpose enclosure similar to the one shown in Figure 1–3, or is the system subject to moisture or dust? Are the motor and controls

Figure 1–3 General purpose enclosure (NEMA 1).

Figure 1–4 Explosion proof enclosure (NEMA 7).

Figure 1–5 Combination motor starter with circuit breaker, disconnect switch, starter, and control transformer. (Courtesy of Square D Company.)

to be operated in a hazardous area that requires explosion proof enclosures similar to that shown in Figure 1–4? Some locations may contain corrosive vapor or liquid, or extremes of temperature. All of these conditions should be considered when selecting motors and control components. Another type of starter commonly found in industry is the combination starter (Figure 1–5). The combination starter contains the disconnecting means, fuses or circuit breaker, starter, and control transformer. They may also have a set of push buttons or switches mounted on the front panel to control the motor.

Codes and Standards

Another important consideration is the safety of the operator or persons that work around the machine. In 1970, the Occupational Safety and Health Act (OSHA) was established. In general, OSHA requires employers to provide an environment free of recognized hazards that are likely to cause serious injury.

Another organization that exhibits much influence on the electrical field is Underwriters Laboratories (UL). Underwriters Laboratories was established by insurance companies in an effort to reduce the number of fires caused by electrical equipment. They test equipment to determine if it is safe under different conditions. Approved equipment is listed in an annual publication that is kept current with bimonthly supplements.

Another previously mentioned organization is the *National Electrical Code*. The *NEC*® is actually part of the National Fire Protection Association. They establish rules and specifications for the installation of electrical equipment. The National Electrical Code is not a law unless it is made law by a local authority.

Two other organizations that have great influence on control equipment are NEMA and IEC. Both of these organizations will be discussed later in the text.

Types of Control Systems

Motor control systems can be divided into three major types: manual, semiautomatic, and automatic. Manual controls are characterized by the fact that the operator must go to the location of the controller to initiate any change in the state of the control system. Manual controllers are generally very simple devices that connect the motor directly to the line. They may or may not provide overload protection or low voltage release. Manual control may be accomplished by simply connecting a switch in series with a motor (Figure 1–1).

Semiautomatic control is characterized by the use of push buttons, limit switches, pressure switches, and other sensing devices to control the operation of a magnetic contactor or starter. The starter actually connects the motor to the line, and the push buttons and other pilot devices control the coil of the starter. This permits the actual control panel to be located away from the motor or starter. The operator must still initiate certain actions, such as starting and stopping, but does not have to go to the location of the motor or starter to perform the action. A typical control panel is shown in Figure 1–6. A schematic and wiring diagram of a start-stop push-button station is shown in Figure 1–7. A schematic diagram shows components in their electrical sequence without regard for physical location. A wiring diagram is basically a pictorial representation of the control components with connecting wires. Although the two circuits shown in Figure 1–7 look different, electrically they are the same.

Automatic control is very similar to semiautomatic control in that pilot sensing devices are employed to operate a magnetic contactor or starter that actually controls the motor. With automatic control, however, an operator does not have to initiate certain actions. Once the control conditions have been set, the system will continue to operate on its own. A good example of an automatic control system is the heating and cooling system found in many homes. Once the thermostat has been set to the desired temperature, the heating or cooling system operates without further attention from the home owner. The control circuit contains sensing devices that automatically shut the system down in the event of an unsafe condition such as motor overload, excessive current, no pilot light or ignition in gas heating systems, and so on.

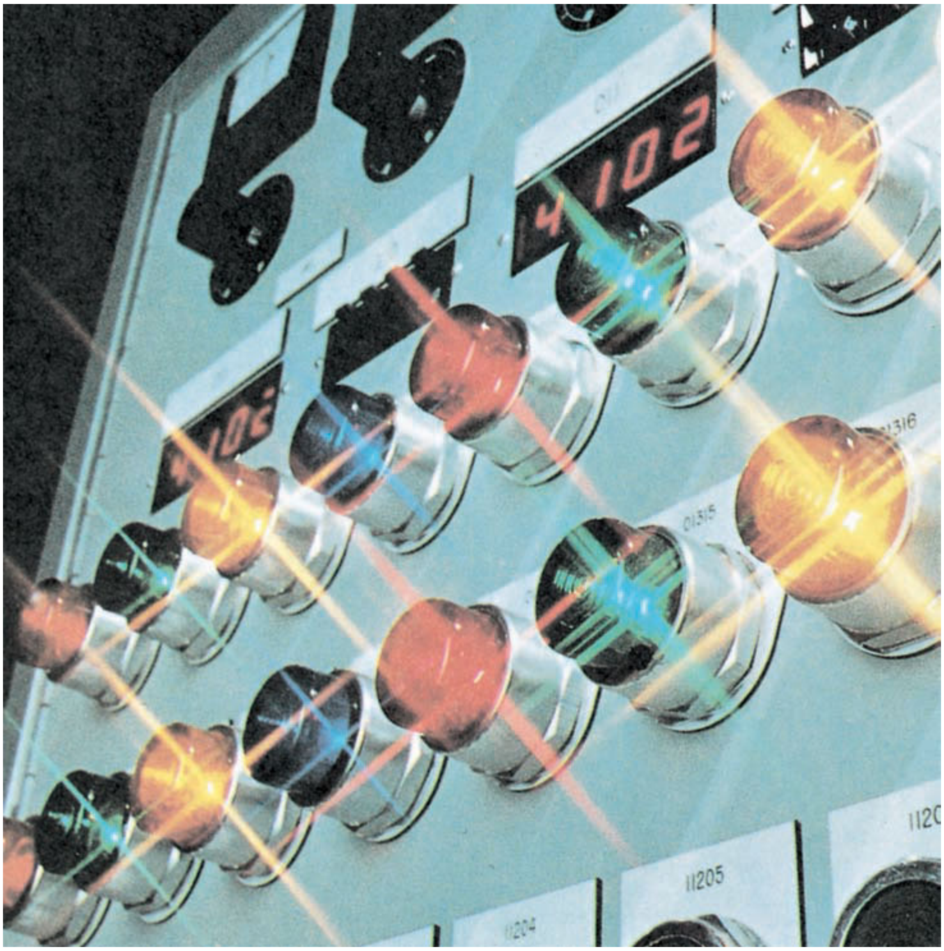


Figure 1–6 Typical push-button control center. (Courtesy Allen-Bradley, a Rockwell International Company.)

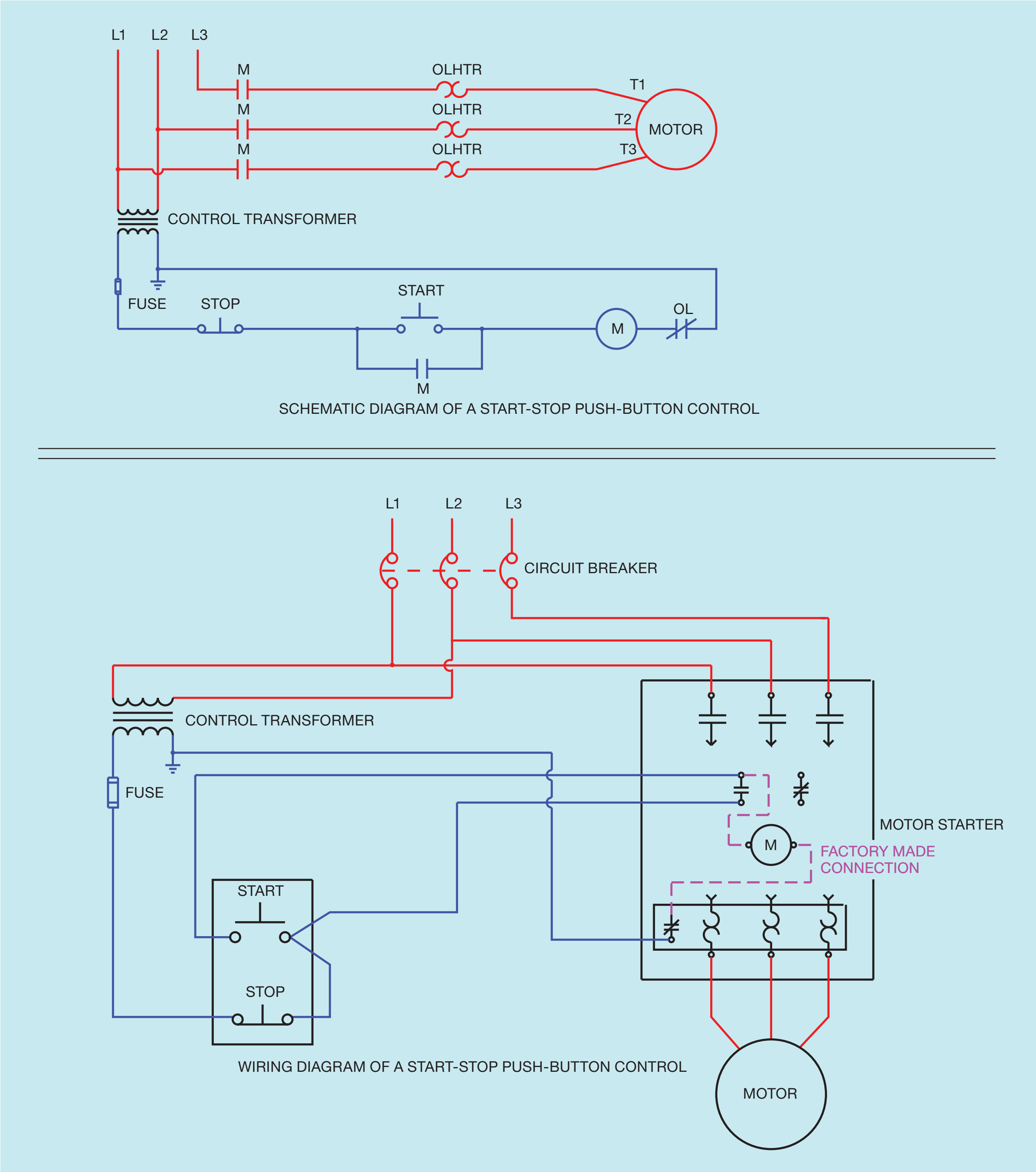


Figure 1–7 Schematic and wiring diagram of a start-stop push-button control. (Source: Delmar/Cengage Learning.)

Functions of Motor Control

There are some basic functions that motor control systems perform. The ones listed below are by no means the only ones, but are very common. These basic functions will be discussed in greater detail in this text. It is important not only to understand these basic functions of a control system, but also to know how control components are employed to achieve the desired circuit logic.

Starting

Starting the motor is one of the main purposes of a motor control circuit. There are several methods that can be employed, depending on the requirements of the circuit. The simplest method is *across-the-line* starting. This is accomplished by connecting the motor directly to the power line. There may be situations, however, that require the motor to start at a low speed and accelerate to full speed over some period of time. This is often referred to as *ramping*. In other situations, it may be necessary to limit the amount of current or torque during starting. Some of these methods will be discussed later in the text.

Stopping

Another function of the control system is to stop the motor. The simplest method is to disconnect the motor from the power line and permit it to coast to a stop. Some conditions, however, may require that the motor be stopped more quickly or that a brake hold a load when the motor is stopped.

Jogging or Inching

Jogging and inching are methods employed to move a motor with short jabs of power. This is generally done to move a motor or load into some desired position. The difference between jogging and inching is that jogging is accomplished by momentarily connecting the motor to full line voltage, and inching is accomplished by momentarily connecting the motor to reduced voltage.

Speed Control

Some control systems require variable speed. There are several ways to accomplish this. One of the most common ways is with variable frequency control for alternating current motors, or by controlling the voltage applied to the armature and fields of a direct current motor. Another method may involve the use of a direct current clutch. These methods will be discussed in more detail later in this text.

Motor and Circuit Protection

One of the major functions of most control systems is to provide protection for both the circuit components and the motor. Fuses and circuit breakers are generally employed for circuit protection, and overload relays are used to protect the motor. The different types of overload relays will be discussed later.

Surge Protection

Another concern in many control circuits is the voltage spikes or surges produced by collapsing magnetic fields when power to the coil of a relay or contactor is turned off. These collapsing magnetic fields can induce voltage spikes that are hundreds of volts (Figure 1–8). These high voltage surges can damage electronic components connected to the power line. Voltage spikes are of greatest concern in control systems that employ computer controlled devices such as programmable logic controllers and measuring instruments used to sense temperature, pressure, and so on. Coils connected to alternating current often have a metal oxide varistor (MOV) connected across the coil (Figure 1–9). Metal oxide varistors are voltage sensitive resistors. They have the ability to change their resistance value in accord with the amount of voltage applied to them. The MOV will have a voltage rating greater than that of the coil it is connected across. An MOV connected across a coil intended to operate on 120 volts, for example, will have a rating of about 140 volts. As long as the voltage applied to the MOV is below its voltage rating, it will exhibit an extremely high amount of resistance, generally several million ohms. The current flow through the MOV is called *leakage current* and is so small that it does not affect the operation of the circuit.

If the voltage across the coil should become greater than the voltage rating of the MOV, the resistance of the MOV will suddenly change to a very low value, generally in the range of 2 or 3 ohms. This effectively short-circuits the coil and prevents the voltage from becoming any higher than the voltage rating of the MOV

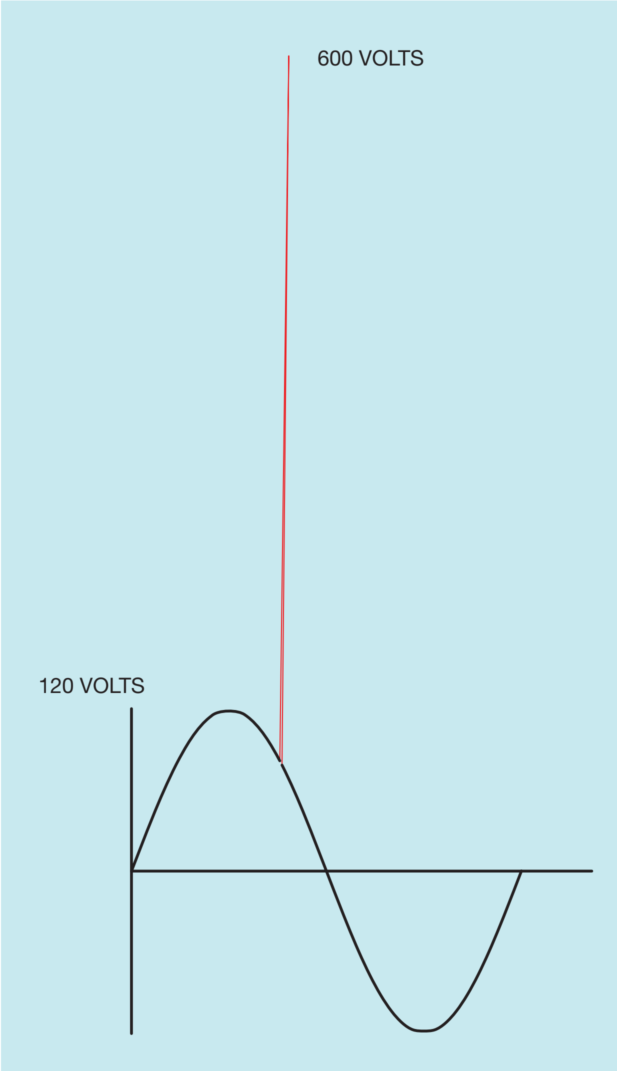


Figure 1–8 Spike voltages produced by collapsing magnetic fields can be hundreds of volts. (Source: Delmar/Cengage Learning.)

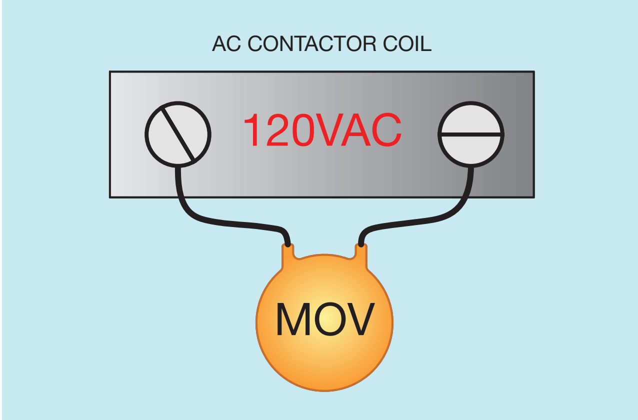


Figure 1–9 A metal oxide varistor (MOV) is used to eliminate voltage spikes on coils connected to alternating current. (Source: Delmar/Cengage Learning.)

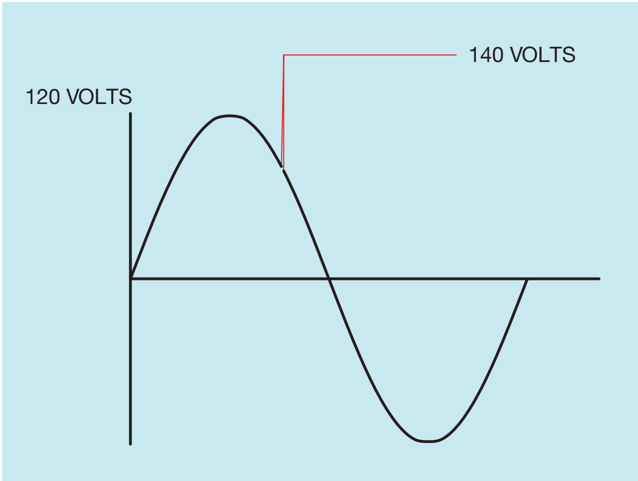


Figure 1–10 The metal oxide varistor limits the voltage spike to 140 volts. (Source: Delmar/Cengage Learning.)

(Figure 1–10). Metal oxide varistors change resistance value very quickly, generally in the range of 3 to 10 nanoseconds. When the circuit voltage drops below the voltage rating of the MOV, it will return to its high resistance value. The energy of the voltage spike is dissipated as heat by the MOV.

Diodes are used to suppress the voltage spikes produced by coils that operate on direct current. The diode is connected reverse bias to the voltage connected to the coil (see Figure 1–11). During normal operation, the diode blocks the flow of current, permitting all the circuit current to flow through the coil. When the

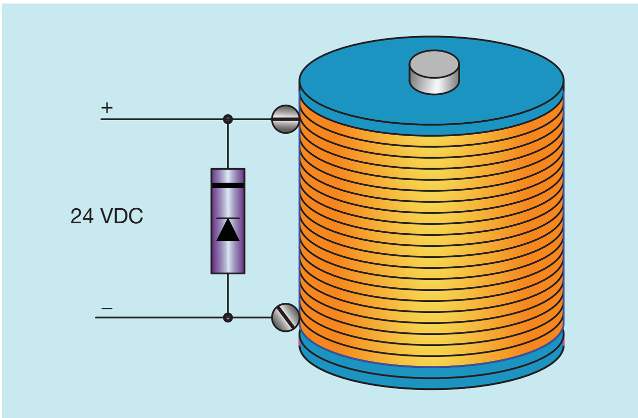


Figure 1–11 A diode is used to prevent voltage spikes on coils connected to direct current. (Source: Delmar/Cengage Learning.)

power is disconnected, the magnetic field around the coil collapses and induces a voltage into the coil. Since the induced voltage is opposite in polarity to the applied voltage (Lenz's Law), the induced voltage causes the diode to become forward biased. A silicon diode exhibits a forward voltage drop of approximately 0.7 volt. This limits the induced voltage to a value of about 0.7 volt. The energy of the voltage spike is dissipated as heat by the diode.

Safety

Probably the most important function of any control system is to provide protection for the operator or persons that may be in the vicinity of the machine. These protections will vary from one type of machine to another depending on the specific function of the machine. Many machines are provided with both mechanical and electrical safeguards.

Review Questions

1. When installing a motor control system, list four major factors to consider concerning the power system.
2. Where is the best place to look to find specific information about a motor, such as horsepower, voltage, full load current, service factor, and full load speed?
3. Is the National Electrical Code a law?
4. Explain the difference between manual control, semiautomatic control, and automatic control.
5. What is the simplest of all starting methods for a motor?
6. Explain the difference between jogging and inching.
7. What is the most common method of controlling the speed of an alternating current motor?
8. What agency requires employers to provide a workplace free of recognized hazards for its employees?
9. What is meant by the term ramping?
10. What is the most important function of any control system?

CHAPTER 2

SYMBOLS AND SCHEMATIC DIAGRAMS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss symbols used in the drawing of schematic diagrams.
- Determine the difference between switches that are drawn normally open, normally closed, normally open held closed, and normally closed held open.
- Draw standard NEMA control symbols.
- State rules that apply to schematic or ladder diagrams.
- Interpret the logic of simple ladder diagrams.

When you learned to read, you were first taught a set of symbols that represented different sounds. This set of symbols is called the alphabet. Schematics and wiring diagrams are the written language of motor controls. Before you can learn to properly determine the logic of a control circuit, you must first learn the written language. Unfortunately, there is no actual standard used for motor control symbols. Different manufacturers and companies often use their own sets of symbols for their in-house schematics. Also, schematics drawn in other countries may use entirely different sets of symbols to represent different control components. Although symbols can vary from one manufacturer to another, or from one country to another, once you have learned to interpret circuit logic it is generally possible to determine what the different symbols represent by the way they are used in the schematic. The most standardized set of symbols in the United States is provided by the National Electrical Manufacturer's Association, or NEMA. These are the symbols that we discuss in this chapter.

Push Buttons

One of the most used symbols in control schematics is the push button. Push buttons can be shown as normally open or normally closed (Figure 2–1). Most are momentary contact devices in that they make or break connection only as long as pressure is applied to them. The pressure is generally supplied by someone's finger pressing on the button. When the pressure is

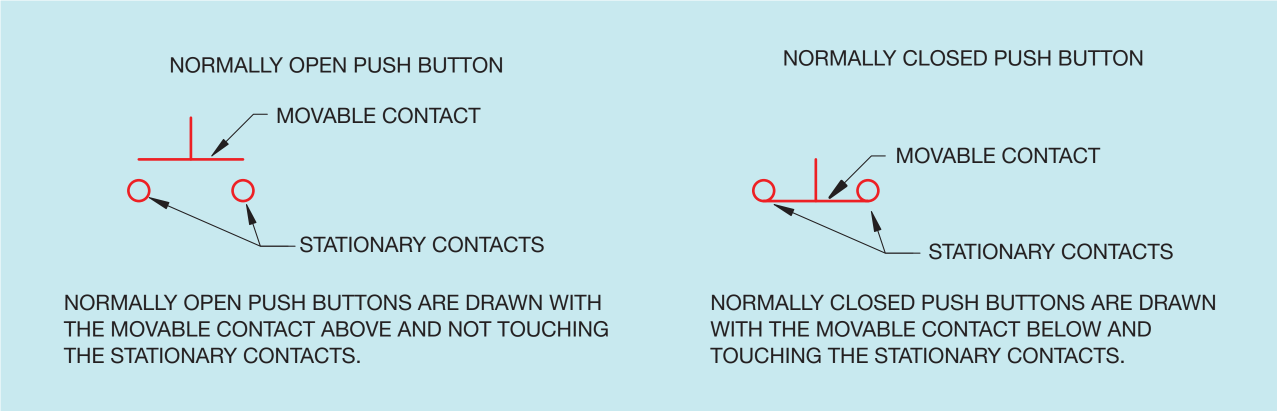


Figure 2–1 NEMA standard push-button symbols. (Source: Delmar/Cengage Learning.)

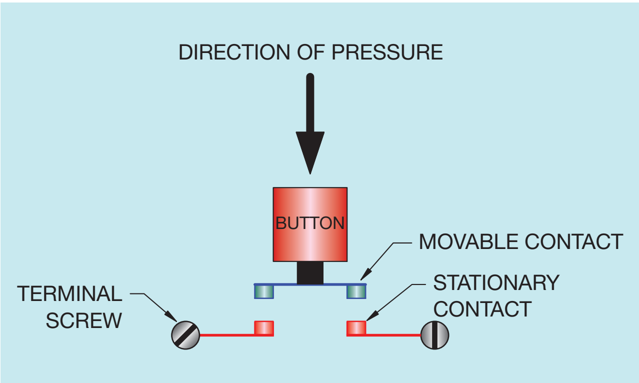


Figure 2–2 The movable contact bridges the stationary contacts when the button is pressed. (Source: Delmar/Cengage Learning.)

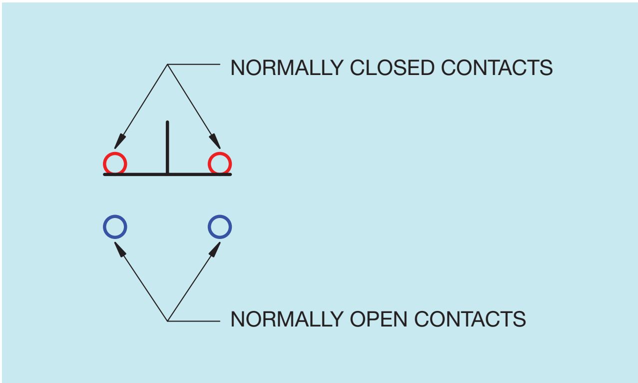


Figure 2–3 Double acting push button. (Source: Delmar/Cengage Learning.)

removed, the button returns to its normal position. Push buttons contain both movable and stationary contacts. The stationary contacts are connected to the terminal screws. The normally open push button is characterized by drawing the movable contact above and not touching the stationary contacts. Since the movable contact does not touch the stationary contacts, there is an open circuit and current cannot flow from one stationary contact to the other. The way the symbol is drawn assumes that pressure will be applied to the movable contact. When the button is pressed, the movable contact moves downward and bridges the two stationary contacts to complete a circuit (Figure 2–2). When pressure is removed from the button, a spring returns the movable contact to its original position.

The normally closed push-button symbol is characterized by drawing the movable contact below and touching the two stationary contacts. Since the movable contact touches the two stationary contacts, a complete circuit exists and current can flow from one stationary contact to the other. If pressure is applied to the button, the movable contact will move away from the two stationary contacts and open the circuit.

Double Acting Push Buttons

Another very common push button found throughout industry is the double acting pushbutton (Figure 2–3). Double acting push buttons contain both normally open and normally closed contacts. When connecting these push buttons in a circuit, you must make certain to connect the wires to the correct set of contacts. A typical double acting push button is shown in Figure 2–4. Note that the double acting push button

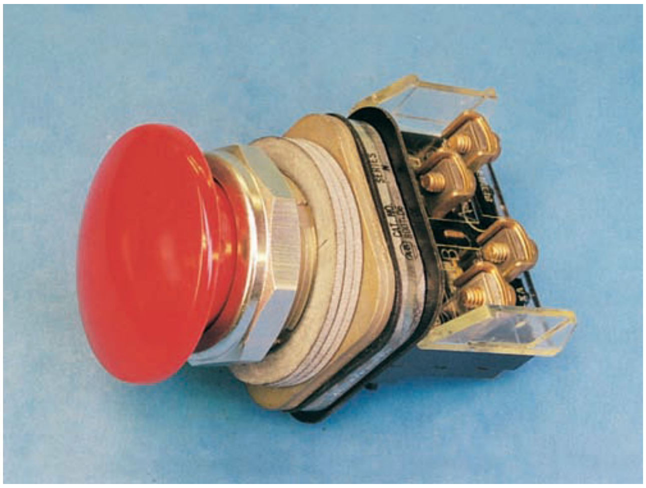


Figure 2–4 The double acting push button has four terminal screws. (Source: Delmar/Cengage Learning.)

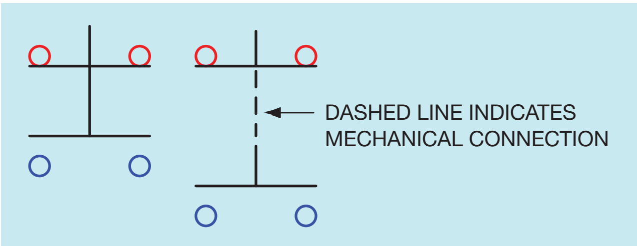


Figure 2–5 Other symbols used to represent double acting push buttons. (Source: Delmar/Cengage Learning.)

has four terminal screws. The symbol for a double acting push button can be drawn in different ways (Figure 2–5). The symbol on the left is drawn with two movable contacts connected by one common shaft. When the button is pressed, the top movable contact breaks away from the top two stationary contacts, and the bottom movable contact bridges the bottom two stationary contacts to complete the circuit. The symbol on the right is very similar in that it also shows two movable contacts. The right-hand symbol, however, connects the two push-button symbols together with a dashed line. When components are shown connected by a dashed line in a schematic diagram, it indicates that the components are mechanically connected together. If one component is pressed, all those that are connected by the dashed line are pressed. This is a very common method of showing several sets of push-button contacts that are actually controlled by one button.

Stacked Push Buttons

A very common connection employing the use of multiple push buttons is shown in Figure 2–6. In this example one stop button, referred to as an emergency stop button, can be used to stop three motors at one time. Push buttons that contain multiple contacts are often called *stacked push buttons*. Stacked push buttons are made by connecting multiple contact units together that are controlled by a single push button (Figure 2–7).

Push-Pull Buttons

Another push button that has found wide use is the push-pull button (Figure 2–8). Some push-pull buttons contain both normally open and normally closed contacts much like a double acting push button, but the contact arrangement is different. This push-pull button is intended to provide both the start and stop functions in one push button, eliminating the space needed for a second push button. The symbol for a push-pull button of this type is shown in Figure 2–9. When the button is pulled, the normally closed contact remains closed and the normally open contact bridges the two stationary contacts to complete the circuit. When the button is released, the normally open contact returns to its normal position and the normally closed section remains closed. When the button is pushed, the normally closed section opens to break the circuit and the normally open section remains open. A schematic diagram showing a push-pull button being used as a start-stop is shown in Figure 2–10.

Push-pull buttons that contain two normally open contacts are also available (Figure 2–11). These buttons are often used to provide a run-jog control on the same button. When this is done, the run function is generally accomplished with the use of a control relay, as shown in Figure 2–12 (page 16). When the button is pressed downward, a circuit is complete to M coil, causing all open M contacts to close and connect the motor to the power line. When the button is released, the contact reopens and de-energizes M coil, causing all M contacts to reopen and disconnect the motor from the power line. When the button is pulled upward, it completes a circuit to CR relay, causing both normally open CR contacts to close. One CR contact connected in parallel with the run section of the button maintains power to CR coil when the button is released. The CR contact connected in parallel with the jog section of the button closes and energizes M coil, causing the motor

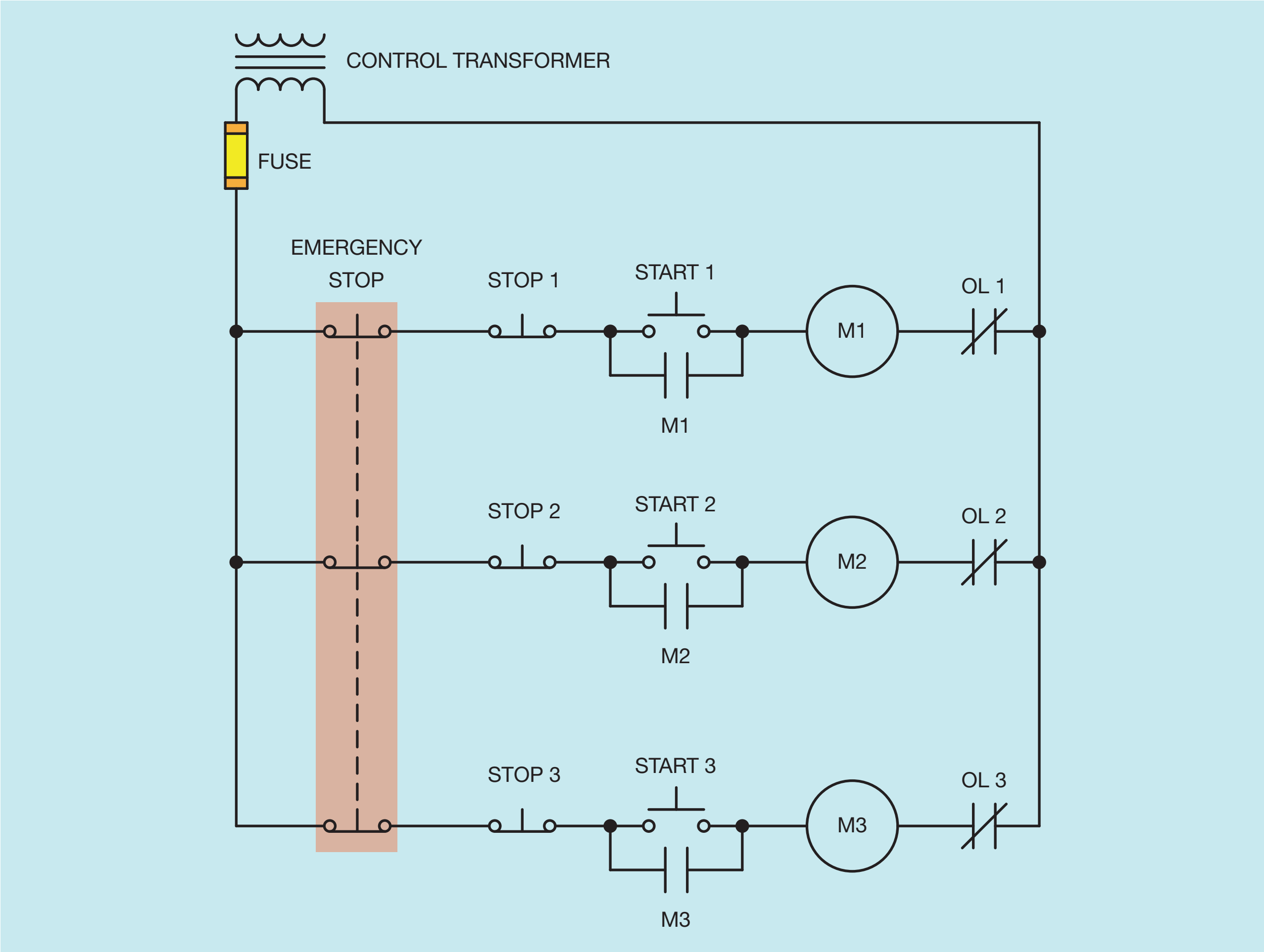


Figure 2–6 Emergency stop button can stop all motors. (Source: Delmar/Cengage Learning.)

to be connected to the power line. The motor will continue to run until the stop button is pressed.

Push-pull buttons that contain two normally closed contacts can be obtained also (Figure 2–13, page 16). These buttons are generally employed to provide stop for two different motors (Figure 2–14, page 17). When the button is pulled upward, the connection to the two top stationary contacts is broken, causing coil M1 to de-energize. The bottom section of the button remains closed. When the button is pressed, the top section remains closed and the bottom section opens and breaks the connection to coil M2.

Regardless of the configuration of the push-pull buttons or how they are employed in a control circuit, they are generally used to provide the function of two different buttons in a single space. They are a good choice if it becomes necessary to add controls to an existing control panel that may not have space for extra push buttons.

Lighted Push Buttons

Lighted push buttons are another example of providing a second function in a single space (Figure 2–15, page 17). They are generally used to indicate that a motor is running, stopped, or tripped on overload. Most lighted push buttons are equipped with a small transformer to reduce the control voltage to a much lower value (Figure 2–16, page 18). Lens caps of different colors are available.

Switch Symbols

Switch symbols are employed to represent many common control sensing devices. There are four basic symbols: normally open (NO), normally closed (NC), normally open held closed (NOHC), and normally

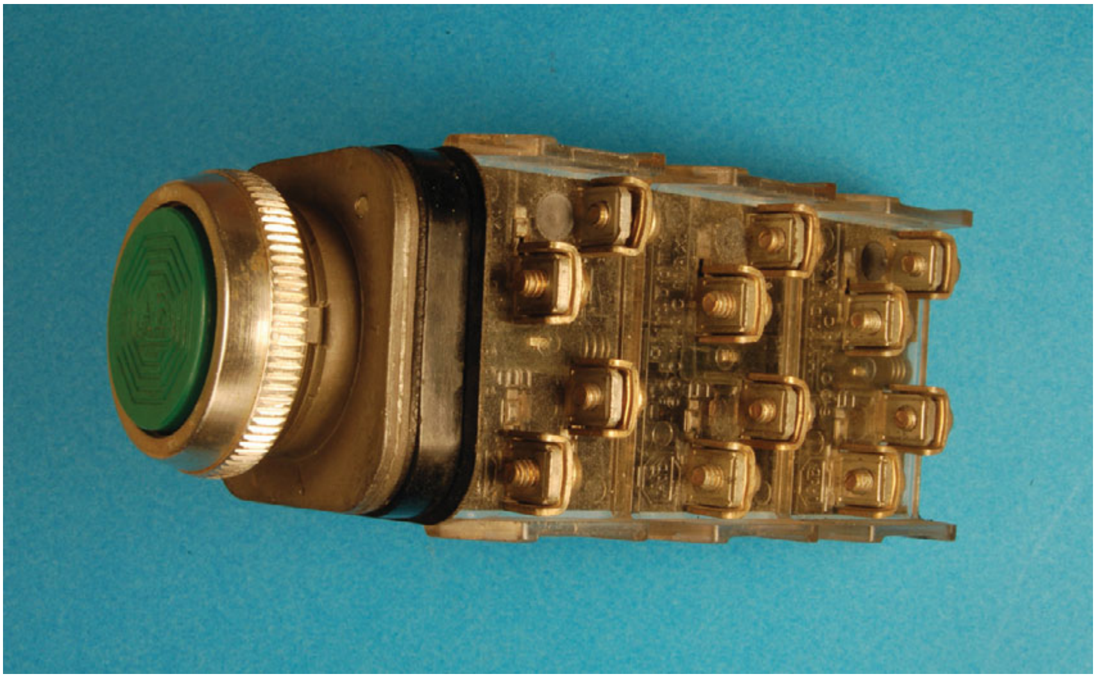


Figure 2–7 Stacked push buttons are made by connecting multiple contacts sets together. (Source: Delmar/Cengage Learning.)

Figure 2–8 Push-pull button. (Source: Delmar/Cengage Learning.)

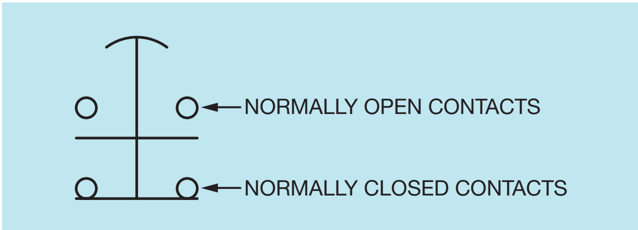


Figure 2–9 This symbol represents a push-pull button. (Source: Delmar/Cengage Learning.)

closed held open (NCHO). To understand how these switches are drawn, it is necessary to begin with how normally open and normally closed switches are drawn (Figure 2–17, page 18). Normally open switches are drawn with the movable contact **below and not touching** the stationary contact. Normally closed switches are drawn with the movable contact **above and touching** the stationary contact.

The normally open held closed and normally closed held open switches are shown in Figure 2–18 (page 19). Note that the movable contact of the normally open held closed switch is drawn below the stationary contact. The fact that the movable contact is drawn **below** the stationary contact indicates that the switch is normally open. Since the movable contact is touching the stationary contact, however, a complete

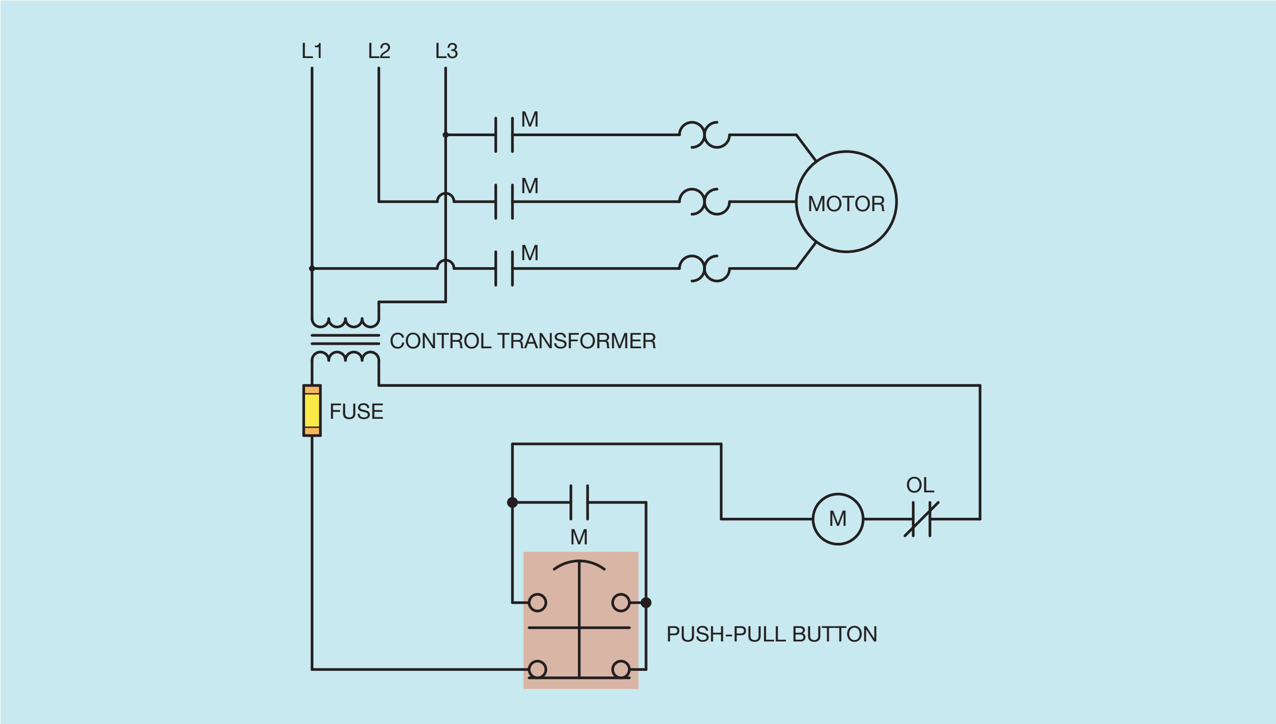


Figure 2–10 Schematic using a push-pull button as a start-stop control. (Source: Delmar/Cengage Learning.)

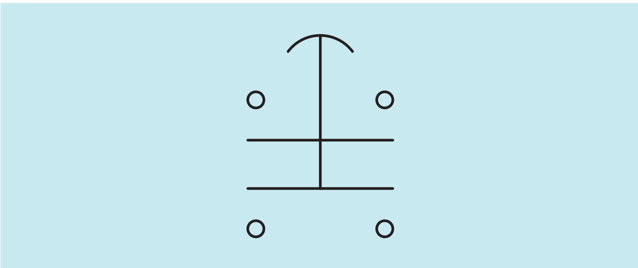


Figure 2–11 Some push-pull buttons contain two normally open contacts instead of one normally open and one normally closed. (Source: Delmar/Cengage Learning.)

circuit does exist because something is holding the contact closed. A very good example of this type of switch is the low pressure switch found in many air conditioning circuits (Figure 2–19, page 19). The low pressure switch is being held closed by the refrigerant in the sealed system. If the refrigerant should leak out, the pressure would drop low enough to permit the contact to return to its normal open position. This would open the circuit and de-energize coil C, causing both C contacts to open and disconnect the compressor from the power line. Although the schematic indicates that the switch is closed during normal operation, it would have to be connected as an open switch when it is wired into the circuit.

The normally closed held open switch is shown open in Figure 2–18. Although the switch is shown open, it is actually a normally closed switch because the movable contact is drawn **above** the stationary contact, indicating that something is holding the switch open. A good example of how this type of switch can be used is shown in Figure 2–20 (page 20). This circuit is a low water warning circuit for a steam boiler. The float switch is held open by the water in the boiler. If the water level should drop sufficiently, the contacts will close and energize a buzzer and warning light.

Basic Schematics

To understand the operation of the circuit shown in Figure 2–20, you must understand some basic rules concerning schematic, or ladder, diagrams:

1. Schematic, or ladder, diagrams show components in their electrical sequence without regard for physical location. In Figure 2–20, a coil is labeled CR and one normally open and one normally closed contact

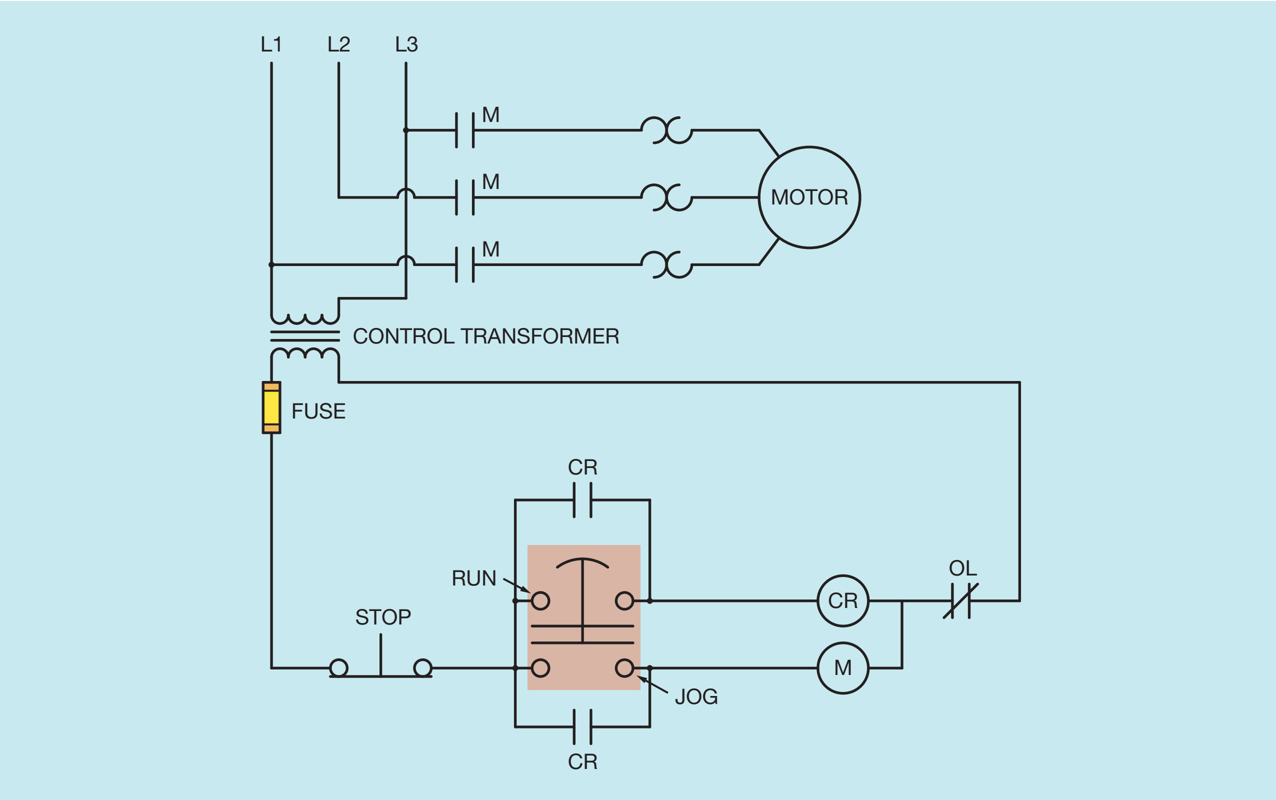


Figure 2–12 Run-Jog circuit using a push-pull button. (Source: Delmar/Cengage Learning.)

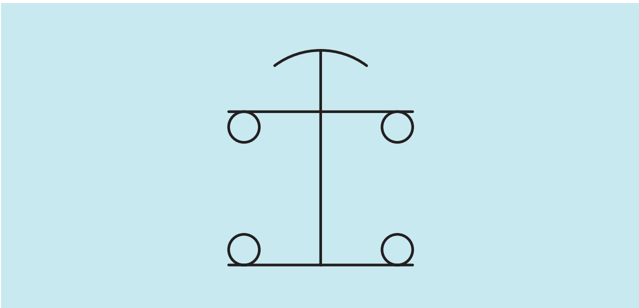


Figure 2–13 Push-pull button with two normally closed contacts. (Source: Delmar/Cengage Learning.)

are labeled CR. All of these components are physically located on control relay CR.

2. Schematics are always drawn to show components in their de-energized, or off, state.
3. Any contact that has the same label or number as a coil is controlled by that coil. In this example, both CR contacts are controlled by CR coil.
4. When a coil energizes, all contacts controlled by it change position. Any normally open contacts will close, and any normally closed contacts will open. When the coil is de-energized, the contacts will return to their normal state.

Referring to Figure 2–20, if the water level should drop far enough, the float switch will close and complete a circuit through the normally closed contact to the buzzer and to the warning light connected in parallel with the buzzer. At this time, both the buzzer and warning light are turned on. If the silence push button is pressed, coil CR will energize and both CR contacts will change position. The normally closed contact will open and turn off the buzzer. The warning light, however, will remain on as long as the low water level exists. The normally open CR contact connected in parallel with the silence push button will close. This contact is generally referred to as a holding, sealing, or maintaining contact. Its function is to maintain a current path to the coil when the push button returns to its normal open position. The circuit

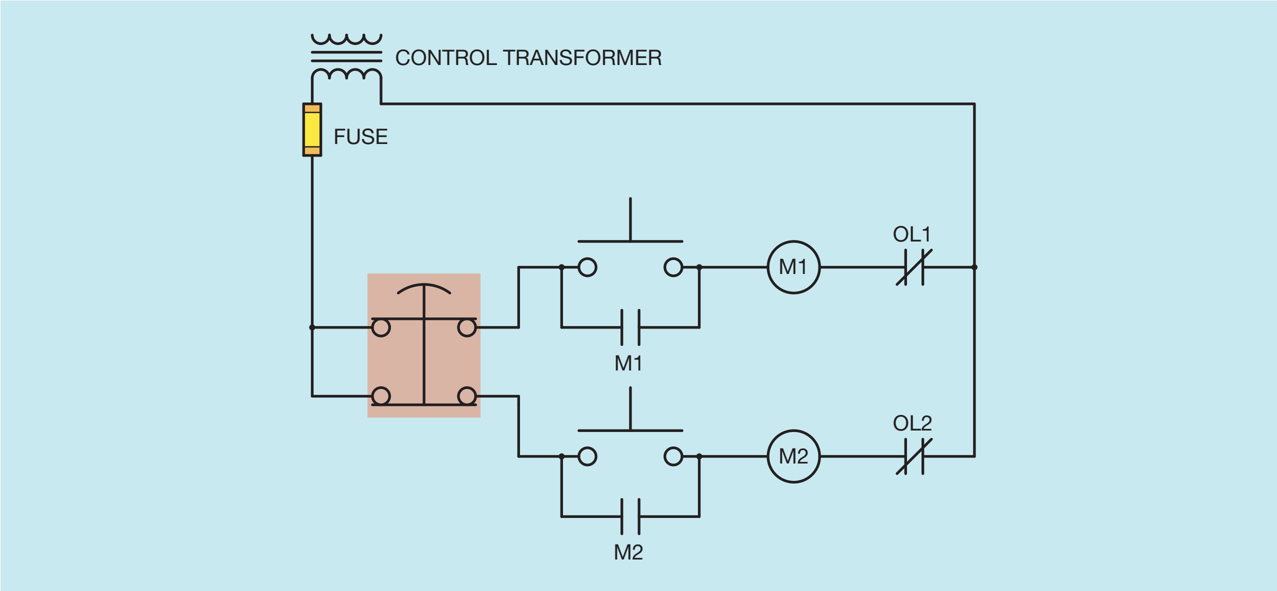


Figure 2–14 A push-pull button with two normally closed contacts used to provide a stop for two different motors. (Source: Delmar/Cengage Learning.)

Figure 2–15 Lighted push button. (Source: Delmar/Cengage Learning.)

Figure 2–16 Lighted push buttons are generally equipped with a small transformer to reduce the voltage to a much lower value. (Source: Delmar/Cengage Learning.)

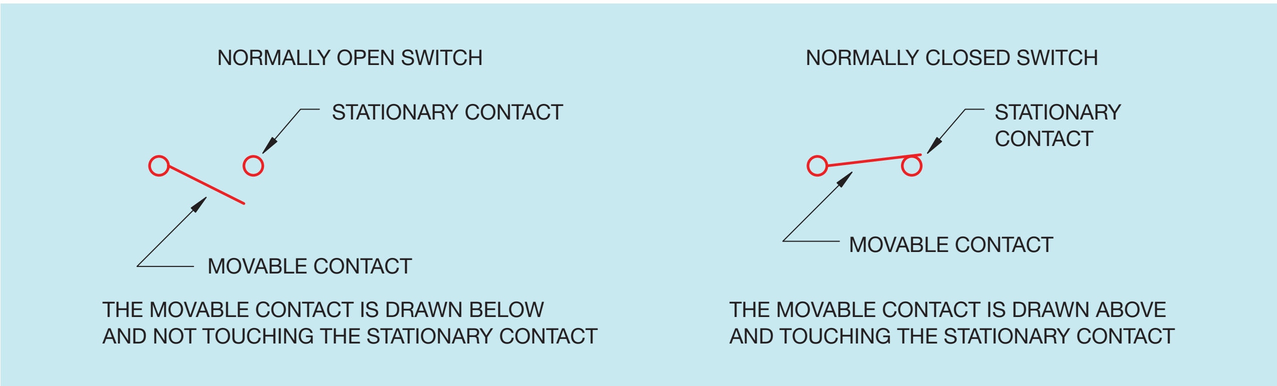


Figure 2–17 Symbols used to represent normally open (NO) and normally closed (NC) switches. (Source: Delmar/Cengage Learning.)

will remain in this state until the water level becomes high enough to reopen the float switch. When the float switch opens, the warning light and CR coil will turn off. The circuit is now back in it original de-energized state.

Sensing Devices

Motor control circuits depend on sensing devices to determine what conditions are occurring. They act very much like the senses of the body. The brain is the

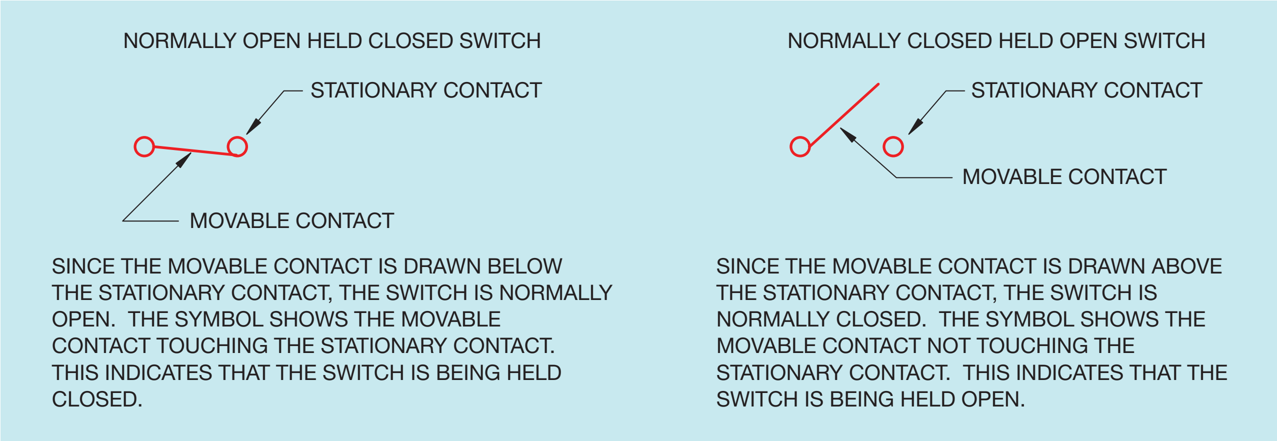


Figure 2–18 Normally open held closed (NOHC) and normally closed held open (NCHO) switch symbols. (Source: Delmar/Cengage Learning.)

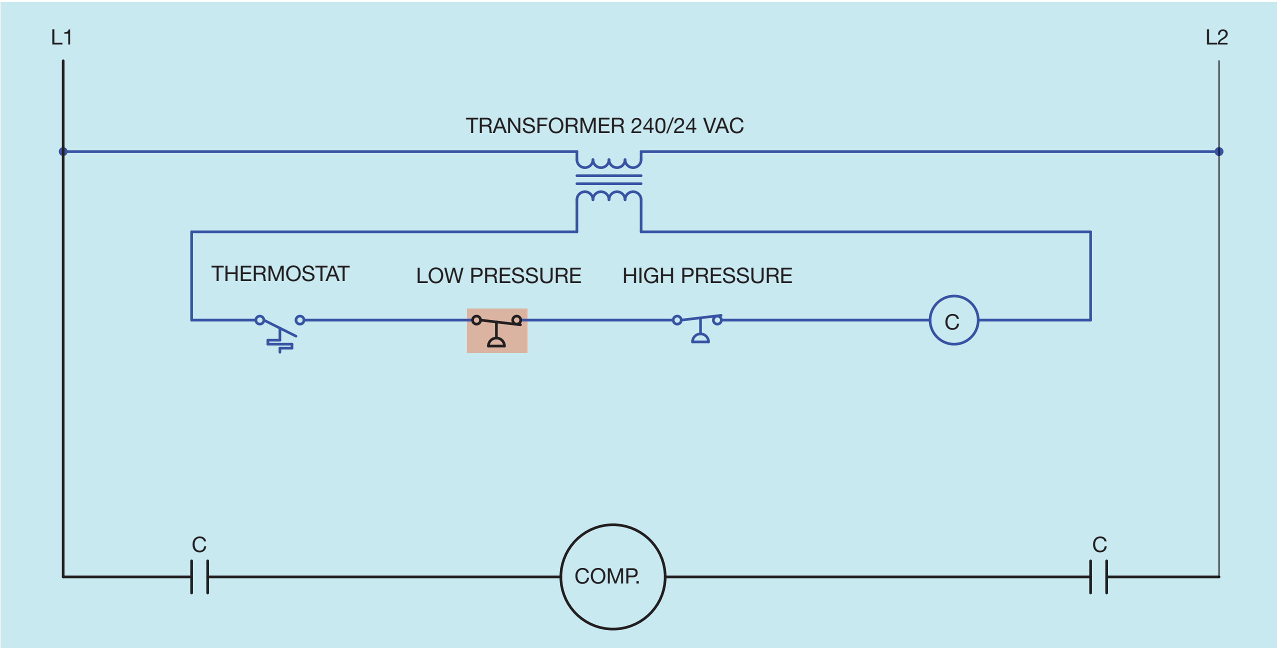


Figure 2–19 If system pressure should drop below a certain value, the normally open held closed low pressure switch will open and de-energize coil C. (Source: Delmar/Cengage Learning.)

control center of the body. It depends on input information such as sight, touch, smell, and hearing to determine what is happening around it. Control systems are very similar in that they depend on such devices as temperature switches, float switches, limit switches, flow switches, and so on to know the conditions that exist in the circuit. These sensing devices will be covered in greater detail later in the text. The four basic types of switches are used in conjunction with other symbols to represent some of these different kinds of sensing switches.

Limit Switches

Limit switches are drawn by adding a wedge to one of the four basic switches, Figure 2–21. The wedge represents the bumper arm. Common industrial limit switches are shown in Figure 2–22.

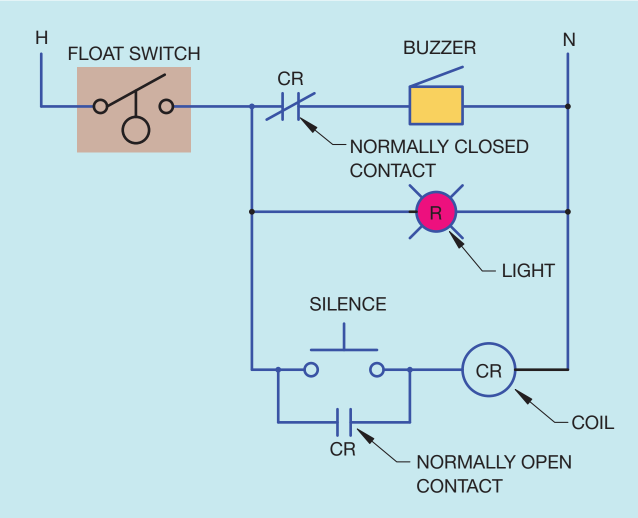


Figure 2–20 The normally closed float switch is held open by the level of the water. If the water level should drop below a certain amount, the switch will return to its normal closed position and complete the circuit. (Source: Delmar/Cengage Learning.)

Figure 2–22 Typical industrial limit switches. (Courtesy of Micro Switch, a Honeywell Division.)

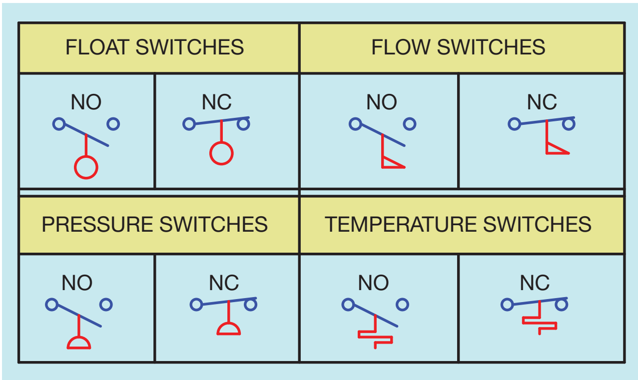


Figure 2–23 Schematic symbols for sensing switches. (Source: Delmar/Cengage Learning.)

Float, Pressure, Flow, and Temperature Switches

The symbol for a float switch illustrates a ball float. It is drawn by adding a circle to a line, Figure 2–23. The flag symbol of the flow switch represents the paddle that senses movement. The flow switch symbol is used for both liquid and air flow switches. The symbol for a pressure switch is a half circle connected to a line. The flat part of the semicircle represents a diaphragm. The symbol for a temperature switch represents a bimetal helix. The helix will contract and expand with a change of temperature. It should be noted that any of these symbols can be used with any of the four basic switches.

There are many other types of sensing switches that do not have a standard symbol. Some of these are photo switches, proximity switches, sonic switches, Hall effect switches, and others. Some manufacturers will employ a special type of symbol and label the symbol to indicate the type of switch. An example of this is shown in Figure 2–24.

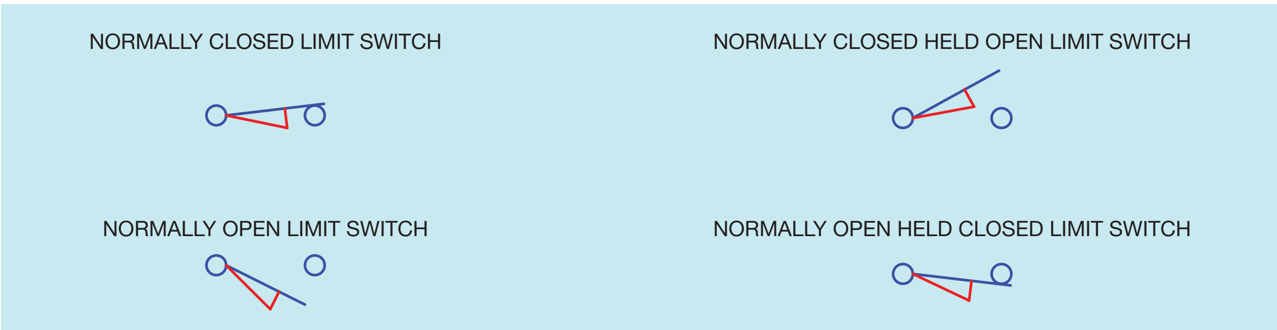


Figure 2–21 Limit switch symbols. (Source: Delmar/Cengage Learning.)

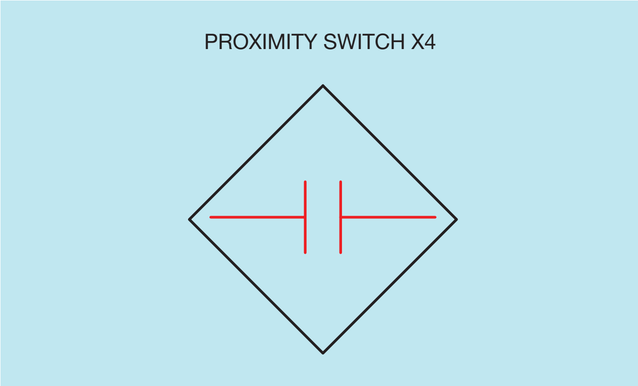


Figure 2–24 Special symbols are often used for sensing devices that do not have a standard symbol. (Source: Delmar/Cengage Learning.)

Coils

The most common coil symbol used in schematic diagrams is the circle. The reason for this is so that letters and/or numbers can be written in the circle to identify the coil. Contacts controlled by the coil are given the same label. Several standard coil symbols are shown in Figure 2–25.

Timed Contacts

Timed contacts are either normally open or normally closed. They are not drawn as normally open held closed or normally closed held open. There are two basic types of timers, on delay and off delay. Timed contact symbols use an arrow to point in the direction that the contact will move at the end of the time cycle. Timers will be discussed in detail in a later chapter. Standard timed contact symbols are shown in Figure 2–26.

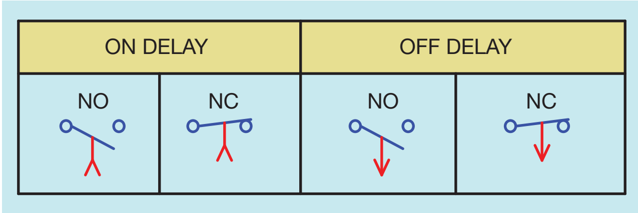


Figure 2–26 Timed contact symbols. (Source: Delmar/Cengage Learning.)

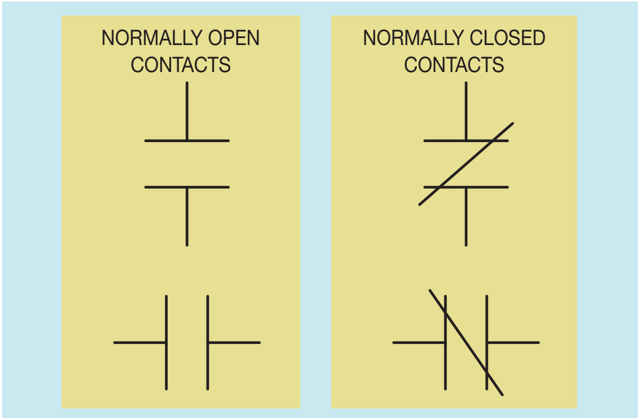


Figure 2–27 Normally open and normally closed contact symbols. (Source: Delmar/Cengage Learning.)

Contact Symbols

Another very common symbol used on control schematics is the contact symbol. The symbol is two parallel lines connected by wires (Figure 2–27). The normally open contacts are drawn to represent an open connection. The normally closed contact symbol is the same as the normally open symbol with the exception that a diagonal line is drawn through the contacts. The diagonal line indicates that a complete current path exists.

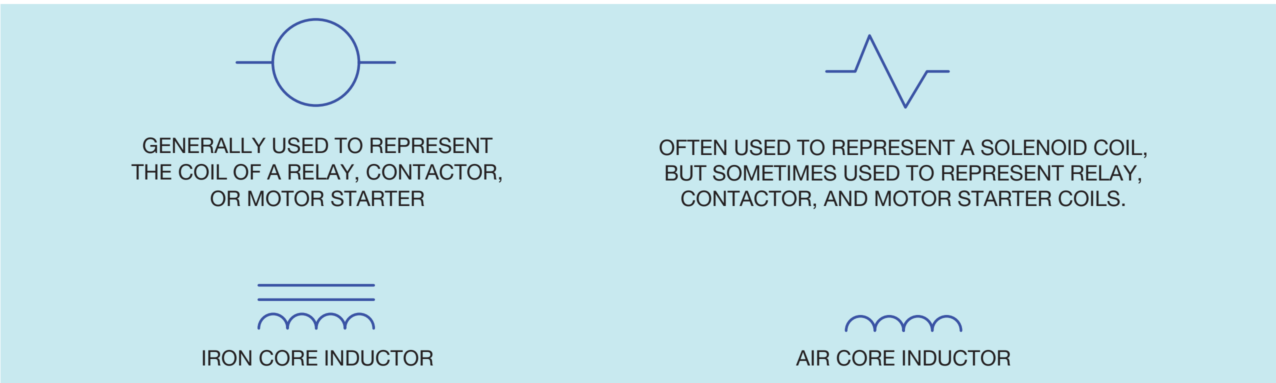


Figure 2–25 Common coil symbols. (Source: Delmar/Cengage Learning.)

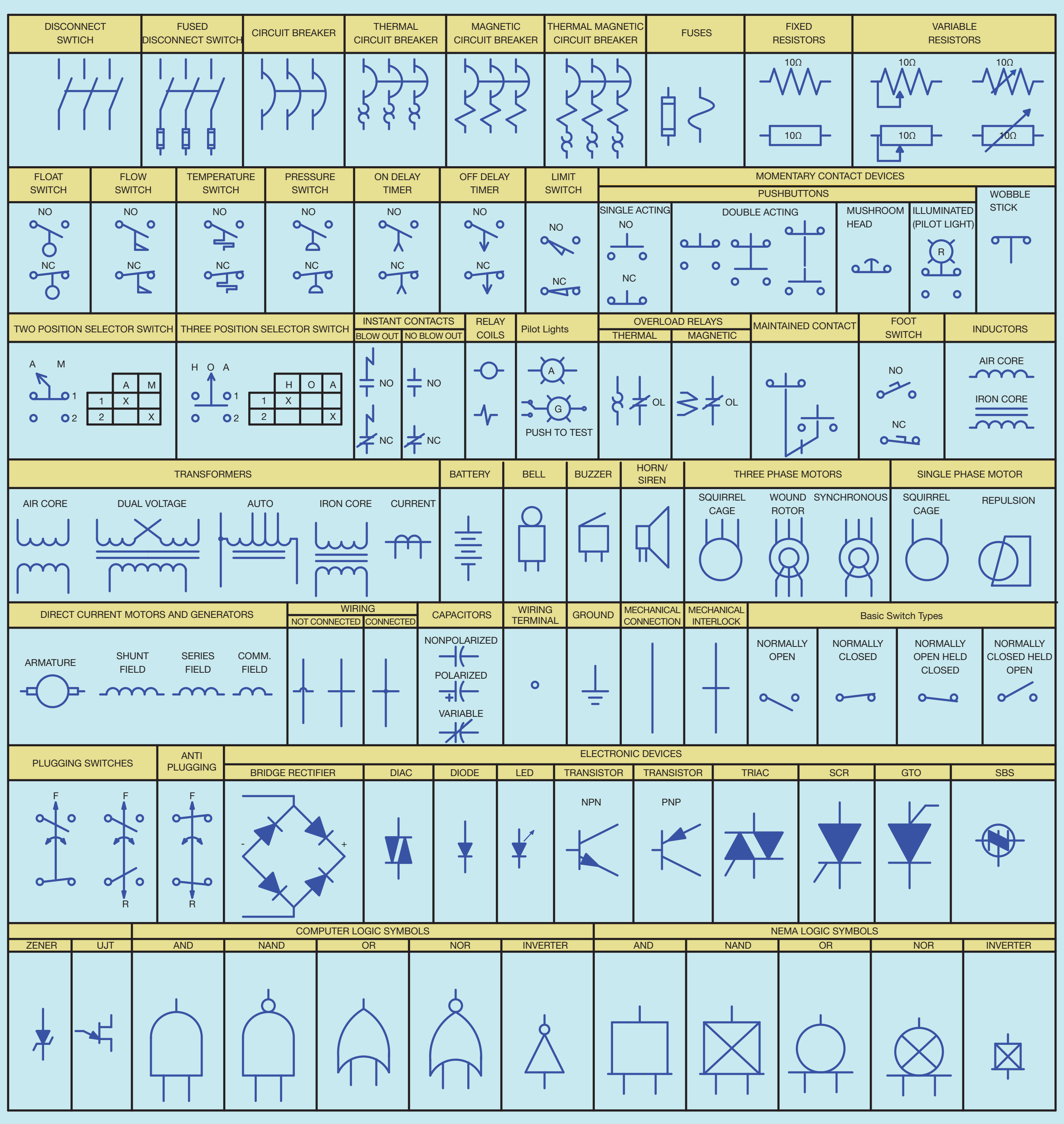


Figure 2–28 Common control and electrical symbols. (Source: Delmar/Cengage Learning.)

Other Symbols

Not only are there NEMA standard symbols for coils and contacts; there are also symbols for transformers, motors, capacitors, and special types of switches. A chart showing both common control and electrical symbols is shown in Figure 2–28.

Selector Switches

Selector switches are operated by turning a knob instead of pushing a button. A very common selector switch is the MAN-OFF-AUTO switch. MAN stands for Manual and AUTO stands for Automatic. This is

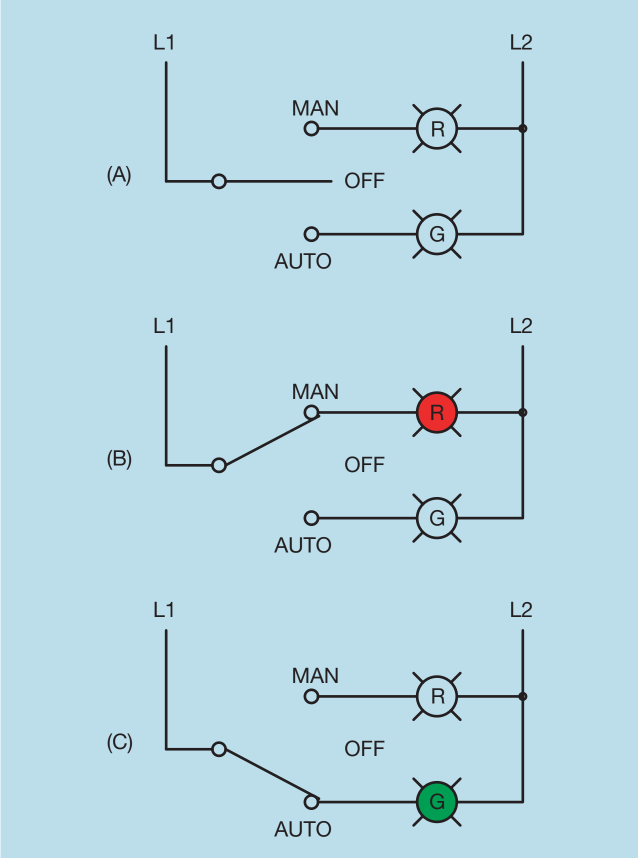


Figure 2–29 A MAN-OFF-AUTO switch is a single-pole double-throw switch with a center off position. (Source: Delmar/Cengage Learning.)

Figure 2–31 A combination START-STOP push-button station with pilot lamp and HAND-OFF-AUTO switch. (Source: Delmar/Cengage Learning.)

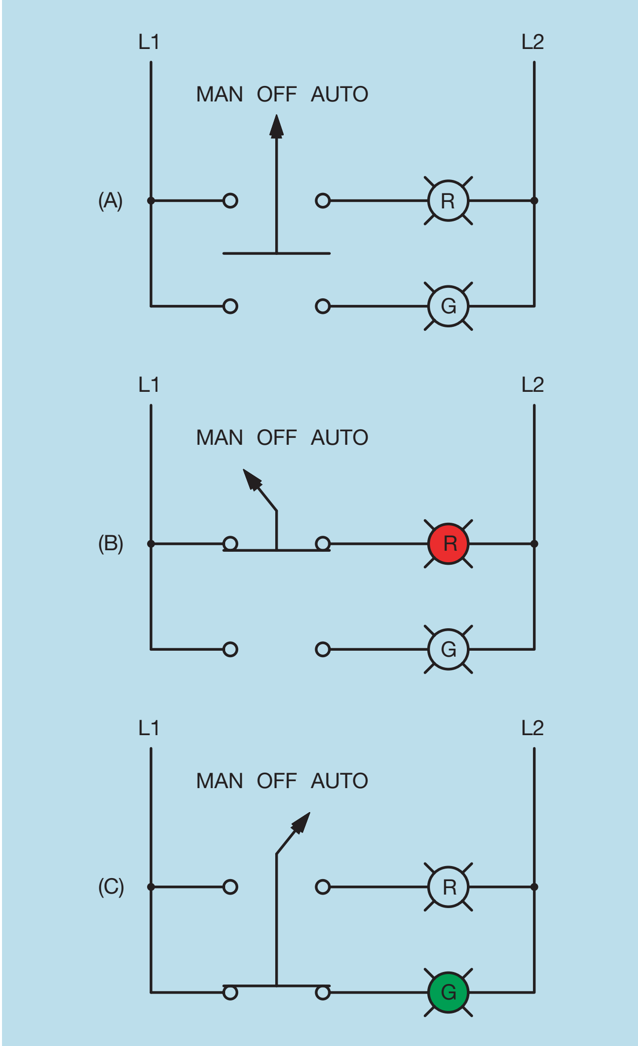
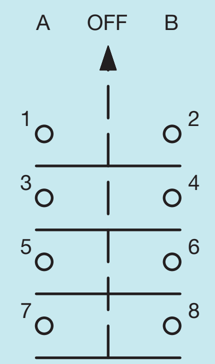


Figure 2–30 The MAN-OFF-AUTO switch is often drawn in this manner. (Source: Delmar/Cengage Learning.)

a single-pole double-throw switch with a center off position, as shown in Figure 2–29. When the switch is in the OFF position, as shown in Figure 2–29A, neither indicator lamp is turned on. If the switch is moved to the MAN position, as shown in Figure 2–29B the red lamp is turned on. If the switch is set in the AUTO position, Figure 2–29C, the green lamp is turned on. Another symbol often used to represent this type of switch is shown in Figure 2–30. A combination START-STOP push-button station, pilot lamp, and HAND-OFF-AUTO switch is shown in Figure 2–31.

Selector switches often contain multiple contacts and multiple poles (Figure 2–32). A symbol used to represent a selector switch with three poles, each having three terminals, is shown in Figure 2–33. This selector

Figure 2–32 Selector switch with multiple poles. (Source: Delmar/Cengage Learning.)



CONTACTS	A	OFF	B
1 - 2	O	O	X
3 - 4	X	O	O
5 - 6	X	O	X
7 - 8	O	O	X

Figure 2–34 A selector switch with different sets of contacts. (Source: Delmar/Cengage Learning.)

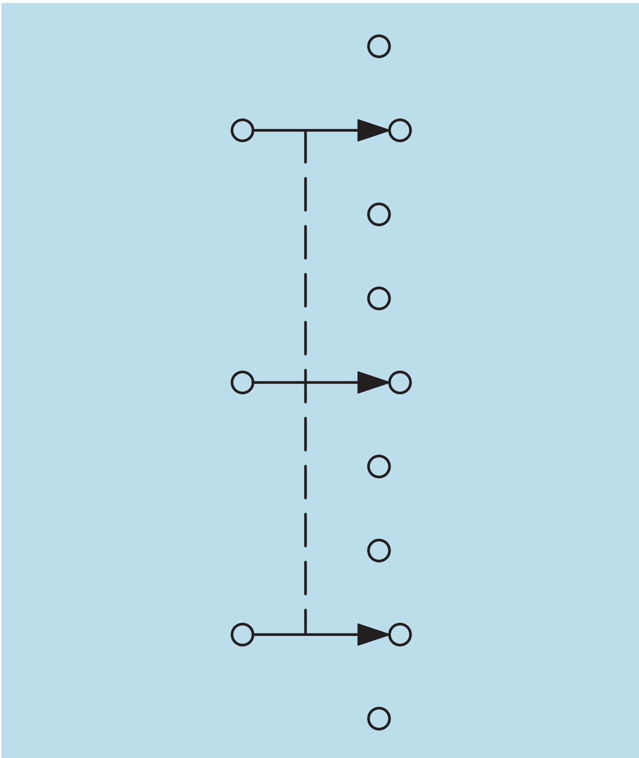


Figure 2–33 Symbol used to represent a three-pole three-terminal selector switch. The movable contacts will be a common terminal for teach of the three poles. (Source: Delmar/Cengage Learning.)

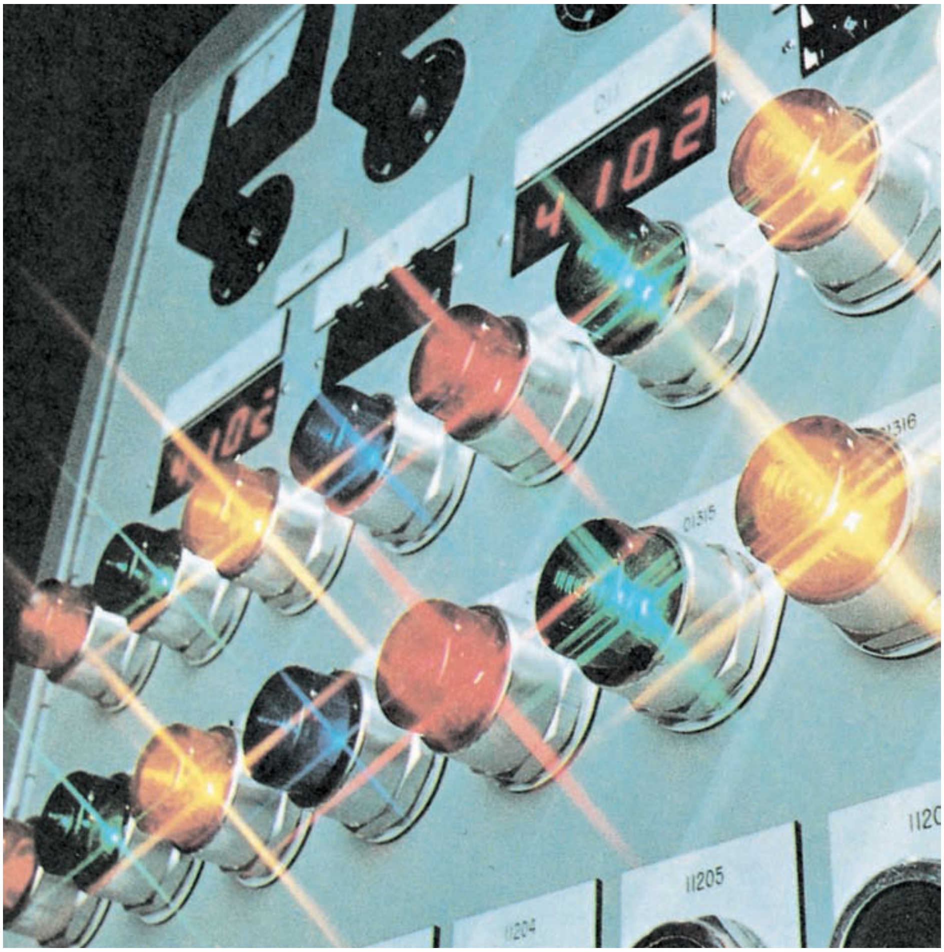
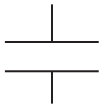


Figure 2–35 Control panel with selector switches, push buttons, indicating lights and meters mounted together. (Courtesy Allen-Bradley, a Rockwell International Company.)

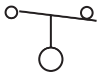
switch contains a common terminal for each of the three poles. The common terminal is connected to the movable contact. A different type of selector switch is shown in Figure 2–34. Switches of this type are often supplied with a chart or truth table indicating connections between contacts when the switch is set in different positions. In this example, there is no connection between any of the contacts when the switch is set in the OFF position. When the switch is set in position A there is connection between contacts 3 and 4, and 5 and 6. When the switch is set in position B there is connection between contacts 1 and 2, 5 and 6, and 7 and 8. It is not uncommon to see a combination of selector switches, push buttons, and meters mounted on a single control panel (Figure 2–35).

Review Questions

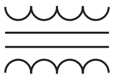
1. The symbol shown is a:
   a. Polarized capacitor.
   b. Normally closed switch.
   c. Normally open held closed switch.
   d. Normally open contact.



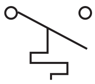
2. The symbol shown is a:
   a. Normally closed float switch.
   b. Normally open held closed float switch.
   c. Normally open float switch.
   d. Normally closed held open float switch.



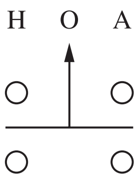
3. The symbol shown is a(n):
   a. Iron core transformer.
   b. Auto transformer.
   c. Current transformer.
   d. Air core transformer.



4. The symbol shown is a:
   a. Normally open pressure switch.
   b. Normally open flow switch.
   c. Normally open float switch.
   d. Normally open temperature switch.



5. The symbol shown is a:



   a. Double acting push button.
   b. Two-position selector switch.
   c. Three-position selector switch.
   d. Maintained contact push button.
6. If you were installing the circuit in Figure 2–20, what type of push button would you use for the silence button?
   a. Normally closed.
   b. Normally open.
7. Referring to the circuit in Figure 2–20, should the float switch be connected as a normally open or normally closed switch?
8. Referring to the circuit in Figure 2–20, what circuit component controls the actions of the two CR contacts?
9. Why is a circle most often used to represent a coil in a motor control schematic?
10. When reading a schematic diagram, are the control components shown as they should be when the machine is turned off or de-energized, or are they shown as they should be when the machine is in operation?
11. Push-pull buttons are generally used because:
    a. they are smaller in size than standard push buttons.
    b. they contain larger contacts that can withstand more current than standard push buttons.
    c. they can perform more than one function while only requiring the space of one single-function push button.
    d. They are larger in size than standard push buttons making them more visible to an operator.
12. What device is generally used by lighted push buttons to reduce the voltage applied to the lamp?
    a. Series resistor.
    b. Transformer.
    c. Series capacitor.
    d. Series inductor.
13. How are components that are mechanically connected together generally identified on a schematic diagram?

CHAPTER 3
MANUAL STARTERS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of manual motor starters.
- Discuss low voltage release.
- Connect a manual motor starter.
- Check a circuit to determine if a motor is drawing excessive current.

Manual starters are characterized by the fact that the operator must go to the location of the starter to initiate any change of action. There are several different types of manual starters. Some look like a simple toggle switch with the addition of an overload heater. Others are operated by push buttons and may or may not be capable of providing low voltage protection.

Fractional Horsepower Single-Phase Starters

One of the simplest manual motor starters resembles a simple toggle switch with the addition of an overload heater (Figure 3–1). The toggle switch lever is mounted on the front of the starter and is used to control the on and off operation of the motor. In addition to being an on and off switch, the toggle switch also provides overload protection for the motor. An overload heater is connected in series with the motor (Figure 3–2). When current flows, the heater will produce heat in

Figure 3–1 Single-phase manual motor starter. (Courtesy Square D Co.)

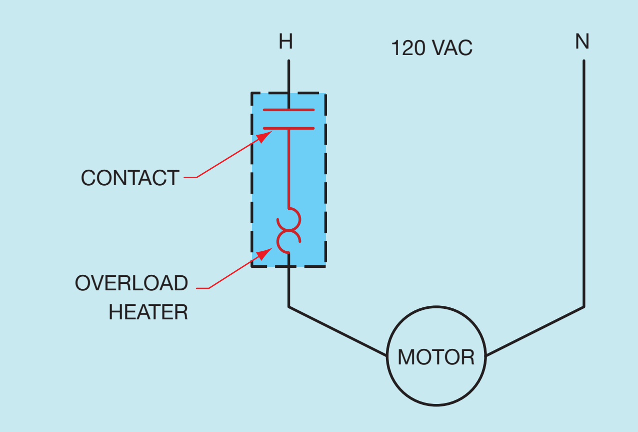


Figure 3–2 Schematic diagram of a single-pole manual starter. (Source: Delmar/Cengage Learning.)

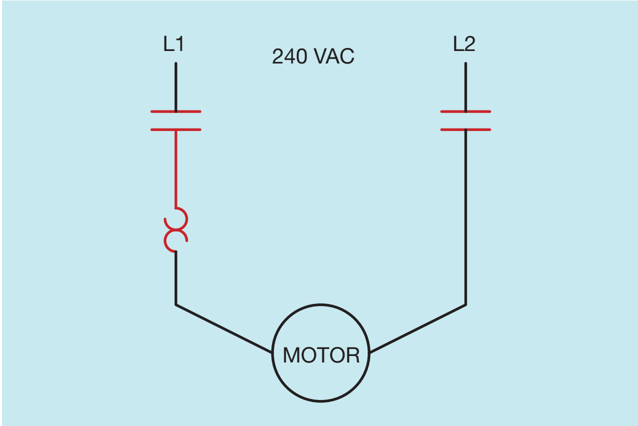


Figure 3–3 Schematic diagram of a two-pole manual starter. (Source: Delmar/Cengage Learning.)

proportion to the amount of motor current. If the heater is sized correctly, it will never get hot enough to open the circuit under normal operating conditions. If the motor should become overloaded, however, current will increase, causing a corresponding increase in heat production by the heater. If the heat becomes great enough, it will cause a mechanical mechanism to trip and open the switch contacts, disconnecting the motor from the power line. If the starter trips on overload, the switch lever will move to a center position. The starter must be reset before the motor can be restarted by moving the lever to the full OFF position. This action is basically the same as resetting a tripped circuit breaker. The starter shown in this example has only one line contact and is generally used to protect single-phase motors intended to operate on 120 volts.

Starters that are intended to protect motors that operate on 240 volts should contain two load contacts (Figure 3–3). Although a starter that contains only one contact would be able to control the operation of a 240 volt motor, it could create a hazardous situation. If the motor were switched off and an electrician tried to disconnect the motor, one power line would still be connected directly to the motor. The National Electrical Code (NEC) requires that a disconnecting means open all ungrounded supply conductors to a motor.

Manual starters of this type are intended to control fractional horsepower motors only. Motors of 1 horsepower or less are considered fractional horsepower. Starters of this type are across-the-line starters. This means that they connect the motor directly to the power line. Some motors can draw up to 600% of rated full load current during starting. These starters generally do not contain large enough contacts to handle the current surge of multi-horsepower motors.

Another factor that should be taken into consideration when using a starter of this type is that it does not provide low voltage release. Most manual starters are strictly mechanical devices and do not contain an electrical coil. The contacts are mechanically opened and closed. This simply means that if the motor is in operation and the power fails, the motor will restart when the power is restored. This can be an advantage in some situations where the starter controls unattended devices such as pumps, fans, blowers, air conditioning, and refrigeration equipment. This feature saves the maintenance electrician from having to go around the plant and restart all the motors when power returns after a power failure.

However, this automatic restart feature can also be a disadvantage on equipment such as lathes, milling machines, saws, drill presses, and any other type of machine that may have an operator present. The unexpected and sudden restart of a piece of equipment could be the source of injury.

Mounting

Mounting a fractional horsepower single-phase starter is generally very simple because it requires very little space. The compact design of this starter permits it to be mounted in a single gang switch or conduit box or directly onto a piece of machinery. The open type starter can be mounted in the wall and covered with a single gang switch cover plate. The ON and OFF markings on the switch lever make it appear to be a simple toggle switch.

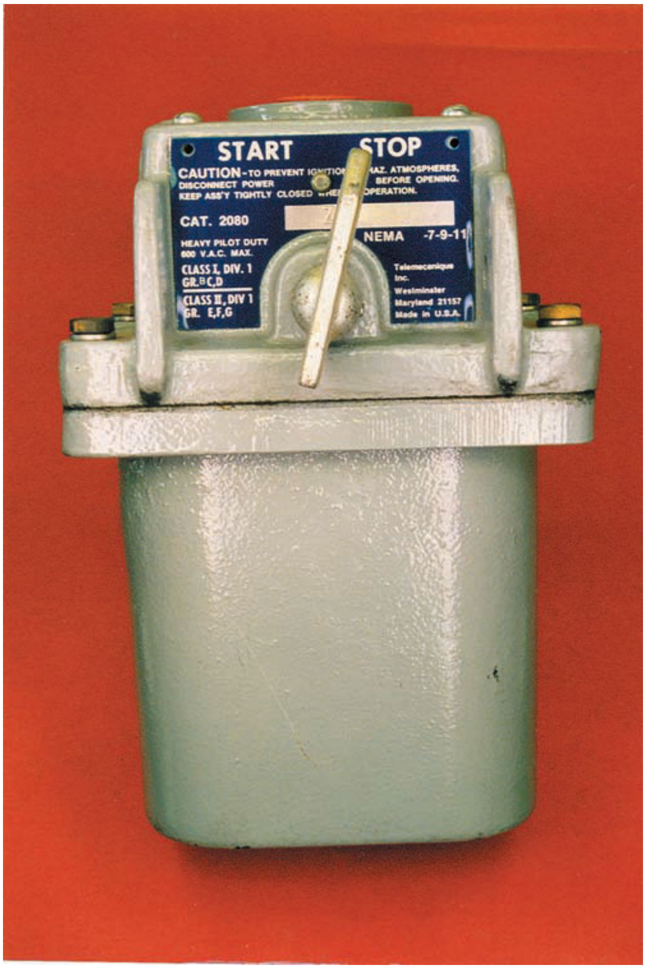


Figure 3–4 Explosion proof enclosure. (Source: Delmar/Cengage Learning.)

Figure 3–5 Waterproof enclosure. (Source: Delmar/Cengage Learning.)

Like larger starters, fractional horsepower starters are available in different enclosures. Some are simple sheet metal and are intended to be mounted on the surface of a piece of machinery. If the starter is to be mounted in an area containing hazardous vapors or gasses, it may require an explosion proof enclosure (Figure 3–4). Areas that are subject to high moisture may require a waterproof enclosure (Figure 3–5). In areas that have a high concentration of flammable dust, the starter may be housed in a dustproof enclosure similar to the one shown in Figure 3–6.

Automatic Operation

It is sometimes necessary to combine the manual starter with other sensing devices to obtain the desired control. When using a sensing pilot device to directly control the operation of a motor, you must make sure that the type of pilot device is equipped with contacts that can handle the rated current of the motor. These devices are generally referred to as "line voltage" devices. Line voltage devices have larger contacts than those sensing pilot devices intended for use in a motor control circuit that employs a magnetic motor starter. The smaller pilot devices intended for use with magnetic motor starters have contacts that are typically rated from 1 to 3 amperes. Line voltage devices may have contacts rated for 15 to 20 amperes. A good example of how a line voltage sensing device can be used in conjunction with the manual starter is shown in Figure 3–7. In this circuit, a line voltage thermostat is used to control the operation of a blower motor. When the temperature rises to a sufficient level, the thermostat contacts close, connecting the motor directly to the power line if the manual starter contacts are closed. When the temperature drops, the thermostat contact opens and turns off the motor. A line voltage thermostat is shown in Figure 3–8.

Another circuit that permits the motor to be controlled either manually or automatically is shown in

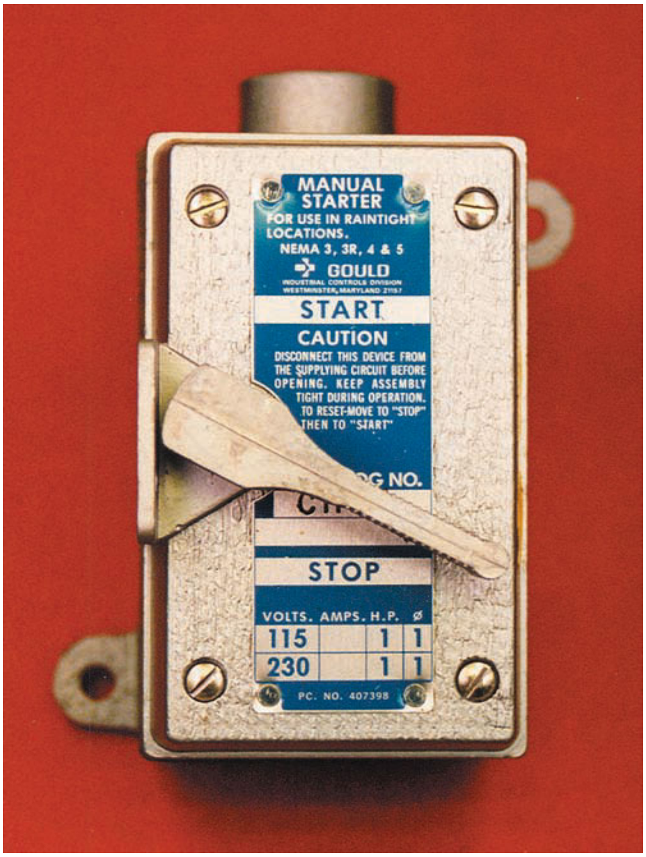


Figure 3–6 Dustproof enclosure. (Source: Delmar/Cengage Learning.)

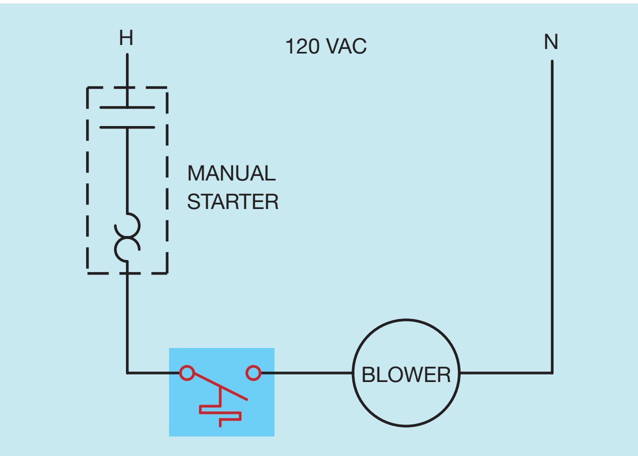


Figure 3–7 A line voltage thermostat controls the operation of a blower motor. (Source: Delmar/Cengage Learning.)

Figure 3–9. In this circuit a manual-automatic switch is used to select either manual or automatic operation of a pump. The pump is used to refill a tank when the water falls to a certain level. The schematic is drawn to

Figure 3–8 Line voltage thermostat. (Source: Delmar/Cengage Learning.)

assume that the tank is full of water during normal operation.

In the Manual position, the pump is controlled by turning the starter on or off. An amber pilot light is used to indicate when the manual starter contacts are closed, or turned on. If the manual-automatic switch is moved to the Automatic position (Figure 3–10), a line voltage float switch controls the operation of the pump motor. If the water in the tank drops to a low enough level, the float switch contact closes and starts the pump motor. If water rises to a high enough level, the float switch contact will open and disconnect the pump motor from the line.

Manual Push-Button Starters

Manual push-button line voltage starters are manufactured with two or three load contacts. The two-contact models are intended to control single-phase motors that

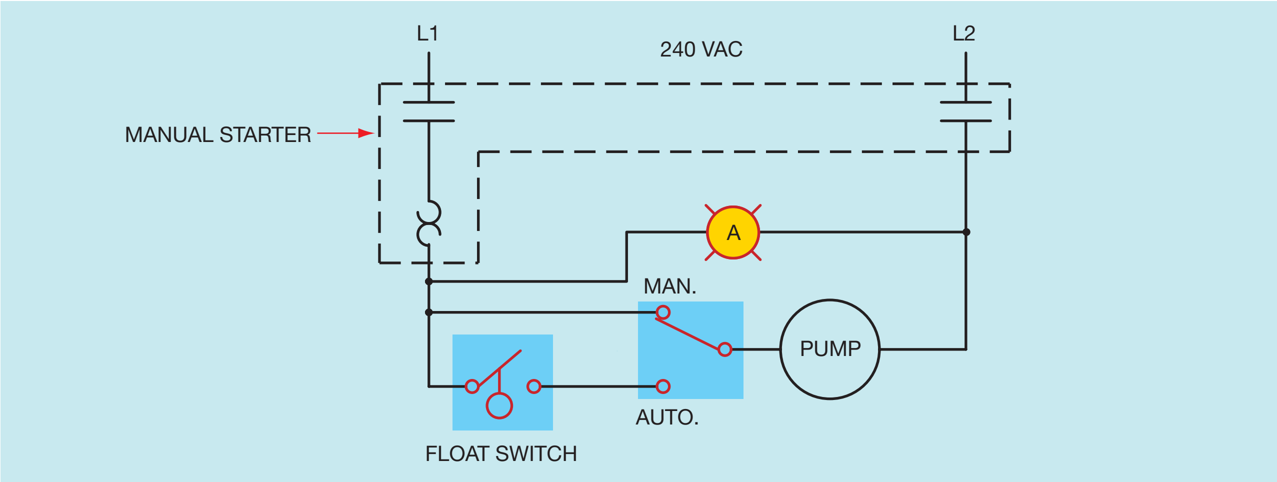


Figure 3–9 Pump can be controlled either manually or automatically. (Source: Delmar/Cengage Learning.)

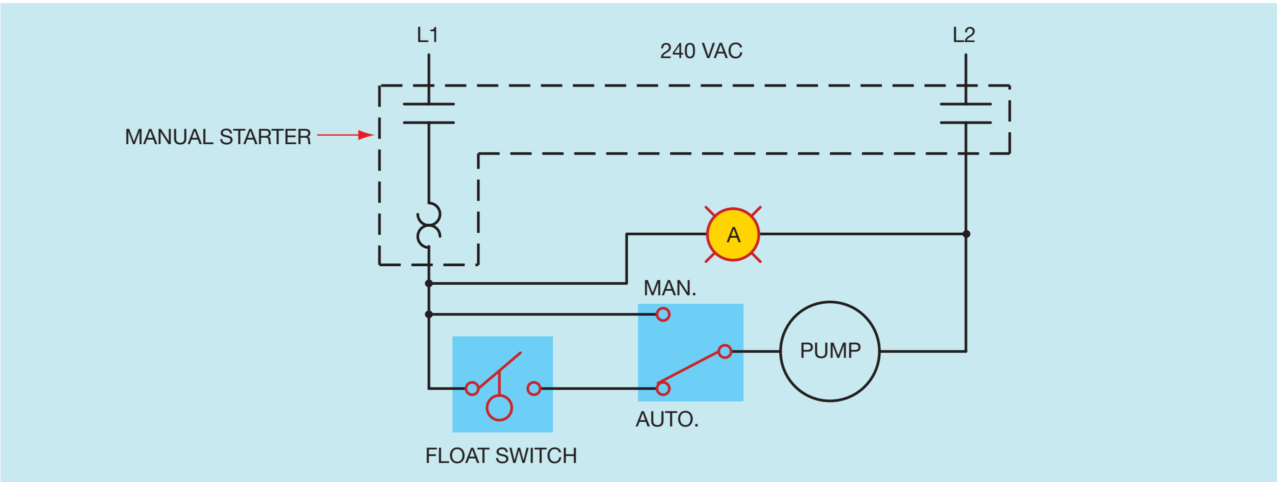


Figure 3–10 Moving the switch to the AUTO. position permits the float switch to control the pump. (Source: Delmar/Cengage Learning.)

operate on 240 volts, or direct current motors. The starters that contain three contacts are intended to control three-phase motors. Push-button type manual starters are integral, not fractional, horsepower starters. Generally, they can control single-phase motors rated up to 5 horsepower, direct current motors up to 2 horsepower, and three-phase motors up to 10 horsepower. A typical three-contact manual push-button starter is shown in Figure 3–11. A schematic diagram for this type of starter is shown in Figure 3–12.

If any one of the overloads should trip, a mechanical mechanism will open the load contacts and disconnect the motor from the line. Once the starter has tripped on overload, it must be reset before the motor can be restarted. After allowing enough time for the overload heaters to cool, the operator resets the starter by pressing the STOP push button with more than normal pressure. This causes the mechanical mechanism to reset so that the motor can restart when the START push button is pressed. These starters are economical and are generally used with loads that are not started or stopped at frequent intervals. Although this type of starter provides overload protection, it does not provide low voltage release. If the power should fail and then be restored, the motor controlled by this starter will restart without warning.

Figure 3–11 Three-phase line voltage manual starter. (Courtesy Square D Company.)

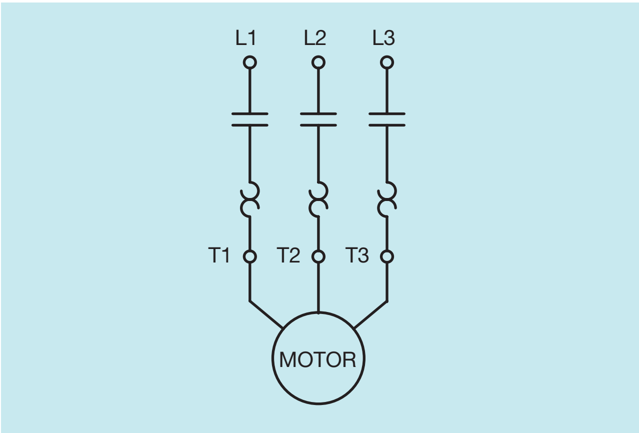


Figure 3–12 Schematic diagram for a three-pole line voltage manual starter. (Source: Delmar/Cengage Learning.)

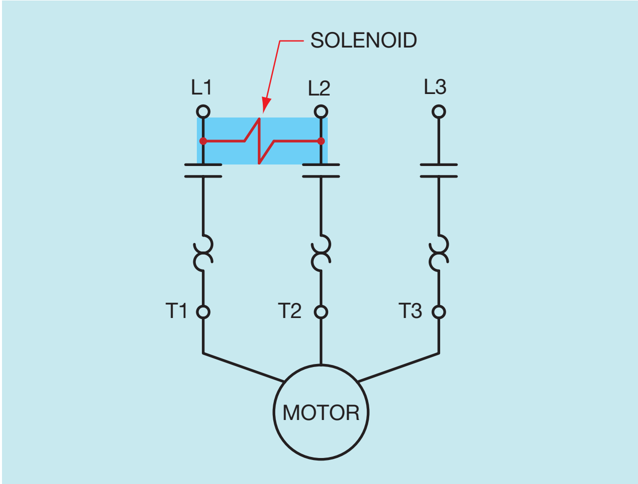


Figure 3–13 Solenoid provides low voltage release for the manual starter. (Source: Delmar/Cengage Learning.)

Figure 3–14 Manual starter with low voltage release. (Courtesy Square D Co.)

Manual Starter with Low Voltage Release

Integral horsepower manual starters with low voltage release will not restart after a power failure without being reset. Resetting is accomplished by connecting a solenoid across the incoming power lines (Figure 3–13). As long as power is supplied to the starter, the solenoid holds a spring loaded mechanism in place. And as long as the mechanism is held in place, the load contacts can be closed when the START button is pressed. If the power should be interrupted, the spring loaded mechanism mechanically opens the contacts and prevents them from being re-closed until the starter has been manually reset. This starter will not operate unless power is present at the line terminal. This starter should not be confused with magnetic starters controlled by a coil. Magnetic type starters are designed to be used with other pilot control devices that control the operation of the starter. A manual starter with low voltage release is shown in Figure 3–14.

Troubleshooting

Anytime a motor has tripped on overload, the electrician should check the motor and circuit to determine why the overload tripped. The first step is generally to determine if the motor is actually overloaded. Some common causes of motor overloads are bad bearings in either the motor or the load the motor operates. Shorted windings in the motor can cause the motor to draw excessive current without being severe enough to blow a fuse or trip a circuit breaker. The simplest way to determine if the motor is overloaded is to find the motor full load current on the nameplate and then check the running current with an ammeter (Figure 3–15). If checking a single-phase motor, it is necessary to check only one of the incoming lines. If checking a three-phase motor, check each line individually. The current flow in each line of a three-phase motor should be close to the same. A small amount of variation is not uncommon, but if the current is significantly different in any of the lines, that is an indication of internally shorted windings. Overloads are generally set to trip at 115% to 125% of motor full load current, depending on the motor. If the ammeter reveals that the motor is drawing excessive current, the electrician must determine the reason before the motor can be put back into operation.

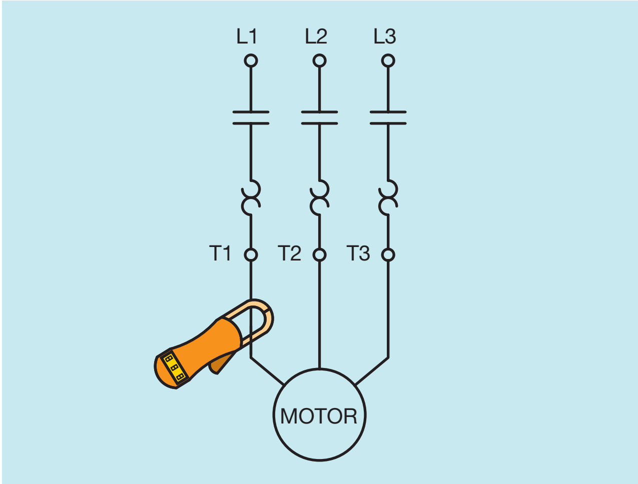


Figure 3–15 Checking motor current. (Source: Delmar/Cengage Learning.)

Excessive current is not the only cause for an overload trip. Thermal overloads react to heat, so any heat source can cause an overload to trip. If the motor is not drawing an excessive amount of current, the electrician should determine any other sources of heat. Loose connections are one of the greatest sources of heat. Check the wires for insulation that has been overheated close to terminal screws. Any loose connection on the starter can cause an overload trip; make sure that all connections are tight. Another source of heat is ambient, or surrounding, air temperature. In hot climates, the surrounding air temperature combined with the heat caused by motor current can be enough to cause the overload to trip. It may be necessary to set a fan that blows on the starter to help remove excess heat. Manual starters that are installed in a switchbox inside a wall are especially susceptible to ambient temperature problems. In this case, it may be necessary to install some type of vented cover plate.

Review Questions

1. A single-phase 120 volt motor is controlled by a manual motor starter. The motor is not running, and the switch handle on the starter is found to be in the center position. What does this indicate?
2. Referring to the above question, what action is necessary to restart the motor and how is it accomplished?
3. A single-phase motor operates on 240 volts. Why should a starter that contains two load contacts be used to control this motor?
4. A push-button manual starter has tripped on overload. Explain how to reset the starter so the motor can be restarted.
5. What is meant by the term "line voltage" on some pilot sensing devices?
6. Explain the difference between manual motor starters that provide low voltage release and those that do not.
7. What is the simplest way to determine if a motor is overloaded?
8. Refer to the circuit shown in Figure 3–7. What type of switch is connected in series with the motor, and is the switch normally open, normally closed, normally open held closed, or normally closed held open?

9. Refer to the circuit shown in Figure 3–10. When would the amber pilot light be turned on?
   a. When the manual-automatic switch is set in the MAN. position.
   b. When the float switch contacts are closed.
   c. Anytime the manual starter is turned on.
   d. Only when the manual-automatic switch is set in the MAN. position.

10. Refer to the circuit shown in Figure 3–10. Is the float switch normally open, normally closed, normally open held closed, or normally closed held open?

CHAPTER 4
OVERLOAD RELAYS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss differences between fuses and overloads.
- List different types of overload relays.
- Describe how thermal overload relays operate.
- Describe how magnetic overload relays operate.
- Describe how dashpot overload relays operate.

Overloads

Overloads should not be confused with fuses or circuit breakers. Fuses and circuit breakers are designed to protect the circuit from a direct ground or short-circuit condition. Overloads are designed to protect the motor from an overload condition. Assume, for example, that a motor has a full load current rating of 10 amperes. Also assume that the motor is connected to a circuit that is protected by a 20 ampere circuit breaker, Figure 4–1. Now assume that the motor becomes overloaded and has a current draw of 15 amperes. The motor is drawing 150% of full load current. This much of an overload will overheat the motor and damage the windings. But, since the current is only 15 amperes, the 20 ampere circuit breaker will not open the circuit to protect the motor. Overload relays are designed to open the circuit when the current becomes 115% to 125% of the motor full load current. The setting of the overload is dependent on the properties of the motor that is to be protected.

Overload Properties

There are certain properties that all overload relays must possess in order to protect a motor:

1. **They must have some means of sensing motor current.** Some overload relays do this by converting motor current into a proportionate amount of heat, and others sense motor current by the strength of a magnetic field.
2. **They must have some type of time delay.** Motors typically have a current draw of 300% to 800% of motor full load current when they start. Motor starting current is referred to as *locked rotor current.* Since overload relays are generally set to trip at 115% to 125% of full load motor current, the motor could never start if the overload relay tripped instantaneously.
3. **They are divided into two separate sections: the current sensing section and the contact section.** The current sensing section is connected in series

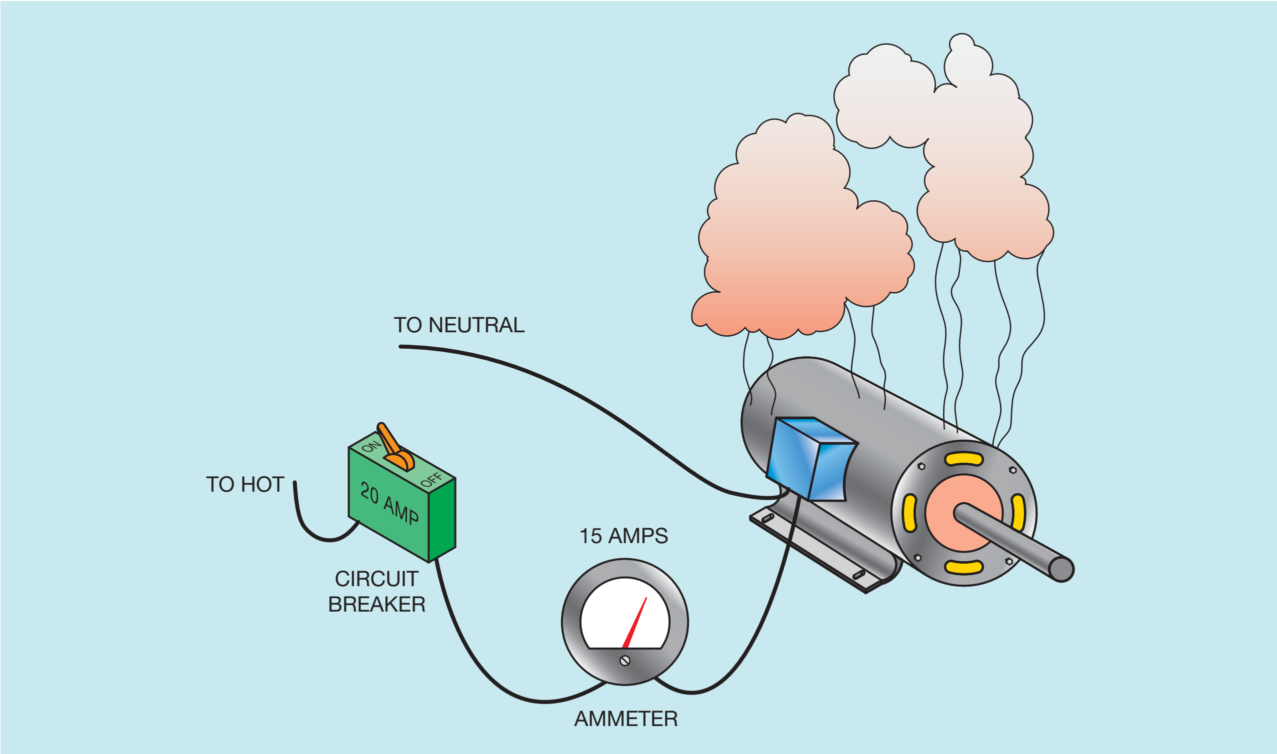


Figure 4–1 The circuit breaker does not protect the motor from an overload. (Source: Delmar/Cengage Learning.)

with the motor and senses the amount of motor current. This section is typically connected to voltages that range from 120 volts to 600 volts. The contact section is part of the control circuit and operates at the control circuit voltage. Control circuit voltages generally range from 24 volts to 120 volts, although some controls operate on line voltages of 240 or 480 volts.

Dual Element Fuses

There are some fuses that are intended to provide both short circuit protection and overload protection. These fuses are called dual element time delay fuses. They contain two sections (Figure 4–2). The first contains a fuse link that is designed to open quickly under a large amount of excessive current. This protects the circuit against direct grounds and short circuits. The second section acts more slowly; it contains a solder link that is connected to a spring. The solder is a highly controlled alloy designed to melt at a particular temperature. If motor current becomes excessive, the solder will melt and the spring will pull the link apart. The desired time delay is achieved because of the time it takes for the solder to melt even under a large amount of current. If motor current returns to normal after starting, the solder will not get hot enough to melt.

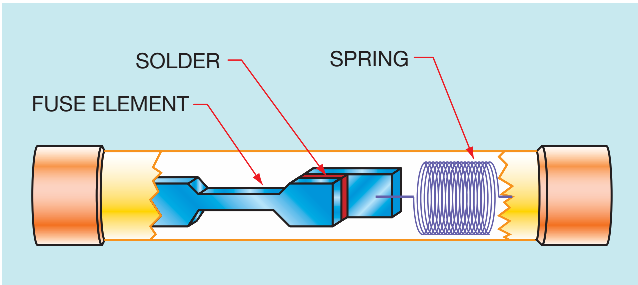


Figure 4–2 Dual element time delay fuse. (Source: Delmar/Cengage Learning.)

Thermal Overload Relays

There are two major types of overload relays: thermal and magnetic. Thermal overloads operate by connecting a heater in series with the motor. The amount of heat produced is dependent on motor current. Thermal overloads can be divided into two types: solder melting type or solder pot, and bimetal strip type. Since thermal overload relays operate on the principle of heat, they are sensitive to ambient (surrounding air) temperature. They will trip faster when located in a warm area than they will in a cool area.

Solder Melting Type

Solder melting type overloads are often called *solder pot overloads*. To create this type of overload, a brass shaft is placed inside a brass tube. A serrated wheel is connected to one end of the brass shaft. A special alloy solder that melts at a very specific temperature keeps the brass shaft mechanically connected to the brass tube (Figure 4–3). The serrated wheel keeps a set of spring loaded contacts closed (Figure 4–4). An electric heater is placed around or close to the brass tube. The heater is connected in series with the motor. Motor current causes the heater to produce heat. If the current is great enough

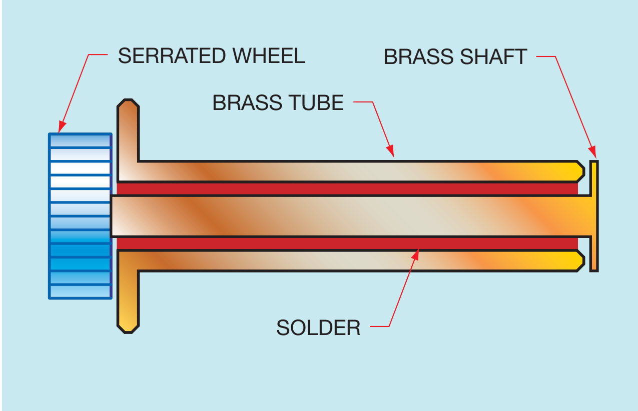


Figure 4–3 Construction of a typical solder pot overload. (Source: Delmar/Cengage Learning.)

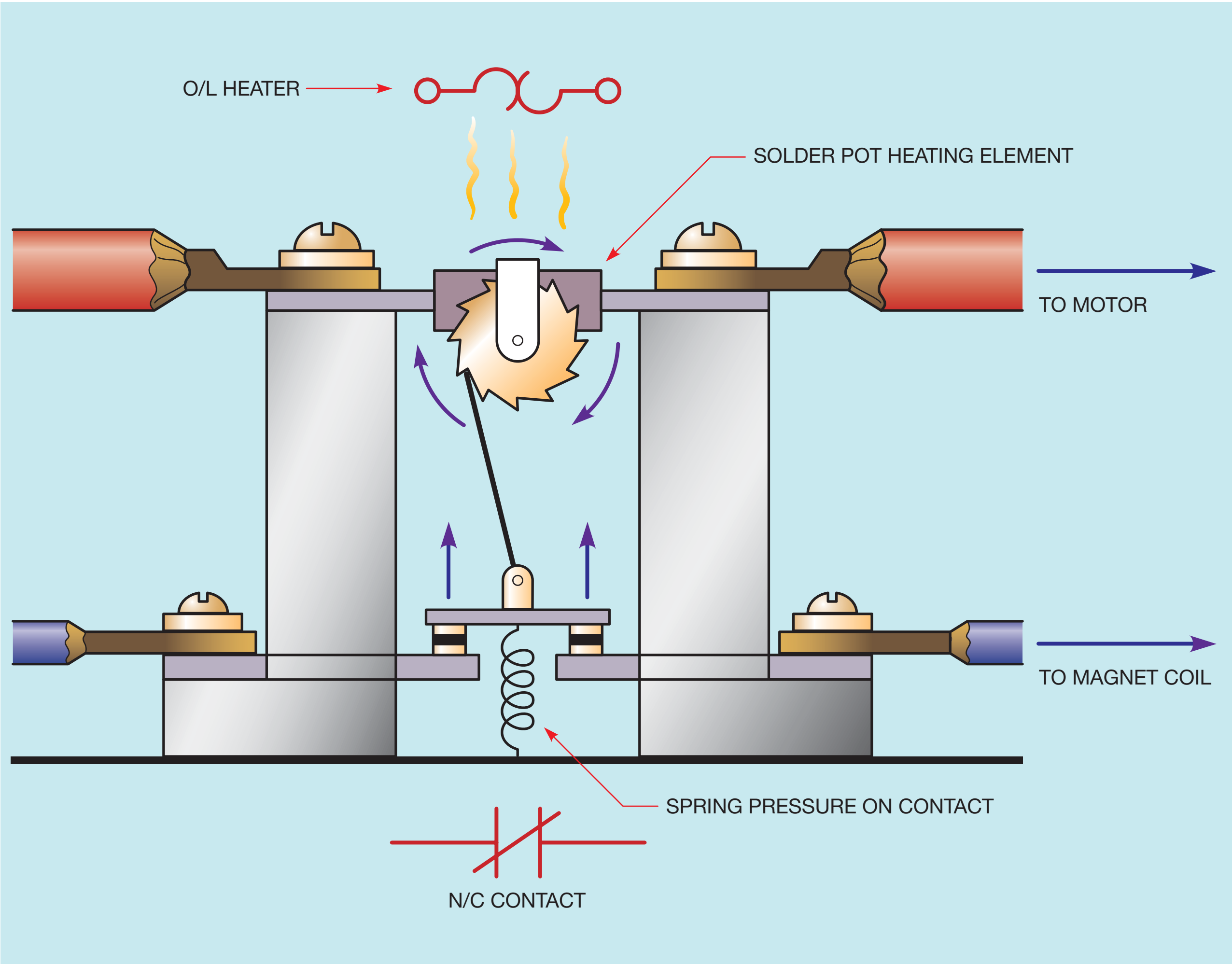


Figure 4–4 Melting alloy thermal overload relay. A spring pushes the contacts open if heat melts the solder and permits the serrated wheel to turn freely. Note the electrical symbols for the normally closed overload contact and the heater element. (Source: Delmar/Cengage Learning.)

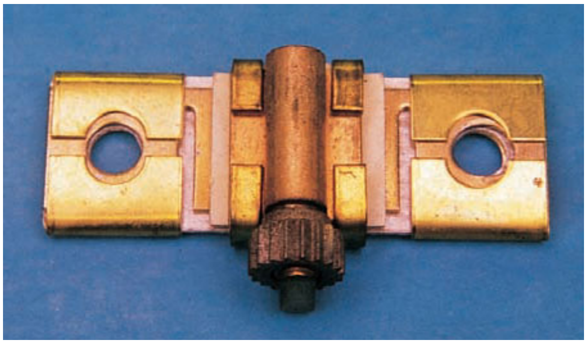


Figure 4–5A Solder melting type overload heater. (Source: Delmar/Cengage Learning.)

for a long enough period of time, the solder will melt and permit the brass shaft to turn inside the tube, causing the contact to open. The fact that some amount of time must elapse before the solder can become hot enough to melt provides the time delay for this overload relay. A large overload will cause the solder to melt faster and cause the contacts to open more quickly than a smaller amount of overload current.

Solder melting type overload heaters are constructed differently by different manufacturers, but all work on the same principle. Two different types of melting alloy heater assemblies are shown in Figure 4–5, parts A and B. A typical melting alloy type overload relay is shown in Figure 4–6. After the overload relay has tripped, it is necessary to allow the relay to cool for two or three minutes before it can be reset. This cool-down time is necessary to permit the solder to become hard again after it has melted.

Figure 4–5B Solder melting overload heater for an allen Bradley overload relay. (Source: Delmar/Cengage Learning.)

The trip current setting can be changed by changing the heater. Manufacturers provide charts that indicate what size heater should be installed for different amounts of motor current. It is necessary to use the chart that corresponds to the particular type of overload relay. Not all charts present the information in the same manner. Be sure to read the instructions contained with the chart when selecting heater sizes. A typical overload heater chart is shown in Figure 4–7.

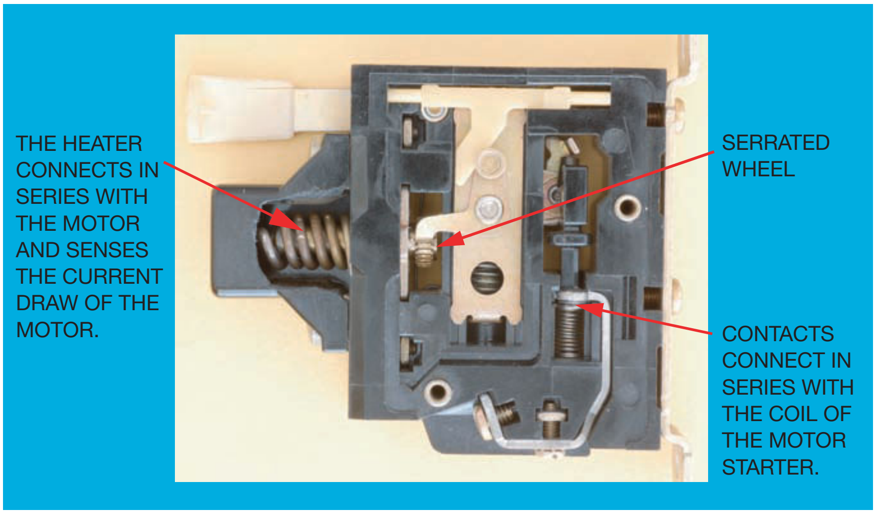


Figure 4–6 Typical alloy melting type of single-phase overload relay. (Source: Delmar/Cengage Learning.)

OVERLOAD HEATER SELECTION FOR NEMA STARTER SIZES 00 - 1. HEATERS ARE CALIBRATED FOR 115% OF MOTOR FULL LOAD CURRENT. FOR HEATERS THAT CORRESPOND TO 125% OF MOTOR FULL LOAD CURRENT USE THE NEXT SIZE LARGER HEATER.					
HEATER CODE	MOTOR FULL LOAD CURRENT	HEATER CODE	MOTOR FULL LOAD CURRENT	HEATER CODE	MOTOR FULL LOAD CURRENT
XX01	.25 - .27	XX18	1.35 - 1.47	XX35	6.5 - 7.1
XX02	.28 - .31	XX19	1.48 - 1.62	XX36	7.2 - 7.8
XX03	.32 - .34	XX20	1.63 - 1.78	XX37	7.9 - 8.5
XX04	.35 - .38	XX21	1.79 - 1.95	XX38	8.6 - 9.4
XX05	.39 - .42	XX22	1.96 - 2.15	XX39	9.5 - 10.3
XX06	.43 - .46	XX23	2.16 - 2.35	XX40	10.4 - 11.3
XX07	.47 - .50	XX24	2.36 - 2.58	XX41	11.4 - 12.4
XX08	.51 - .55	XX25	2.59 - 2.83	XX42	12.5 - 13.5
XX09	.56 - .62	XX26	2.84 - 3.11	XX43	13.6 - 14.9
XX10	.63 - .68	XX27	3.12 - 3.42	XX44	15.0 - 16.3
XX11	.69 - .75	XX28	3.43 - 3.73	XX45	16.4 - 18.0
XX12	.76 - .83	XX29	3.74 - 4.07	XX46	18.1 - 19.8
XX13	.84 - .91	XX30	4.08 - 4.39	XX47	19.9 - 21.7
XX14	.92 - 1.00	XX31	4.40 - 4.87	XX48	21.8 - 23.9
XX15	1.01 - 1.11	XX32	4.88 - 5.3	XX49	24.0 - 26.2
XX16	1.12 - 1.22	XX33	5.4 - 5.9		
XX17	1.23 - 1.34	XX34	6.0 - 6.4		

Figure 4–7 Typical overload heater chart. (Source: Delmar/Cengage Learning.)

Bimetal Strip Overload Relay

The second type of thermal overload relay is the bimetal strip overload. Like the melting alloy type, it operates on the principle of converting motor current into a proportionate amount of heat. The difference is that the heat is used to cause a bimetal strip to bend or warp. A bimetal strip is made by bonding together two different types of metal that expand at different rates (Figure 4–8). Since the metals expand at different rates, the strip will bend or warp with a change of temperature (Figure 4–9). The amount of warp is determined by:

1. The type of metals used to construct the bimetal strip.
2. The difference in temperature between the two ends of the strip.
3. The length of the strip.

The overload heater heats the bimetal strip when motor current flows through it. The heat causes the

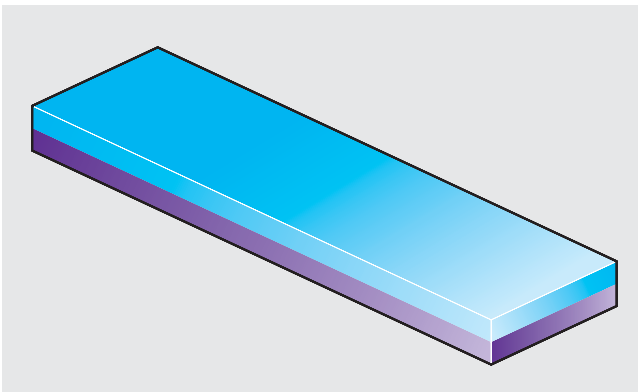


Figure 4–8 A bimetal strip is constructed by bonding two different types of metal together. (Source: Delmar/Cengage Learning.)

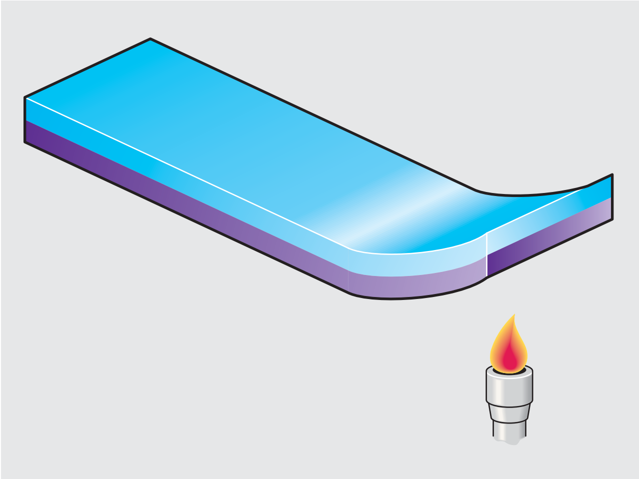


Figure 4–9 A bimetal strip warps with a change of temperature. (Source: Delmar/Cengage Learning.)

bimetal strip to warp. If the bimetal strip becomes hot enough, it will cause a set of contacts to open (Figure 4–10). Once the overload contact has opened, about 2 minutes of cool-down time is needed to permit the bimetal strip to return to a position that will permit the contacts to be re-closed. The time delay factor for this overload relay is the time required for the bimetal strip to warp a sufficient amount to open the normally closed contact. A large amount of overload current will cause the bimetal strip to warp at a faster rate and open the contact sooner.

Most bimetal strip type overload relays have a couple of features that are not available with solder melting type overload relays. As a general rule, the trip range can be adjusted by turning a knob, as shown in Figure 4–10. This knob adjusts the distance the bimetal strip must warp before opening contacts. This adjustment permits the sensitivity to be changed due to changes in ambient air temperature. If the knob is set in the 100% position (Figure 4–11), the overload operates at the full load current rating as determined by the size of overload heater installed. In cold winter months, this setting may be too high to protect the motor. The knob can be adjusted in cold conditions to operate at any point from 100% to 85% of the motor full load current. In hot summer months, the motor may “nuisance trip” due to high ambient temperatures. For hot conditions, the adjustment knob permits the overload relay to be adjusted between 100% and 115% of motor full load current.

Another difference from the solder melting type is that many bimetal strip type overload relays can be set for either manual or automatic reset. A spring located on the side of the overload relay permits this setting (Figure 4–12). When set in the manual position, the contacts must be reset manually by pushing the reset lever. This is probably the most common setting for an overload relay. If the overload relay has been adjusted for automatic reset, the contacts will re-close by themselves after the bimetal strip has cooled sufficiently. This may be a safety hazard if it could cause the sudden restarting of a machine. Overload relays should be set

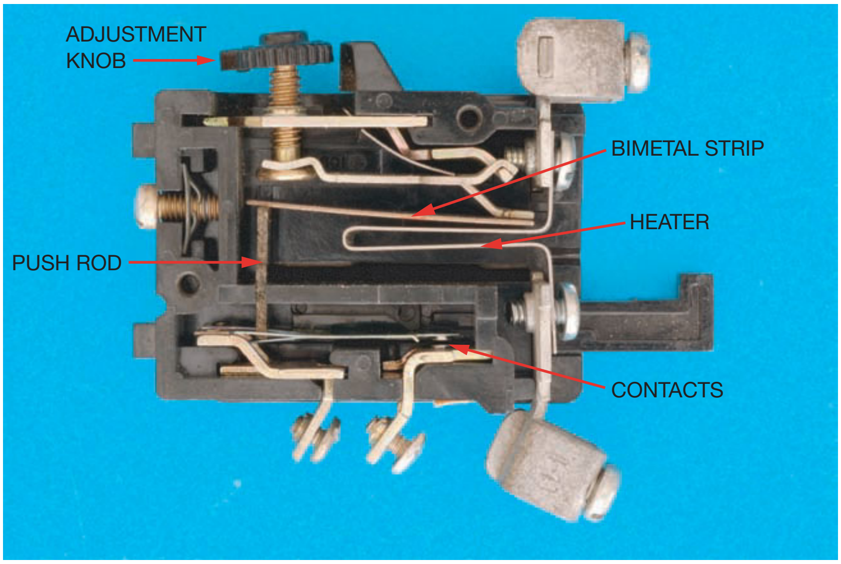


Figure 4–10 Bimetal strip type of overload relay. (Source: Delmar/Cengage Learning.)

Figure 4–11 An adjustment knob permits the current setting to be adjusted between 85% and 115% of the heater rating. (Source: Delmar/Cengage Learning.)

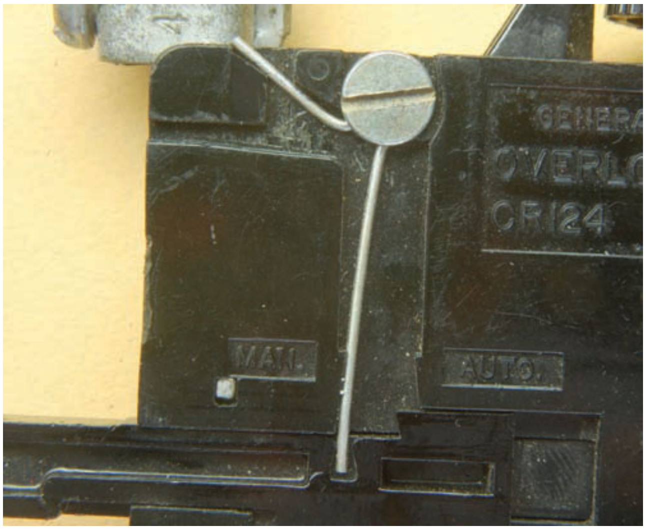


Figure 4–12 Many bimetal strip type overload relays can be adjusted for manual or automatic reset. (Source: Delmar/Cengage Learning.)

in the automatic reset position only when there is no danger of someone being hurt or equipment being damaged when the overload contacts suddenly re-close.

Three-Phase Overloads

The overload relays discussed so far are intended to detect the current of a single conductor supplying power to a motor (Figure 4–13). An application for this

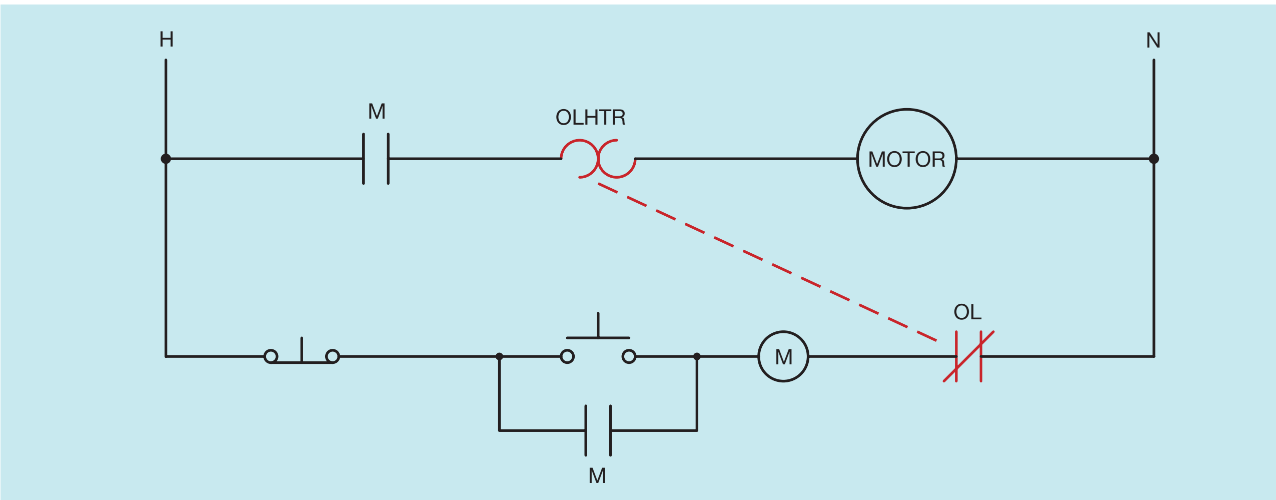


Figure 4–13 A single-overload relay is used to protect a single-phase motor. (Source: Delmar/Cengage Learning.)

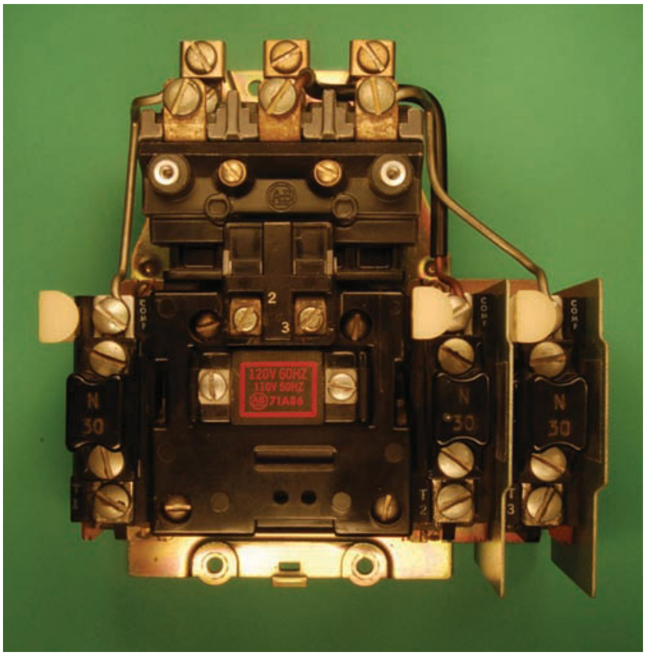


Figure 4–14 Three single-phase overload relays are used to sense the current in each line of a three-phase motor. (Source: Delmar/Cengage Learning.)

type of overload relay is to protect a single-phase or direct current motor. NEC requires only one overload sensor device to protect a direct current motor or a single-phase motor, whether it operates on 120 or 240 volts. Three-phase motors, however, must have an overload sensor (heaters or magnetic coils) in each of the three-phase lines. Some motor starters accomplish this by employing three single-overload relays to independently sense the current in each of the three-phase lines (Figure 4–14). When this is done, the normally closed contact of each overload relay is connected in series as shown in Figure 4–15. If any one of the relays should open its normally closed contact, power to the starter coil is interrupted and the motor is disconnected from the power line.

Overload relays are also made that contain three overload heaters and one set of normally closed contacts, Figure 4–16. These relays are generally used to protect three-phase motors. Although there is only one set of normally closed contacts, if an overload occurs on any one of the three heaters it causes the contacts to open and disconnect the coil of the motor starter (Figure 4–17).

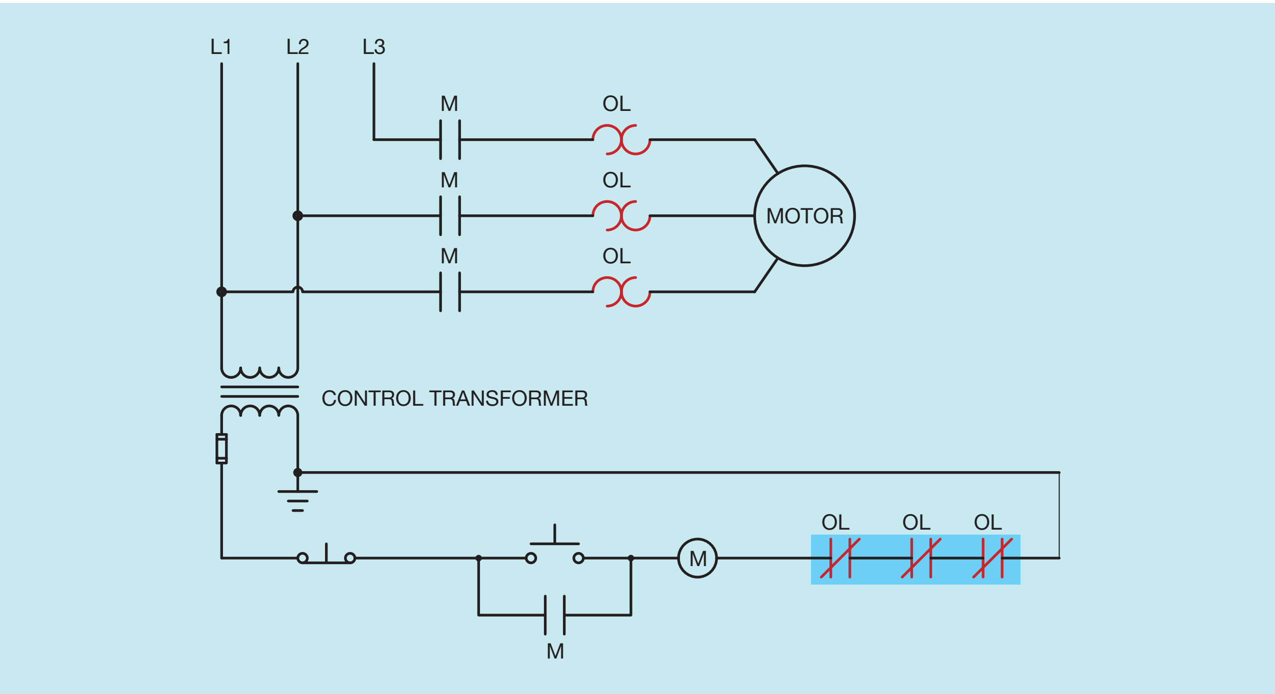


Figure 4–15 When three single-phase overload relays are employed to protect a three-phase motor, the normally closed contacts of each overload relay are connected in series. (Source: Delmar/Cengage Learning.)

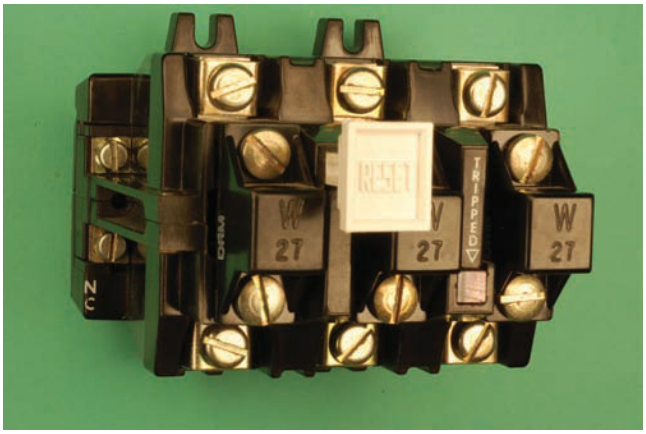


Figure 4–16 Three-phase thermal overload relay. (Source: Delmar/Cengage Learning.)

Magnetic Overload Relays

Magnetic type overload relays operate by sensing the strength of the magnetic field produced by the current flowing to the motor. The greatest difference between magnetic type and thermal type overload relays is that magnetic types are **not** sensitive to ambient temperature. Magnetic type overload relays are generally used in areas that exhibit extreme changes in ambient temperature. Magnetic overload relays can be divided into two major types: electronic and dashpot.

Electronic Overload Relays

Electronic overload relays employ a current transformer to sense the motor current. The conductor that supplies power to the motor passes through the core of a toroid transformer (Figure 4–18). As current flows through the conductor, the alternating magnetic field around the conductor induces a voltage into the toroid transformer. The amount of induced voltage is proportional to the amount of current flowing through the conductor. This is the same basic principle of operation employed by most clamp-on type ammeters. The voltage induced into the toroid transformer is transmitted through a connected electronic interface that provides the time delay necessary to permit the motor to start. Many electronic type overload relays are programmable and can be set for the amount of full load motor current, maximum and minimum voltage levels, percentage of overload, and other factors. A three-phase electronic overload relay is shown in Figure 4–19.

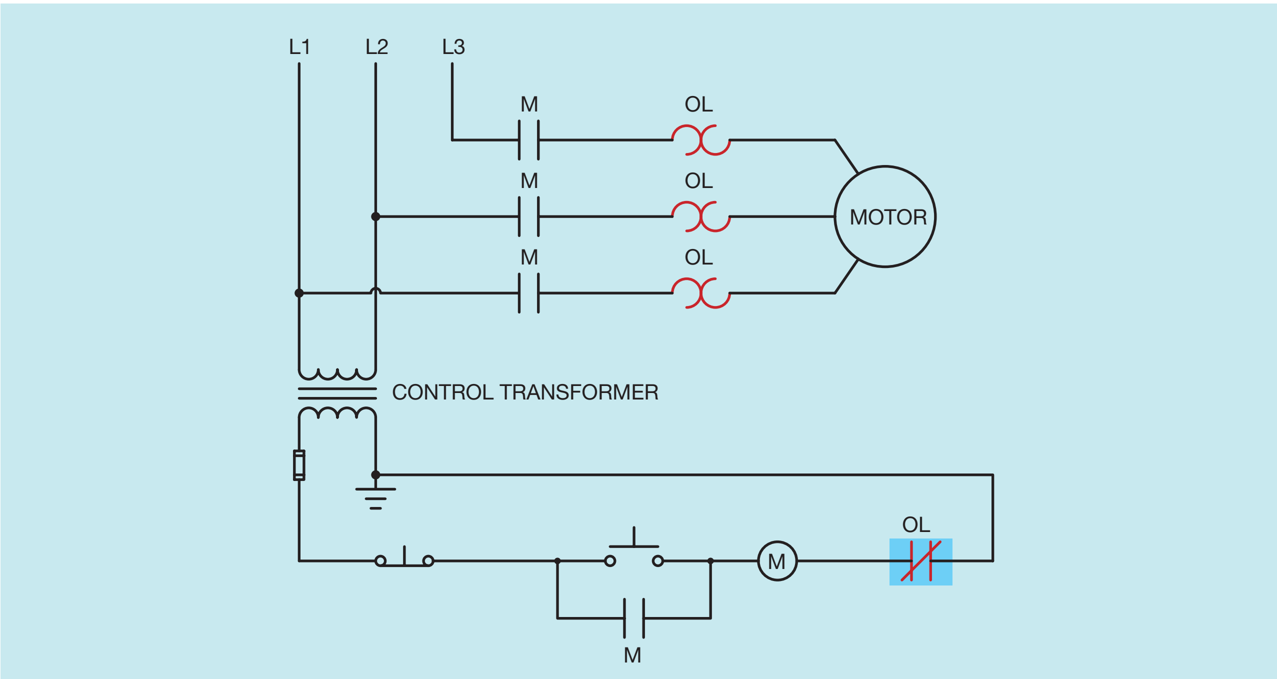


Figure 4–17 A three-phase overload relay contains three overload heaters but one set of normally closed contacts. (Source: Delmar/Cengage Learning.)

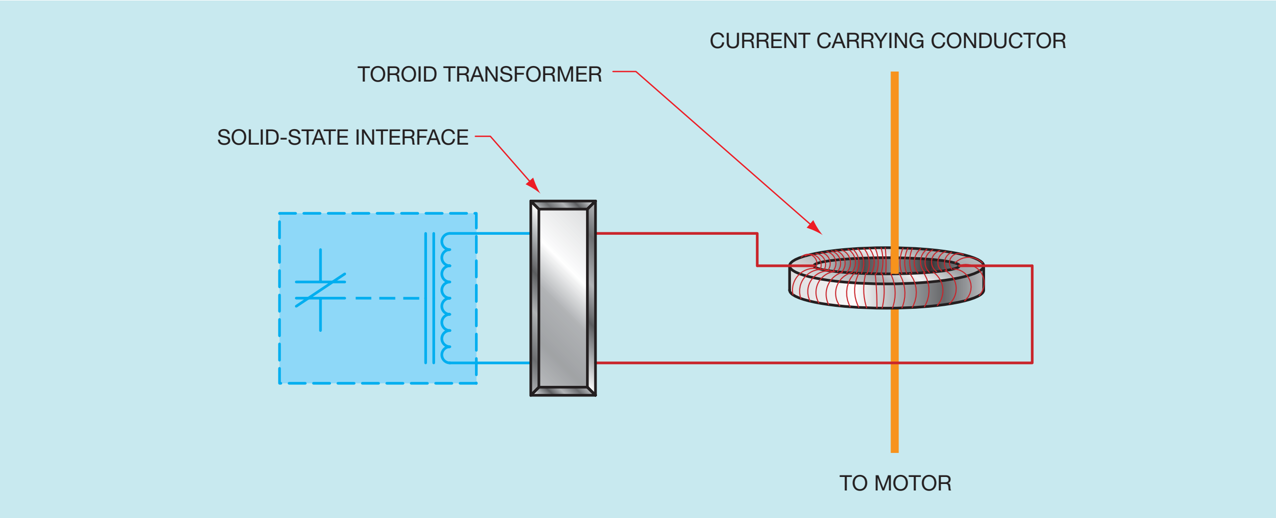


Figure 4–18 Electronic overloads sense motor current by measuring the strength of a magnetic field. (Source: Delmar/Cengage Learning.)

Figure 4–19 Three-phase electronic overload relay. (Courtesy Square D Co.)

Figure 4–20 A dashpot timer consists mainly of a piston, shaft, and container. (Source: Delmar/Cengage Learning.)

Dashpot Overload Relays

Dashpot overload relays receive their name from the device used to accomplish the time delay that permits the motor to start. A dashpot timer is basically a container, a piston, and a shaft (Figure 4–20). The piston is placed inside the container, and the container is filled with a special type of oil called *dashpot oil* (Figure 4–21). Dashpot oil maintains a constant viscosity over a wide range of temperatures. The type and viscosity of oil used is one of the factors that determine the amount of time delay for the timer. The other factor is the setting of the opening of the orifice holes in the piston (Figure 4–22). Orifice holes permit the oil to flow through the piston as it rises through the oil. The opening of the orifice holes can be set by adjusting a sliding valve on the piston.

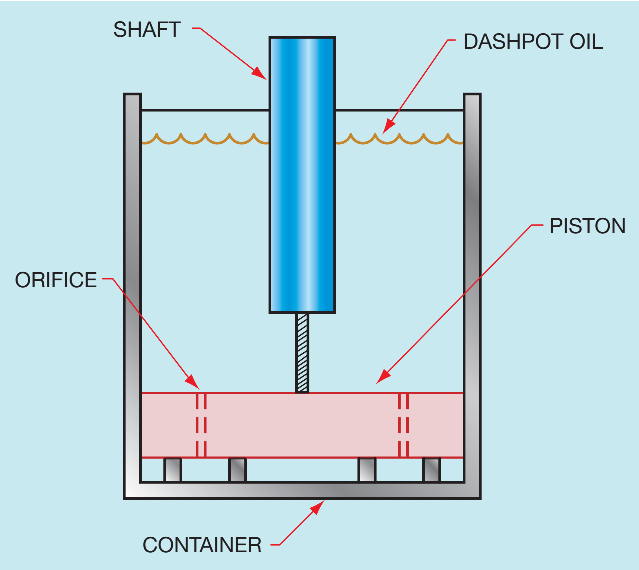


Figure 4–21 Basic construction of a dashpot timer. (Source: Delmar/Cengage Learning.)

Figure 4–22 Setting the opening of the orifices affects the time delay of the dashpot timer. (Source: Delmar/Cengage Learning.)

The dashpot overload relay contains a coil that is connected in series with the motor (Figure 4–23). As current flows through the coil, a magnetic field is developed around the coil. The strength of the magnetic field is proportional to the motor current. This magnetic field draws the shaft of the dashpot timer into the coil. The shaft's movement is retarded by the fact that the piston must displace the oil in the container. If

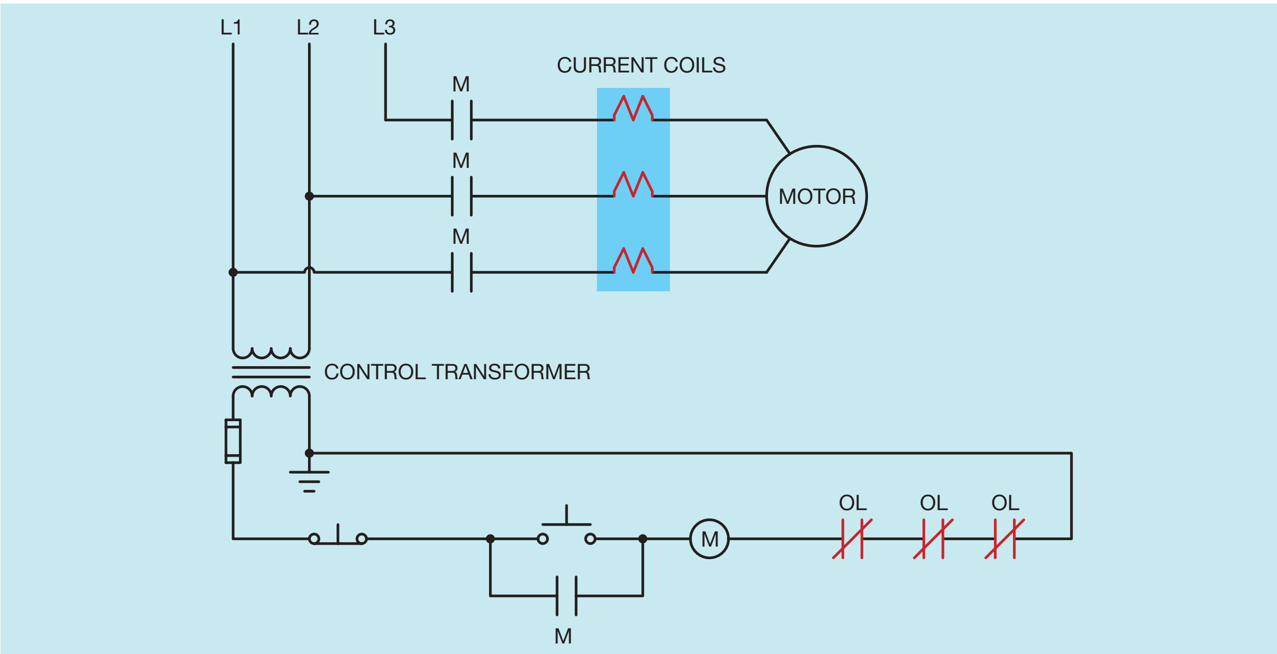


Figure 4–23 Dashpot overload relays contain coils that are connected in series with the motor. (Source: Delmar/Cengage Learning.)

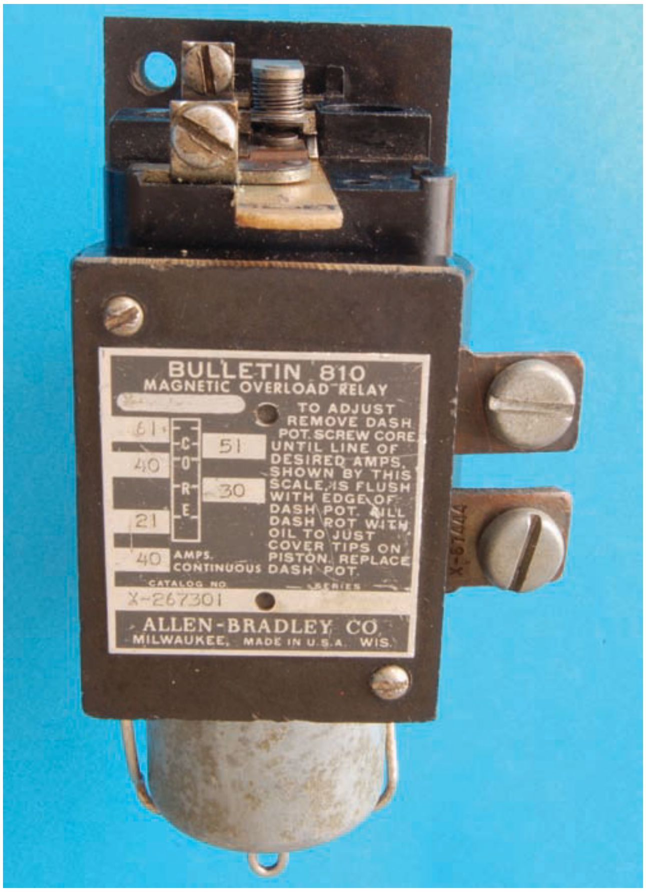


Figure 4–24 Normally closed contacts of a dashpot overload relay. (Source: Delmar/Cengage Learning.)

Figure 4–25 The length of the shaft can be adjusted for different values of current. (Source: Delmar/Cengage Learning.)

the motor is operating normally, the motor current will drop to a safe level before the shaft is drawn far enough into the coil to open the normally closed contact (Figure 4–24). If the motor is overloaded, however, the magnetic field will be strong enough to continue drawing the shaft into the coil until it opens the overload contact. When power is disconnected from the motor, the magnetic field collapses and the piston returns to the bottom of the container. Check valves permit the piston to return to the bottom of the container almost immediately when motor current ceases.

Dashpot overloads generally provide some method that permits the relay to be adjusted for different full load current values. To make this adjustment, the shaft is connected to a threaded rod (Figure 4–25). This permits the shaft to be lengthened or shortened inside the coil. The greater the length of the shaft, the less current is required to draw the shaft into the coil far enough to open the contacts. A nameplate on the coil lists the different current settings for a particular overload relay (Figure 4–26). The adjustment is made by moving the

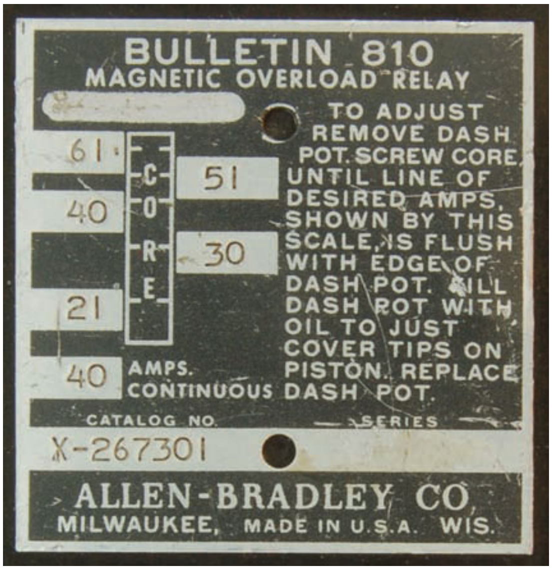


Figure 4–26 The nameplate lists different current values. (Source: Delmar/Cengage Learning.)

Figure 4–27 The line on the shaft that represents the desired amount of current is set flush with the top of the dashpot container. (Source: Delmar/Cengage Learning.)

shaft until the line on the shaft representing the desired current is flush with the top of the dashpot container (Figure 4–27). A dashpot overload relay is shown in Figure 4–28.

Overload Contacts

Although all overload relays contain a set of normally closed contacts, some manufacturers also add a set of normally open contacts as well. These two sets of contacts are either in the form of a single-pole double-throw switch or of two separate contacts. The single-pole double-throw switch arrangement will contain a common terminal (C), a normally closed terminal (NC), and a normally open terminal (NO) (Figure 4–29). There are several reasons for adding the normally open set of contacts. The starter shown in Figure 4–30 uses the normally closed section to disconnect the motor starter in the event of an overload, and uses the normally open

Figure 4–28 Dashpot overload relay. (Courtesy Square D Co.)

Figure 4–29 Overload relay containing both a normally closed and normally open contact. The normally closed contact is labeled OL and the normally open contact is labeled ALAR. (The common contact is labeled COM.) (Source: Delmar/Cengage Learning.)

section to turn on an indicator light to inform an operator that the overload has tripped.

The overload relay shown in Figure 4–31 contains two separate sets of contacts, one normally open and the other normally closed. Another common use for the normally open set of contacts on an overload relay is to provide an input signal to a programmable logic controller (PLC). If the overload trips, the normally closed set of contacts will open and disconnect the starter coil from the line. The normally open set of contacts

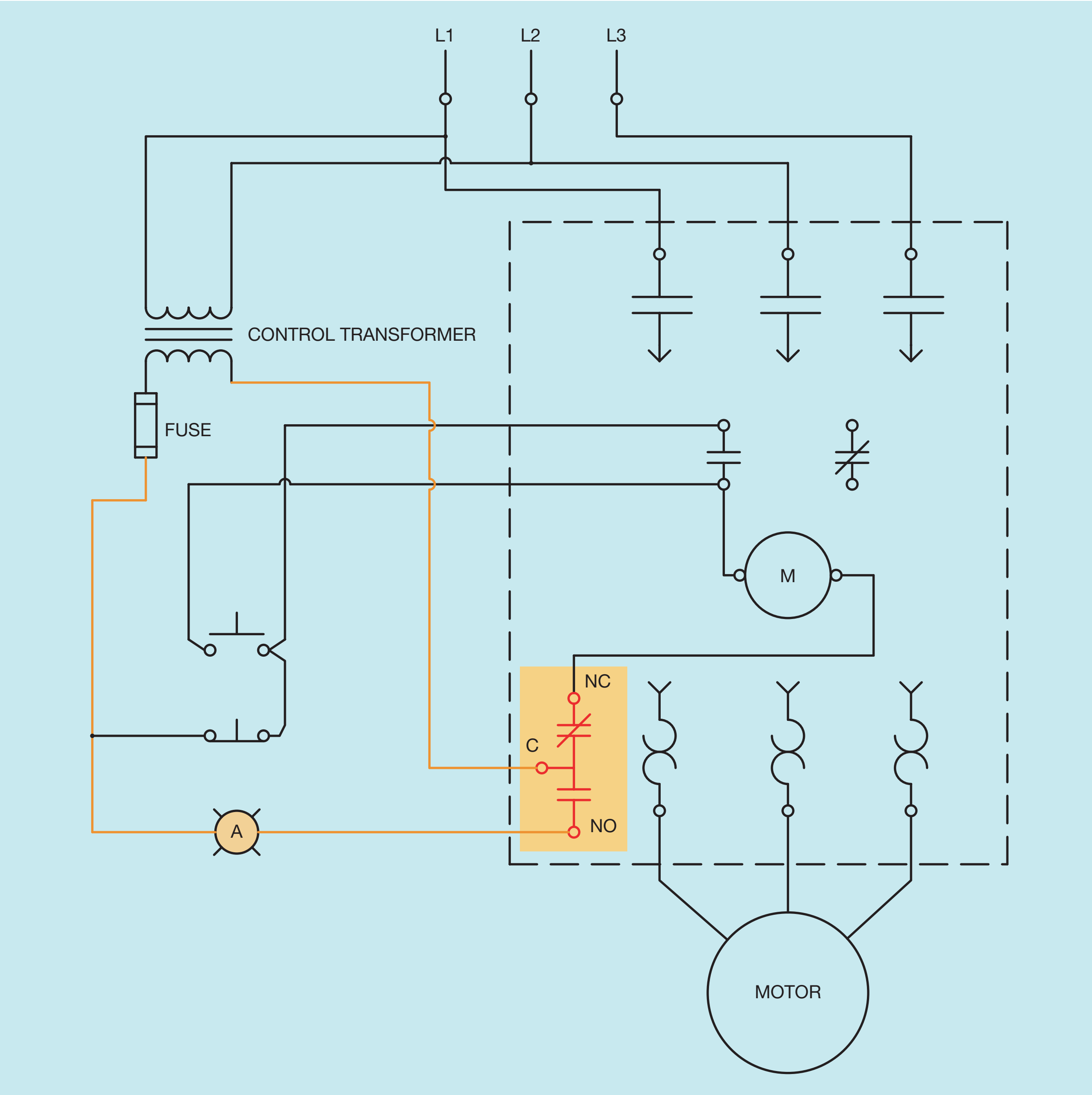


Figure 4–30 The overload relay contains a single-pole double-throw set of contacts. The normally closed section (NC) protects the motor in the event of an overload condition and the normally open section (NO) turns on an indicator lamp to alert an operator that the motor has tripped on overload. (Source: Delmar/Cengage Learning.)

will close and provide a signal to the input of the PLC (Figure 4–32). Notice that two interposing relays, CR1 and CR2, are used to separate the PLC and the motor starter. This is often done for safety reasons. The control relays prevent more than one source of power from entering the starter or PLC. Note that the starter and PLC each have a separate power source. If the power were disconnected from the starter during service or repair, it could cause an injury if the power from the PLC were connected to any part of the starter.

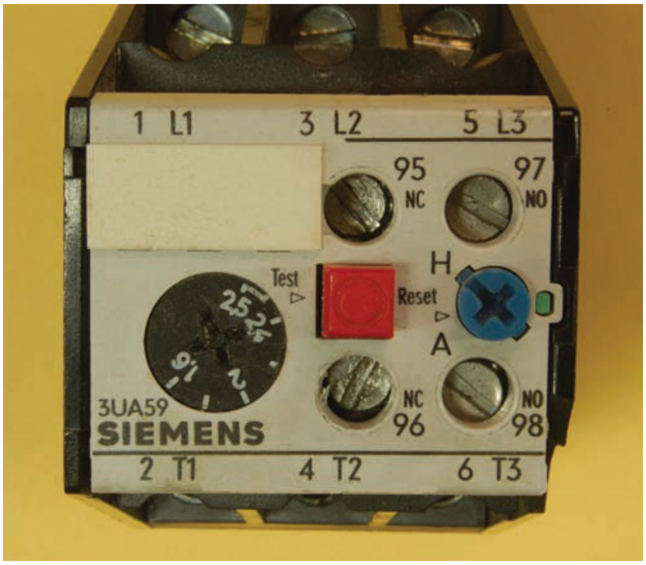


Figure 4–31 An overload relay that contains a normally closed and a normally open contact. (Source: Delmar/Cengage Learning.)

Protecting Large Horsepower Motors

Large horsepower motors often have current draws of several hundred amperes, making the sizing of overload heaters difficult. When this is the case, it is common practice to used current transformers to reduce the amount of current to the overload heaters (Figure 4–33). The current transformers shown in Figure 4–33 have ratios of 150:5. This means that when 150 amperes of current flows through the primary, which is the line connected to the motor, the transformer secondary will produce a current of 5 amperes if the secondary terminals are shorted together. The secondaries of the current transformers are connected to the overload heaters to provide protection for the motor (Figure 4–34). Assume that the motor connected to the current transformers in Figure 4–34 has a full load current of 136 amperes. A simple calculation reveals that current transformers with a ratio of 150:5

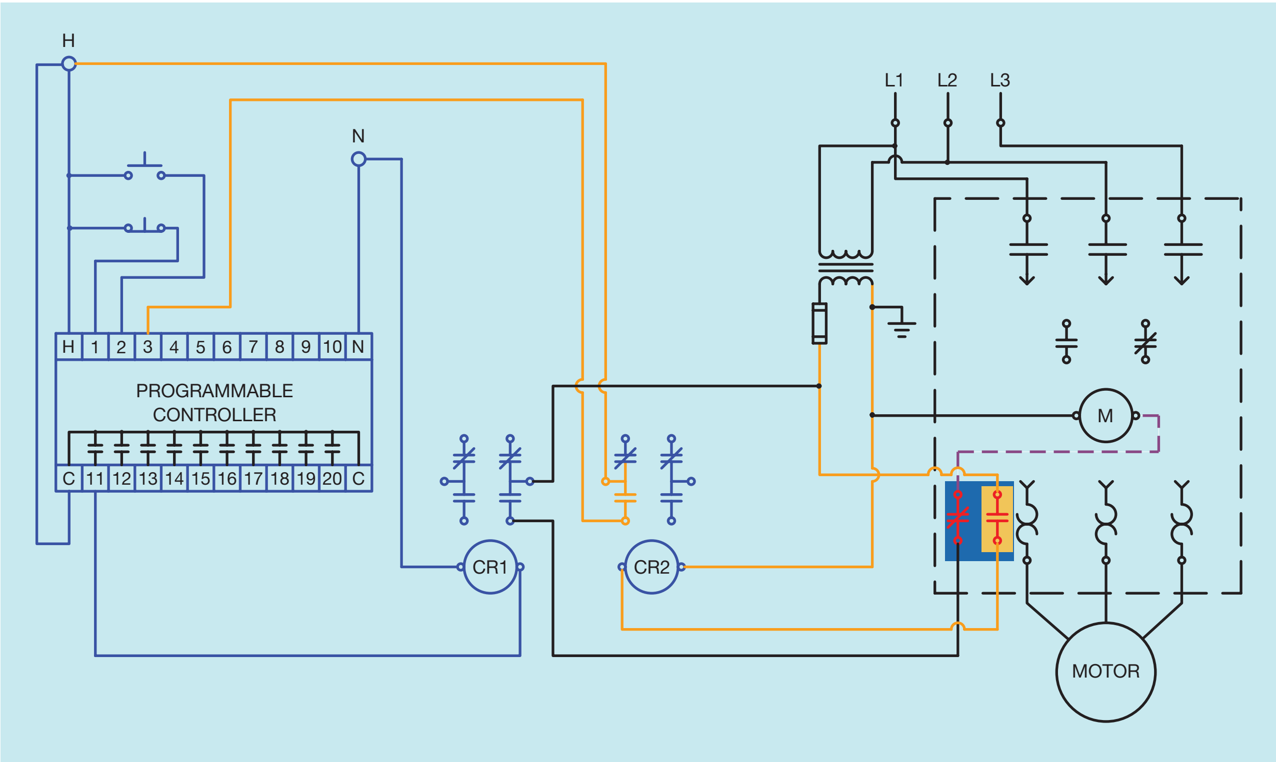


Figure 4–32 The normally open contacts provide a signal to the input of a programmable logic controller. (Source: Delmar/Cengage Learning.)

Figure 4–33 Current transformers are used to reduce overload current. (Source: Delmar/Cengage Learning.)

would produce a secondary current of 4.533 amperes when 136 amperes flow through the primary.

$$\frac{150}{5} = \frac{136}{X}$$

$$150X = 680$$

$$X = \frac{680}{150}$$

$$X = 4.533$$

The overload heaters would actually be sized for a motor with a full load current of 4.533 amperes.

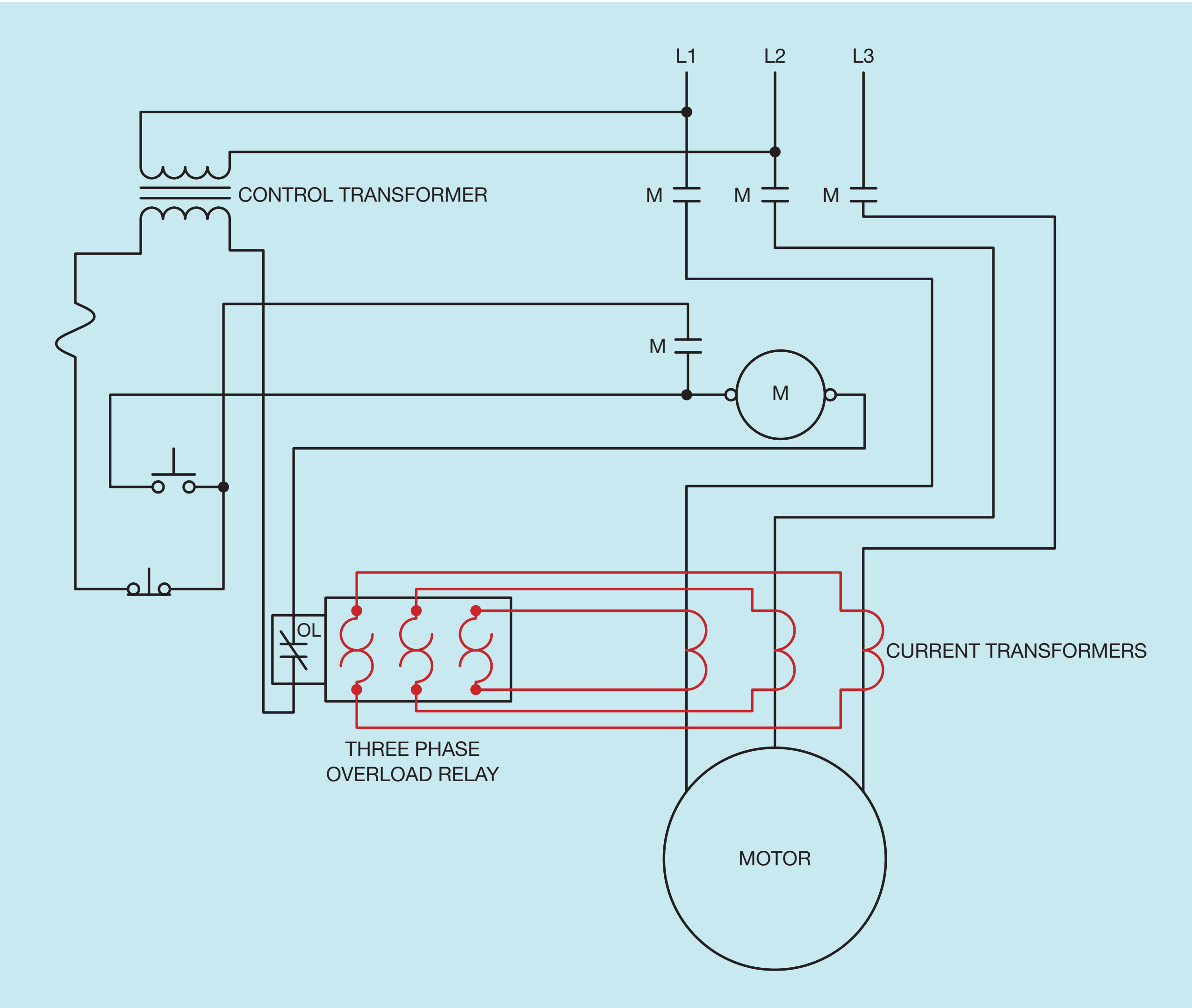


Figure 4–34 Current transformers reduce the current to the overload heaters. (Source: Delmar/Cengage Learning.)

Review Questions

1. What are the two basic types of overload relays?
2. What is the major difference in characteristics between thermal type and magnetic type overload relays?
3. What are the two major types of thermal overload relays?
4. What type of thermal overload relay can generally be set for manual or automatic operation?
5. Why is it necessary to permit a solder melting type of overload relay to cool for 2 to 3 minutes after it has tripped?
6. All overload relays are divided into two sections. What are these two sections?
7. What device is used to sense the amount of motor current in an electronic overload relay?
8. What two factors determine the time setting for a dashpot timer?
9. How many overload sensors are required by the NEC to protect a direct current motor?
10. A large motor has a full load current rating of 425 amperes. Current transformers with a ratio of 600:5 are used to reduce the current to the overload heaters. What should be the full load current rating of the overload heaters?

CHAPTER 5

RELAYS, CONTACTORS, AND MOTOR STARTERS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of magnetic type relay devices.
- Explain the differences between relays, contactors, and motor starters.
- Connect a relay in a circuit.
- Identify the pins of eight- and eleven-pin relays.
- Discuss the differences between DC and AC type relays and contactors.
- Discuss the differences between NEMA and IEC rated starters.

Relays and contactors are electromechanical switches. They operate on the solenoid principle. A coil of wire is connected to an electric current. The magnetic field developed by the current is concentrated in an iron pole piece. The electromagnet attracts a metal armature. Contacts are connected to the metal armature. When the coil is energized, the contacts will open or close. There are two basic methods of constructing a relay or contactor. The clapper type uses one movable contact to make connection with a stationary contact. The bridge type uses a movable contact to make connection between two stationary contacts.

Relays

Relays are electromechanical switches that contain auxiliary contacts. Auxiliary contacts are small and are intended to be used for control applications. As a general rule, they are not intended to control large amounts of current. Current ratings for most relays can vary from 1 to 10 amperes, depending on the manufacturer and type of relay. A clapper type relay is illustrated in Figure 5–1. When the coil is energized, the armature is attracted to the iron core inside the coil. This causes the movable contact to break away from one stationary

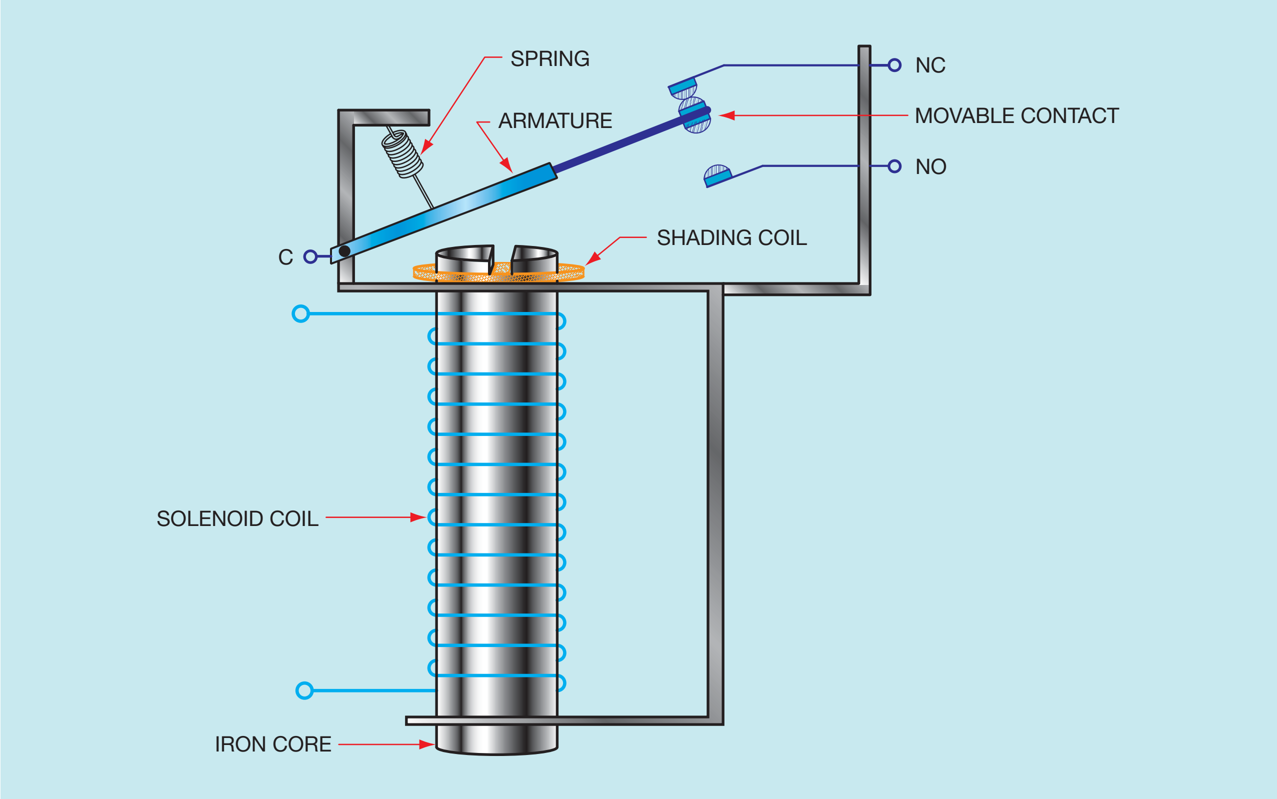


Figure 5–1 A magnetic relay is basically a solenoid with movable contacts attached. (Source: Delmar/Cengage Learning.)

contact and make connection with another. The common terminal is connected to the armature, which is the movable part of the relay. The movable contact is attached to the armature. The two stationary contacts form the normally closed and normally open contacts. A spring returns the armature to the normally closed position when power is removed from the coil. The shading coil is necessary to prevent the contacts from chattering. All solenoids that operate on alternating current must have a shading coil. Relays that operate on direct current do not require them. A clapper type relay is shown in Figure 5–2.

Bridge Type Relay

A bridge type relay operates by drawing a piece of metal or plunger inside a coil (Figure 5–3). The plunger is connected to a bar that contains movable contacts. The movable contacts are mounted on springs and are insulated from the bar. The plunger and bar assembly are called the armature because they are the moving part of the relay. Bridge contacts receive their name because when the solenoid coil is energized and the plunger is drawn inside the coil, the movable contacts bridge across the two stationary contacts. Bridge contacts can control more voltage than the clapper type because they break connection at two places instead of one. When power is removed from the coil, the force of gravity or a spring returns the movable contacts to their original position. A relay with bridge type contacts is shown in Figure 5–4.

Electromagnet Construction

The construction of the electromagnetic part of a relay or contactor greatly depends on whether it is to be operated by direct or alternating current. Relays and contactors that are operated by direct current generally contain solid core materials, while those intended for use with alternating current contain laminated cores. The main reason for the laminated core is the core losses associated with alternating current caused by the continuous changing of the electromagnetic field.

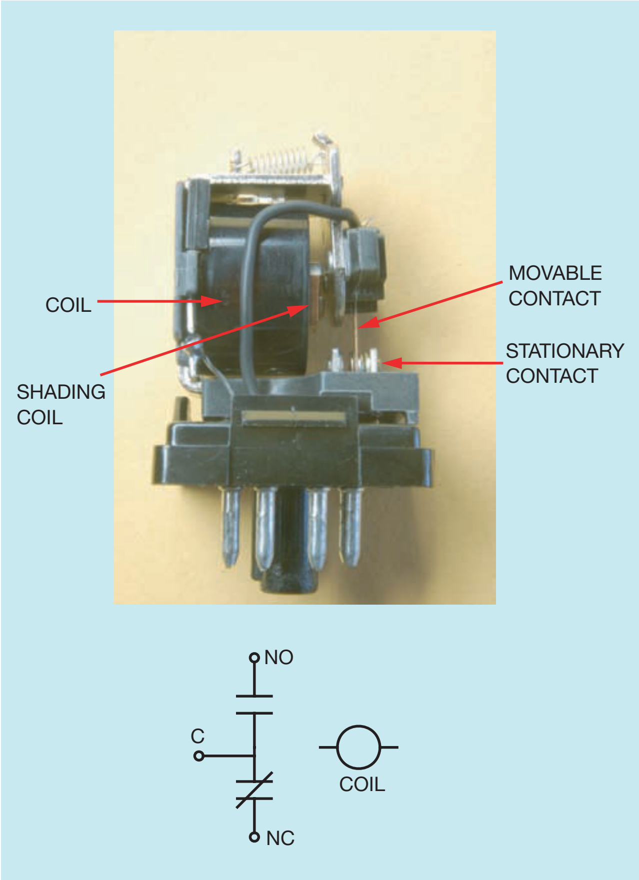


Figure 5–2 Clapper type relay that contains one movable contact and two stationary contacts. This relay is single-pole double throw. (Source: Delmar/Cengage Learning.)

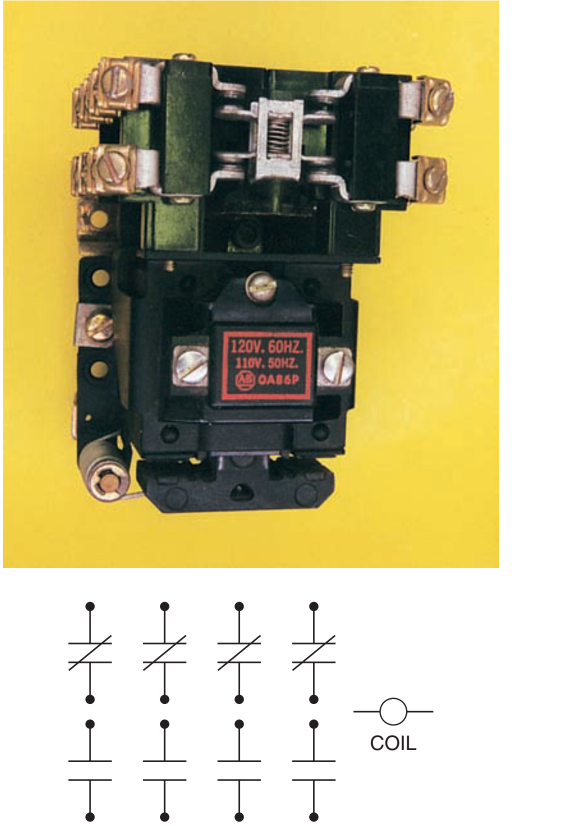


Figure 5–4 A relay with bridge type contacts. (Source: Delmar/Cengage Learning.)

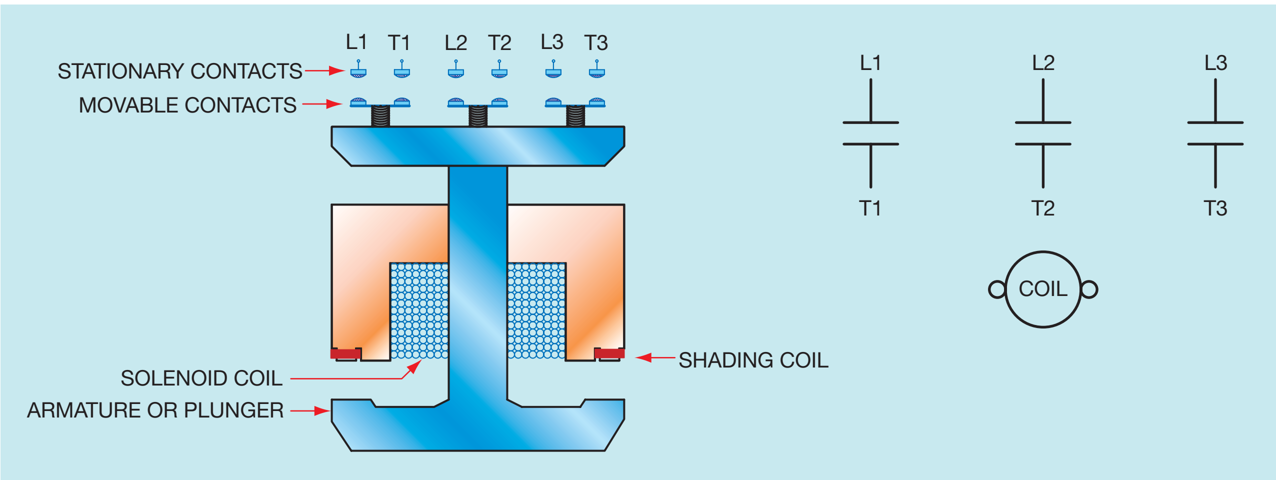


Figure 5–3 Bridge type contacts use one movable and two stationary contacts. They can control higher voltages because they break connection at two places instead of one. (Source: Delmar/Cengage Learning.)

Core Losses

The continuous change of both amplitude and polarity of the magnetic field causes currents to be induced into the metal core material. These currents are called *eddy currents* because they are similar to eddies (swirling currents) found in rivers. Eddy currents tend to swirl around inside the core material, producing heat (Figure 5–5). Laminated cores are constructed with thin sheets of metal stacked together. A thin layer of oxide forms between the laminations. This oxide is an insulator and helps reduce the formation of eddy currents.

Another type of core loss associated with alternating current devices is called *hysteresis loss.* Hysteresis loss is caused by the molecules inside magnetic materials changing direction. Magnetic materials such as iron or soft steel contain magnetic domains or magnetic molecules. In an unmagnetized piece of material, these magnetic domains are not aligned in any particular order (Figure 5–6). If the metal becomes magnetized, the magnetic molecules or domains will align themselves in an orderly fashion (Figure 5–7). If the polarity of the magnetic field is reversed, the molecules will realign themselves to the new polarity (Figure 5–8). Although the domains will realign to correspond to a change of polarity, they resist the realignment. The power required to cause them to change polarity is a power loss in the form of heat. Hysteresis loss is often referred to as *molecular friction* because the molecules are continually changing direction in an alternating current field. Hysteresis loss is proportional to the frequency. At low frequencies such as 60 hertz, it is generally so small that it is of little concern.

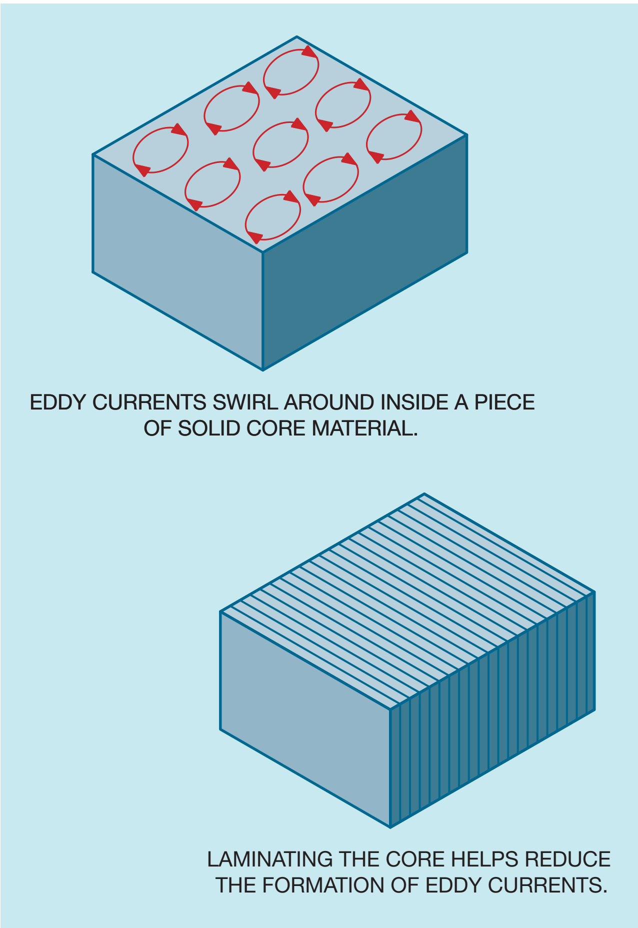


Figure 5–5 Eddy currents are induced into the metal core and produce power loss in the form of heat. (Source: Delmar/Cengage Learning.)

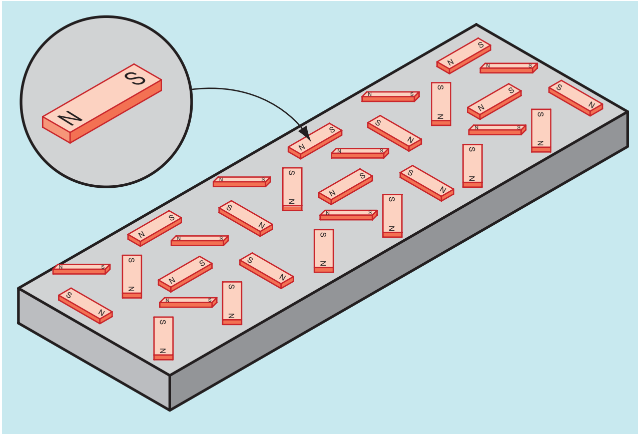


Figure 5–6 The molecules are in disarray in a piece of unmagnetized metal. (Source: Delmar/Cengage Learning.)

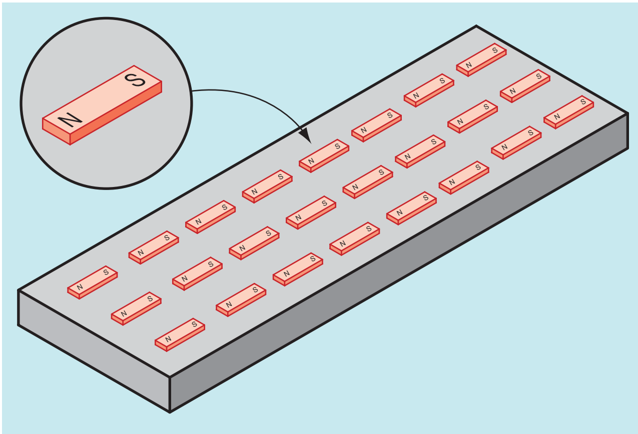


Figure 5–7 The molecules are aligned in a piece of magnetized metal. (Source: Delmar/Cengage Learning.)

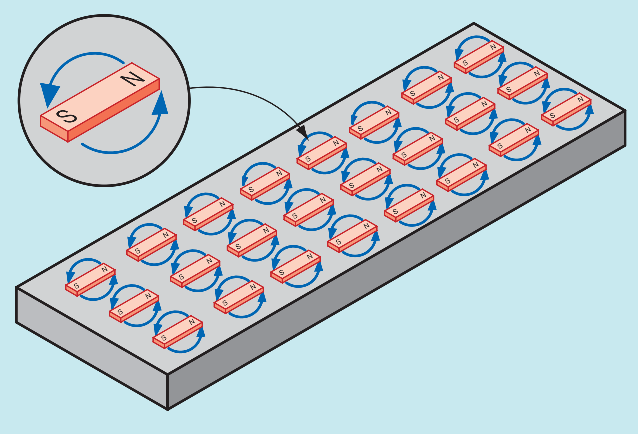


Figure 5–8 When the magnetic polarity changes, all the molecules change position. (Source: Delmar/Cengage Learning.)

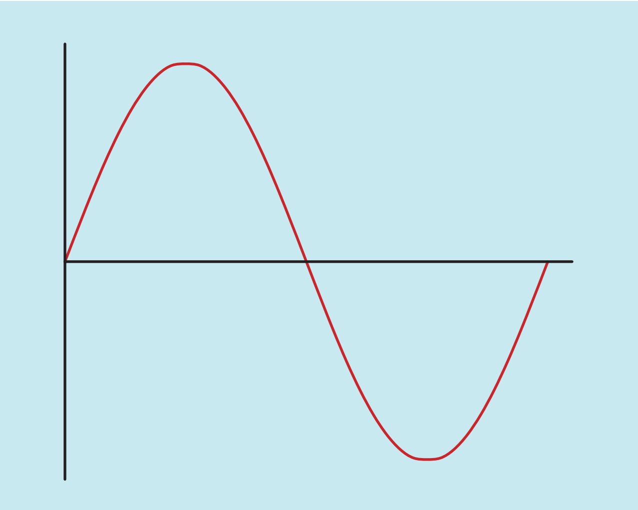


Figure 5–9 The current in an AC circuit continually changes amplitude and direction. (Source: Delmar/Cengage Learning.)

Shading Coils

As mentioned previously, all solenoid type devices that operate on alternating current contain shading coils to prevent chatter. The current in an AC circuit is continually increasing from zero to a maximum value in one direction, returning to zero, and then increasing to a maximum value in the opposite direction (Figure 5–9). Since the current is continually falling to zero, the solenoid spring or gravity would continually try to drop the armature out when the magnetic field collapses. Shading coils provide a time delay for the magnetic field to prevent this from happening. As current increases from zero, magnetic lines of flux concentrate in the metal pole piece (Figure 5–10). This

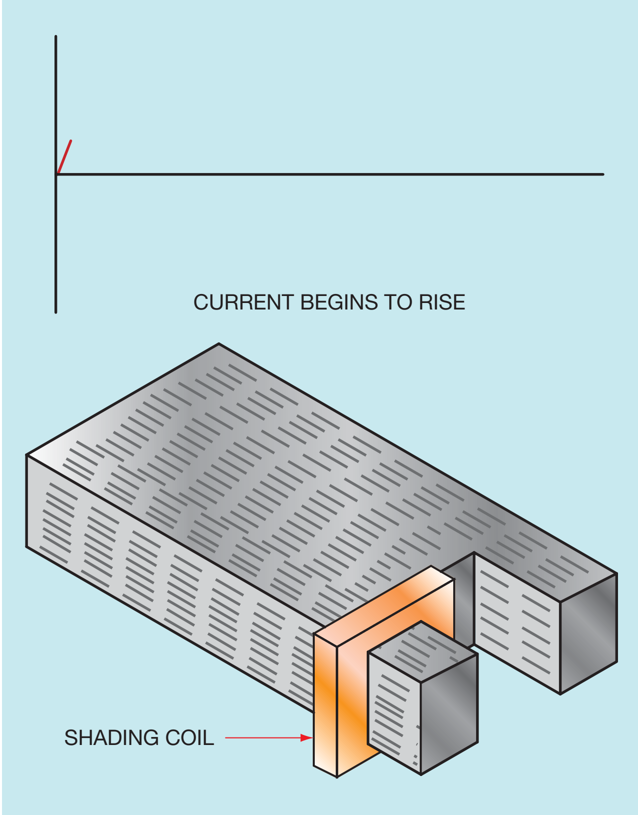


Figure 5–10 As current begins to rise, a magnetic field is concentrated in the pole piece. (Source: Delmar/Cengage Learning.)

increasing magnetic field cuts the shading coil and induces a voltage into it. Since the shading coil or loop is a piece of heavy copper, it has a very low resistance. A very small induced voltage can cause a large amount of current to flow in the loop. The current flow in the shading coil causes a magnetic field to be developed around the shading coil, also. This magnetic field acts in opposition to the magnetic field in the pole piece and causes it to bend away from the shading coil (Figure 5–11). As long as the AC current is changing in amplitude, a voltage will be induced in the shading loop.

When the current reaches it maximum, or peak, value, the magnetic field is no longer changing and there is no voltage induced in the shading coil. Since the shading coil has no current flow, there is no magnetic field to oppose the magnetic field of the pole piece (Figure 5–12).

When the current begins to decrease, the magnetic field of the pole piece begins to collapse. The collapsing magnetic field again induces a voltage into the shading coil. Since the collapsing magnetic field is moving in the opposite direction, the voltage induced

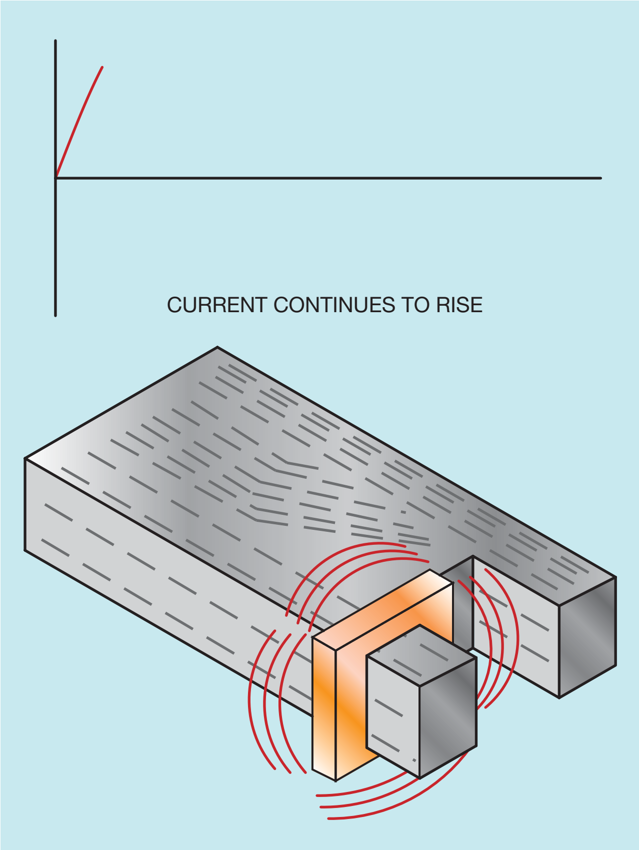


Figure 5–11 The magnetic field of the shading coil causes the magnetic field of the pole piece to bend away and concentrate in the unshaded portion of the pole piece. (Source: Delmar/Cengage Learning.)

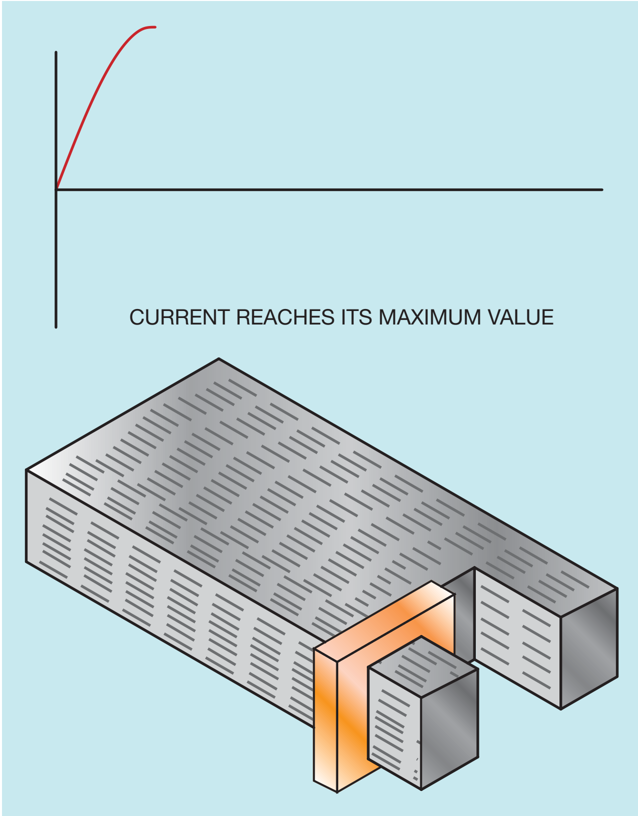


Figure 5–12 When the current reaches its peak value, the magnetic field is no longer changing and the shading coil offers no resistance to the magnetic field of the pole piece. (Source: Delmar/Cengage Learning.)

into the shading coil causes current to flow in the opposite direction, producing a magnetic field of the opposite polarity around the shading coil. The magnetic field of the shading coil now tries to maintain the collapsing magnetic field of the pole piece (Figure 5–13). This causes the magnetic flux lines of the pole piece to concentrate in the shaded part of the pole piece. The shading coil provides a continuous magnetic field to the pole piece, preventing the armature from dropping out. A laminated pole piece with shading coils is shown in Figure 5–14.

Control Relay Types

Control relays can be obtained in a variety of styles and types (Figure 5–15). Most have multiple sets of contacts, and some are constructed in such a manner that their contacts can be set as either normally open or normally closed. This flexibility can be a great advantage in many instances. When a control circuit is being constructed, one relay may require three normally open contacts and one normally closed, while another may need two normally open and two normally closed contacts.

Relays that are designed to plug into eight- or eleven-pin tube sockets are popular for many applications (Figure 5–16). These relays are relatively inexpensive, and replacement is fast and simple in the event of failure. Since the relays plug into a socket, the wiring is connected to the socket, not the relay. Replacement is a matter of removing the defective relay and plugging in a new one. An eleven-pin tube socket is shown in Figure 5–17. Eight- and eleven-pin relays can be obtained with different coil voltages. Coil voltages of 12 volts DC, 24 volts DC, 24 volts AC and 120 volts AC are common. Their contact ratings generally range from 5 to 10 amperes, depending on relay type and manufacturer. The connection diagram for eight- and eleven-pin relays is shown in Figure 5–18. The pin numbers for eight- and eleven-pin relays can be determined by holding the relay with the bottom facing you. Hold the relay so that the key is facing down. The pins are numbered as shown in Figure 5–18. The eleven-pin relay contains three separate single-pole double-throw contacts. Pins 1

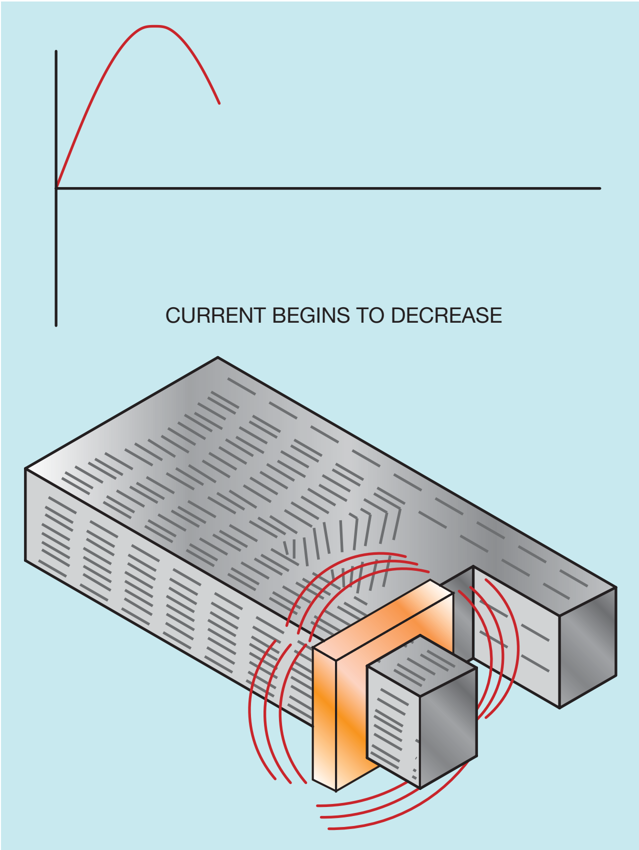


Figure 5–13 As current decreases, the collapsing magnetic field again induces a voltage into the shading coil. The shading coil now aids the magnetic field of the pole piece and flux lines are concentrated in the shaded section of the pole piece. (Source: Delmar/Cengage Learning.)

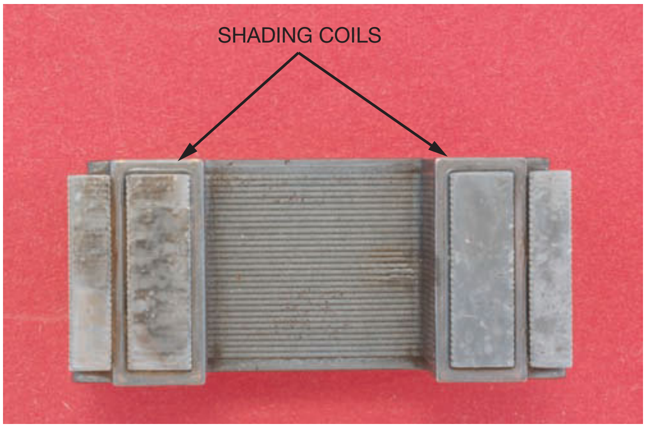


Figure 5–14 Laminated pole piece with shading coils. (Source: Delmar/Cengage Learning.)

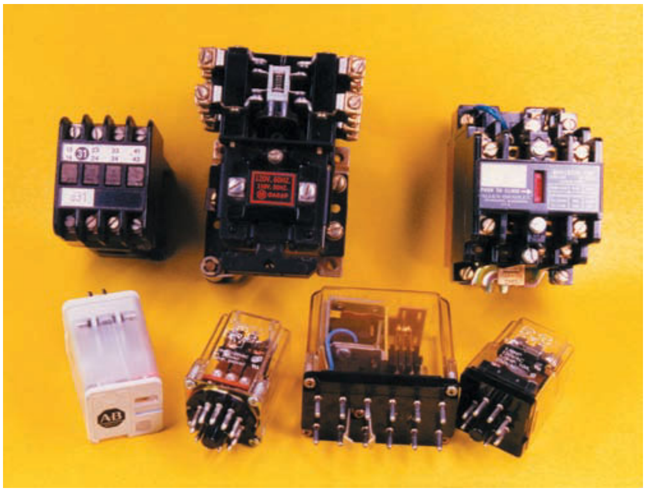


Figure 5–15 Control relays can be obtained in a variety of case styles. (Source: Delmar/Cengage Learning.)

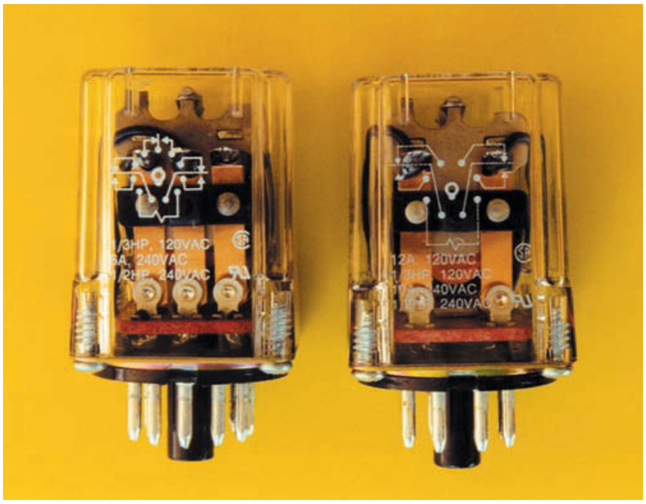


Figure 5–16 Relays designed to plug into eight- and eleven-pin tube sockets. (Source: Delmar/Cengage Learning.)

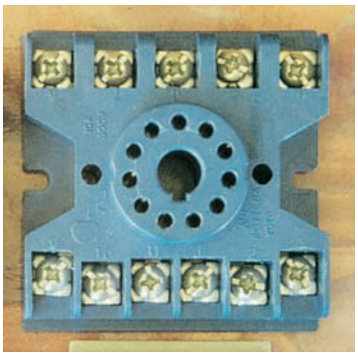


Figure 5–17 Eleven-pin tube socket. (Source: Delmar/Cengage Learning.)

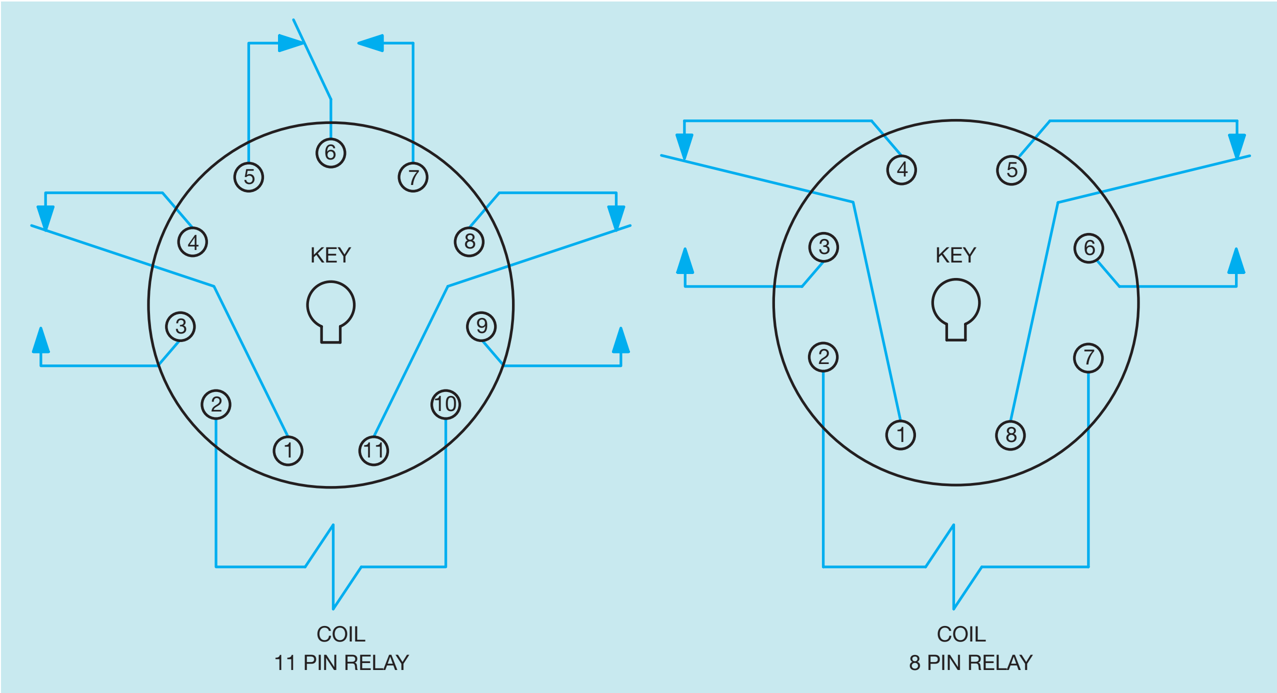


Figure 5–18 Connection diagrams for eight- and eleven-pin relays. (Source: Delmar/Cengage Learning.)

and 4, 6 and 5, and 11 and 8 are normally closed contacts. Pins 1 and 3, 6 and 7, and 11 and 9 are normally open contacts. The coil is connected to pins 2 and 10.

The eight-pin relay contains two separate single-pole double-throw contacts. Pins 1 and 4, and 8 and 5 are normally closed. Pins 1 and 3, and 8 and 6 are normally open. The coil is connected across pins 2 and 7.

Solid-State Relays

Another type of relay that is found in many applications is the solid-state relay. Solid-state relays employ the use of solid-state devices instead of mechanical contacts to connect the load to the line. Solid-state relays that are intended to connect alternating current loads to the line use a device called a *triac*. The triac is a bidirectional device, which means that it will permit current to flow through it in either direction. There are a couple of methods used to control when the triac turns on or off. One method employs a small relay device that controls the gate of the triac (Figure 5–19). The relay can be controlled by a low voltage source. When energized, the relay contact closes, supplying power to the gate of the triac that connects the load to the line. Another common method for controlling the operation of a solid state relay is called *optoisolation,* or optical isolation. This method is used by many PLCs to communicate with the output device. Optoisolation is achieved by using the light from a light-emitting diode (LED) to energize a photo triac (Figure 5–20). The arrows pointing away from the diode symbol indicate that it emits light when energized. The arrows pointing toward the triac symbol indicate that it must receive light to turn on. Optical isolation is very popular with electronic devices such as computers and PLCs because there are no moving contacts to wear and because the load side of the relay is electrically isolated from the control side. This isolation prevents any electrical noise generated on the load side from being transferred to the control side.

Solid-state relays are also available to control loads connected to direct current circuits (Figure 5–21). These relays use a transistor instead of a triac to connect the load to the line.

Solid-state relays can be obtained in a variety of case styles and ratings. Some have a voltage rating that ranges from about 3 to 30 volts and can control only a small amount of current, while others can control hundreds of volts and several amperes. The eight-pin IC (Integrated Circuit) shown in Figure 5–22 contains two solid-state relays that are intended for low power applications. The solid-state relay shown in Figure 5–23 is

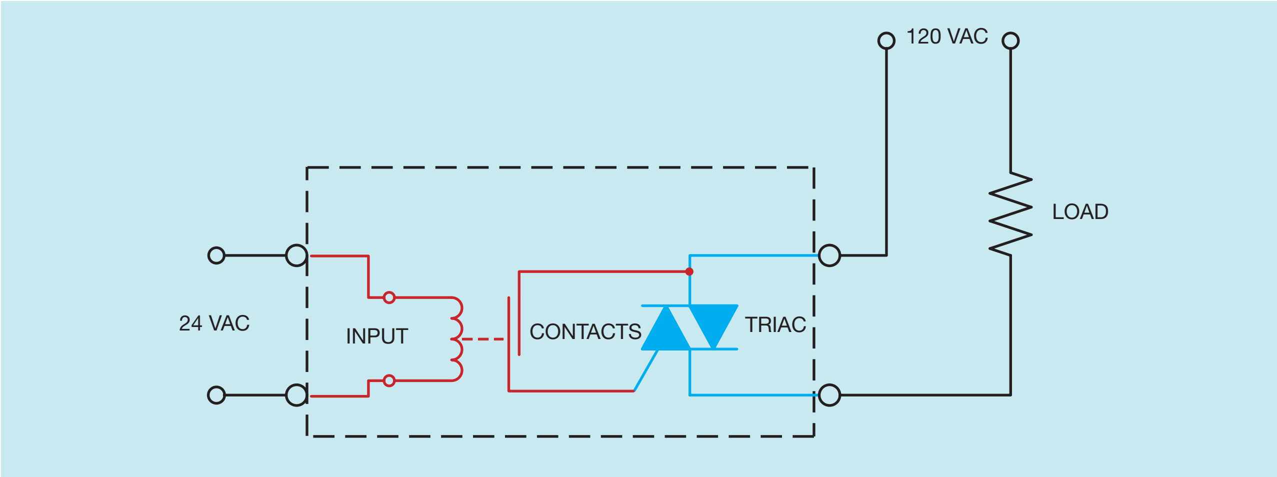


Figure 5–19 Solid-state relay using a reed relay to control the action of a triac. (Source: Delmar/Cengage Learning.)

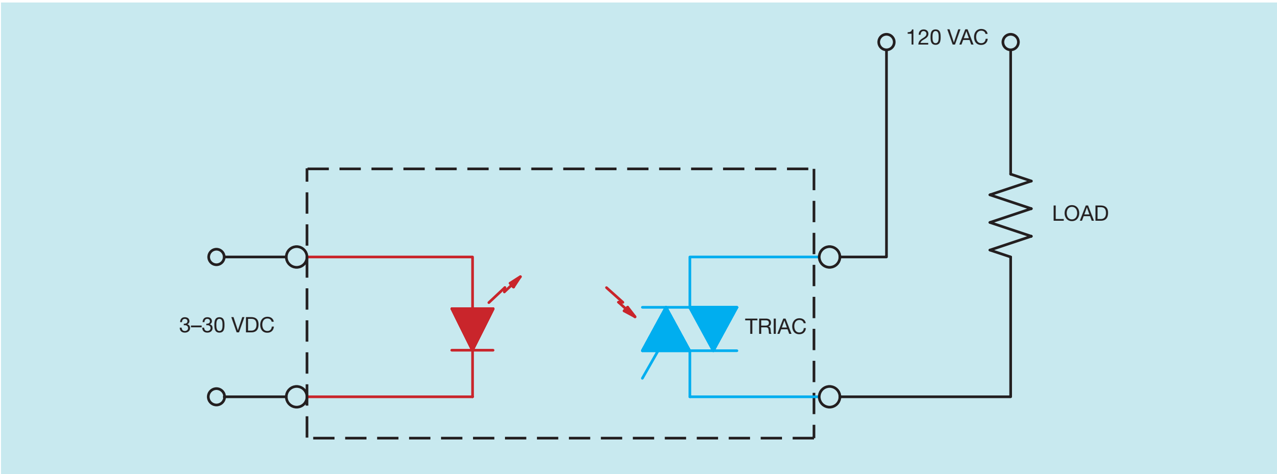


Figure 5–20 Solid-state relay using optical isolation to control the action of a triac. (Source: Delmar/Cengage Learning.)

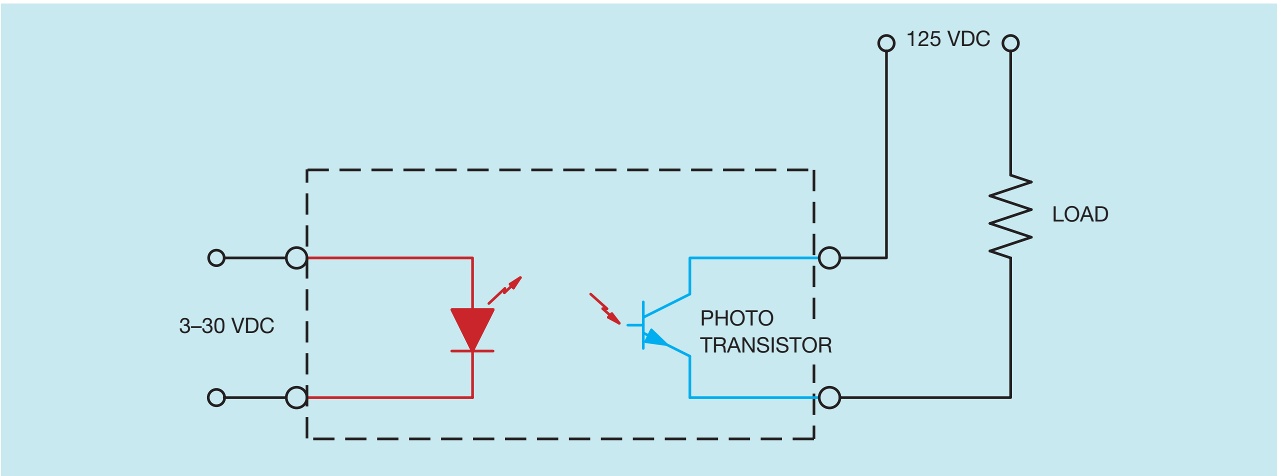


Figure 5–21 A solid-state relay that controls a DC load uses a transistor instead of a triac to connect the load to the line. (Source: Delmar/Cengage Learning.)

Figure 5–22 Eight-pin integrated circuit containing two low power solid-state relays. (Courtesy International Rectifier.)

Figure 5–23 Solid-state relay that can control 8 amperes at 240 volts. (Source: Delmar/Cengage Learning.)

rated to control a load of 8 amperes connected to a 240 volt AC circuit. For this solid-state relay to be capable of controlling that amount of power, it must be mounted on a heat sink to increase its ability to dissipate heat. Although this relay is rated 240 volts, it can also control devices at a lower voltage.

Contactors

Contactors are very similar to relays in that they are electromechanical devices. Contactors can be obtained with coils designed for use on higher voltages than most relays. Most relay coils are intended to operate on voltages that range from 5 to 120 volts AC or DC. Contactors can be obtained with coils that have voltage ranges from 24 to 600 volts. Although these higher voltage coils are available, most contactors operate on voltages that generally do not exceed 120 volts for safety reasons. Contactors can be made to operate on different control circuit voltages by changing the coil. Manufacturers make coils to interchange with specific types of contactors. Most contain many turns of wire and are mounted in some type of molded case that can be replaced by disassembling the contactor (Figure 5–24).

It should be noted that NEMA standards require the magnetic switch device to operate properly on voltages that range from 85% to 110% of the rated coil voltage. Voltages can vary from one part of the country to another, and variation of voltage often occurs inside a plant as well. If coil voltage is excessive, it will draw too much current, causing the insulation to overheat and eventually burn out. Excessive voltage also causes the armature to slam into the stationary pole pieces with a force that can cause rapid wear of the pole pieces and shorten the life of the contactor. Another effect of too much voltage is the wear caused by the movable contacts slamming into the stationary contacts, causing excessive contact bounce. Contact bounce can produce arcing, which creates more heat and more wear on the contacts.

Insufficient coil voltage can produce as much if not more damage than excessive voltage. If the coil voltage is too low, the coil will have less current flow, causing the magnetic circuit to be weaker than normal. The armature may pick up, but not completely seal against the stationary pole pieces. This can cause an air gap between the pole pieces, preventing the coil current from dropping to its sealed value. This causes excessive coil current, overheating, and coil burnout. A weak

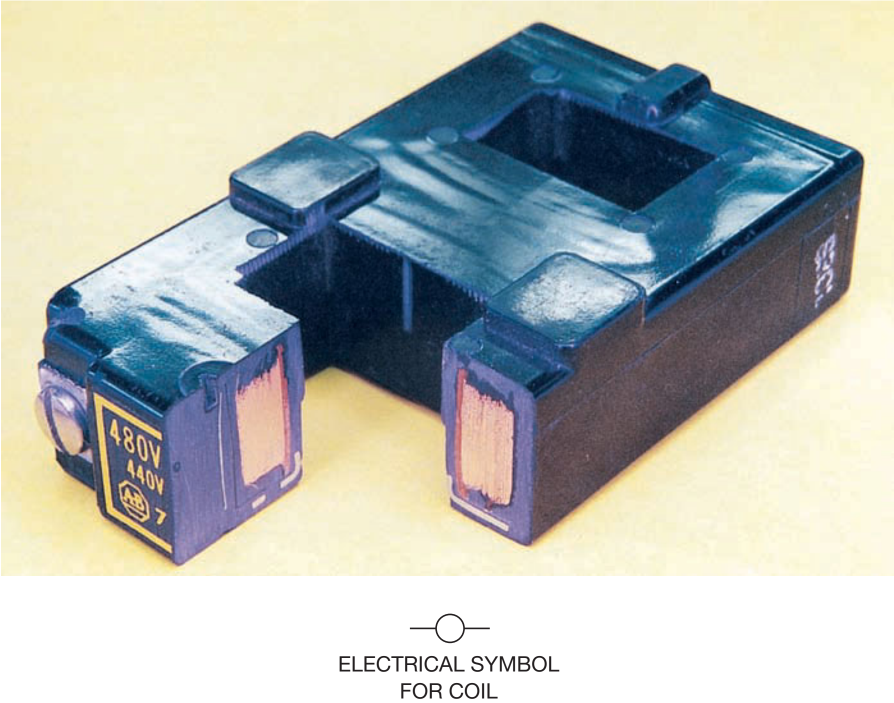


Figure 5–24 Magnetic coil cut away to show insulated copper wire wound on a spool and protected by a molding. (Source: Delmar/Cengage Learning.)

magnetic circuit can cause the movable contacts to touch the stationary contacts and provide a connection, but not have the necessary force to permit the contact springs to provide proper contact pressure. This can cause arcing and possible welding of the contacts. Without proper contact pressure, high currents will produce excessive heat and greatly shorten the life of the contacts.

Load Contacts

The greatest difference between relays and contactors is the fact that contactors are equipped with large contacts that are intended to connect high current loads to the power line (Figure 5–25). These large contacts are called *load* contacts. Depending on size, load contacts can be rated to control several hundred amperes. Most will contain some type of arcing chamber to help extinguish the arc that is produced when heavy current loads are disconnected from the power line. Arcing chambers can be seen in Figure 5–25.

Other contacts may contain arc chutes that lengthen the path of the arc to help extinguish it. When the contacts open, the established arc will rise because of the heat produced by the arc (Figure 5–26). The arc is pulled farther and farther apart by the horns of the arc chute until it can no longer sustain itself. Another device that operates according to a similar principle is the blowout coil. Blowout coils are generally used on contactors intended for use with direct current and are connected in series with the load (Figure 5–27). When the contact opens, the arc is attracted to the magnetic field and rises at a rapid rate. This is the same basic action that causes the armature of a direct current motor to turn.

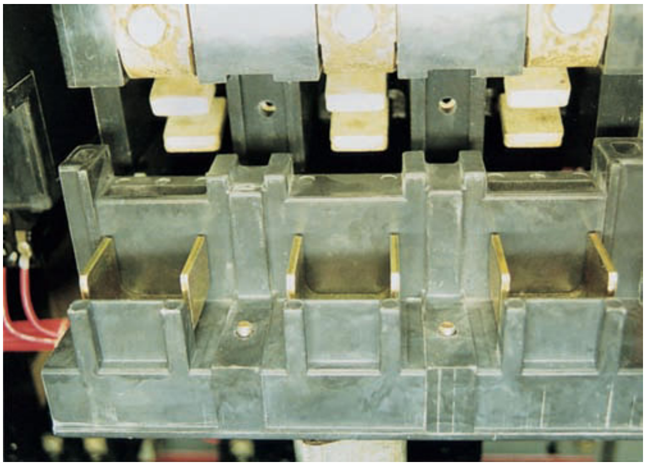


Figure 5–25 Contactors contain load contacts designed to connect high current loads to the power line. (Source: Delmar/Cengage Learning.)

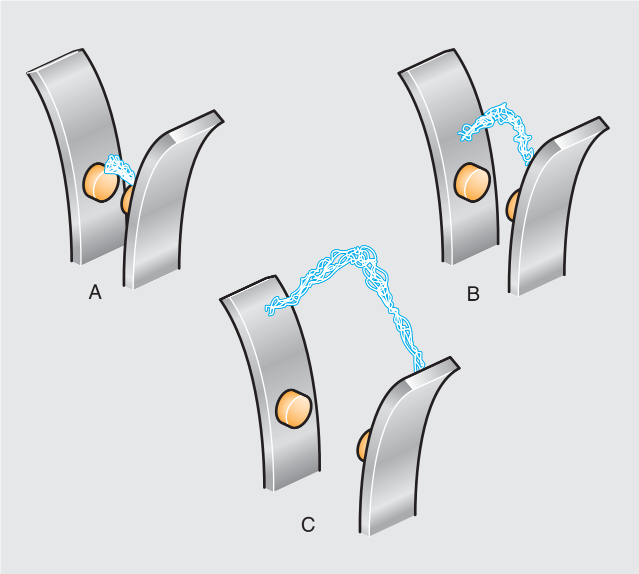


Figure 5–26 The arc rises between the arc chutes because of heat. (Source: Delmar/Cengage Learning.)

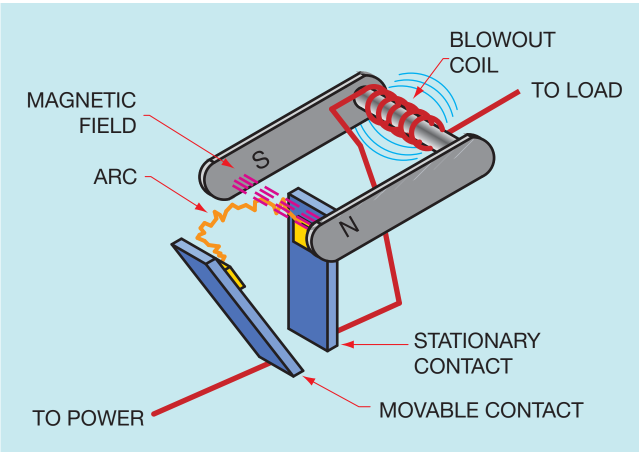


Figure 5–27 Magnetic blowout coils are connected in series with the load to establish a magnetic field. (Source: Delmar/Cengage Learning.)

Since the arc is actually a flow or current, a magnetic field exists around the arc. The arc's magnetic field is attracted to the magnetic field produced by the blowout coil, causing the arc to move upward. The arc is extinguished at a faster rate than is possible with an arc chute, which depends on heat to draw the arc upward. Blowout coils are sometimes used on contactors that control large amounts of alternating current, but they are most often employed with contactors that control direct current loads. Alternating current turns off each half cycle when the waveform passes through zero. This helps to extinguish arcs in alternating current circuits. Direct current,

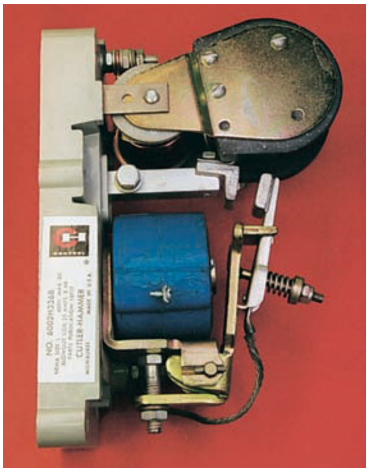


Figure 5–28 Clapper type contactor with blowout coil. (Source: Delmar/Cengage Learning.)

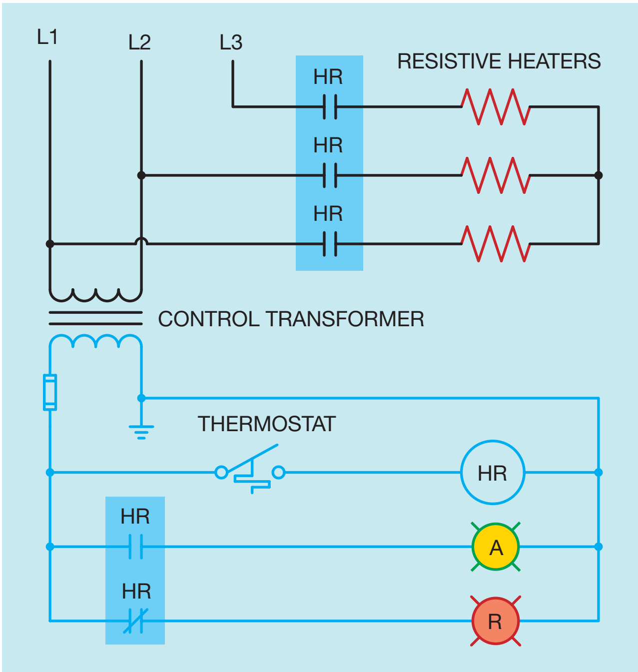


Figure 5–29 The contactor contains both load and auxiliary contacts. (Source: Delmar/Cengage Learning.)

however, does not turn off at periodic intervals. Once a DC arc is established, it is much more difficult to extinguish. Blowout coils are an effective means of extinguishing these arcs. A contactor with a blowout coil is shown in Figure 5–28.

Most contactors contain auxiliary contacts as well as load contacts. The auxiliary contacts can be used in the control circuit if required. The circuit shown in Figure 5–29 uses a three-pole contactor to connect a

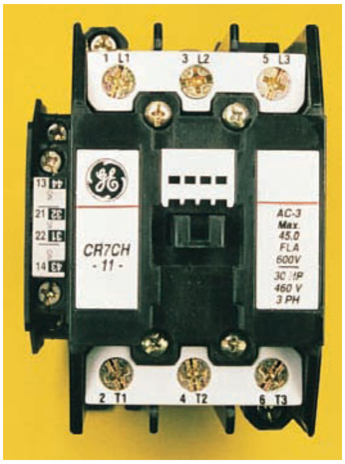


Figure 5–30 Size 1 contactor with auxiliary contacts. (Source: Delmar/Cengage Learning.)

bank of three-phase heaters to the power line. Note that a normally open auxiliary contact is used to control an amber pilot light that indicates that the heaters are turned on, and a normally closed contact controls a red pilot light that indicates that the heaters are turned off. A thermostat controls the action of HR contactor coil. In the normal de-energized state, the normally closed HR auxiliary contact provides power to the red pilot light. When the thermostat contact closes, coil HR energizes and all HR contacts change position. The three load contacts close and connect the heaters to the line. The normally closed HR auxiliary contact opens and turns off the red pilot light, and the normally open HR auxiliary contact closes and turns on the amber pilot light. A size 1 contactor with auxiliary contacts is shown in Figure 5–30.

Vacuum Contactors

Vacuum contactors enclose their load contacts in a sealed vacuum chamber. A metal bellows connected to the movable contact permits it to move without breaking the seal (Figure 5–31). Sealing contacts inside a vacuum chamber permits them to switch higher voltages within a relatively narrow space between the contacts without establishing an arc. The contacts shown in Figure 5–31 are rated 7.2 kilovolts and 400 amperes.

An electric arc is established when the voltage is high enough to ionize the air molecules between stationary and movable contacts. Medium voltage contactors are generally large because they must provide enough distance between the contacts to break the arc path. Some medium voltage contactors use arc suppressers, arc shields, and oil immersion to quench or prevent an arc. Vacuum contactors operate on the principle that if there is no air surrounding the contact, there is no ionization path for the establishment of an arc. Vacuum contactors are generally smaller in size than other types of medium voltage contactors. A three-phase vacuum contactor rated at 7.2 kilovolts and 400 amperes is shown in Figure 5–32. A three-phase vacuum contactor rated at 12 kilovolts and 400 amperes is shown in Figure 5–33.

Mechanically Held Contactors and Relays

Mechanically held contactors and relays are often referred to as *latching* contactors or relays. They employ two electromagnets to operate. One coil is generally called the *latch* coil and the other is called the *unlatch* coil (Figure 5–34). The latch coil causes the contacts to change position and mechanically hold in position after power is removed from the latch coil. To return the contacts to their normal de-energized position, the unlatch coil must be energized. A circuit using a latching relay is shown in Figure 5–35. Power to both coils is provided by momentary contact push buttons. The coils of most mechanically held contactors and relays are intended for momentary use, and continuous power will often cause burnout.

Unlike common magnetic contactors or relays, the contacts of latching relays and contacts do not return to a normal position if power is interrupted. They should be used only where there is not a danger of harm to persons or equipment if power is suddenly restored after a power failure.

Sequence of Operation

Many latching type relays and contactors contain contacts that are used to prevent continuous power from being supplied to the coil after it has been energized. These contacts are generally called *coil clearing contacts.* In Figure 5–35, L coil is the latching coil and U coil is the unlatch coil. When the ON push button is pressed, current can flow to L coil, through normally closed L contact to neutral. When the relay changes to the latch position, the normally closed L contact,

Figure 5–31 Vacuum contacts are sealed inside a vacuum chamber. (Courtesy GEC Alsthom.)

connected in series with L coil, opens and disconnects power to L coil. This prevents further power from being supplied to L coil. At the same time, the open U contact, connected in series with U coil, closes to permit operation of U coil when the OFF push button is pressed. When L coil energizes, it also closes the L load contacts, energizing a bank of lamps. The lamps can be turned off by pressing the OFF push button and energizing U coil. This causes the relay to return to the normal position. Notice that the coil clearing contacts prevent power from being supplied continuously to the coils of the mechanically held relay.

Mercury Relays

Mercury relays employ the used of mercury-wetted contacts instead of mechanical contacts. Mercury relays contain one stationary contact, called the electrode. The electrode is located inside the electrode chamber. When the coil is energized, a magnetic sleeve is pulled down inside a pool of liquid mercury, causing the mercury to rise in the chamber and make connection with the stationary electrode (Figure 5–36). The advantage of mercury relays is that each time the relay is used the contact is renewed, eliminating burning and

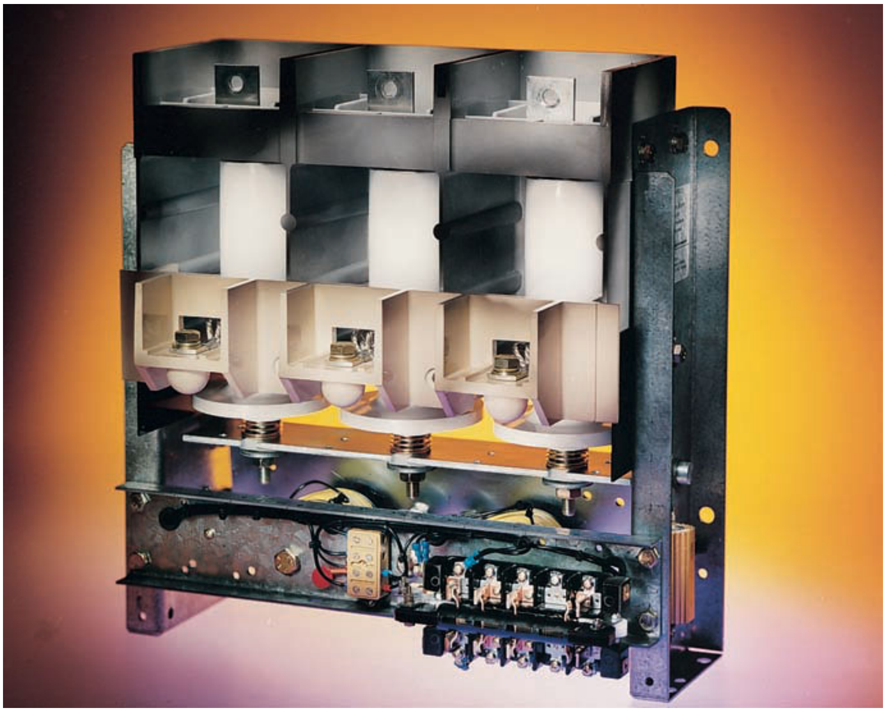


Figure 5–32 Three-phase vacuum contactor rated at 7.2 kV and 400 amperes. (Courtesy GEC Alsthom.)

Figure 5–33 Three-phase vacuum contactor rated at 12 kV and 400 amperes. (Courtesy GEC Alsthom.)

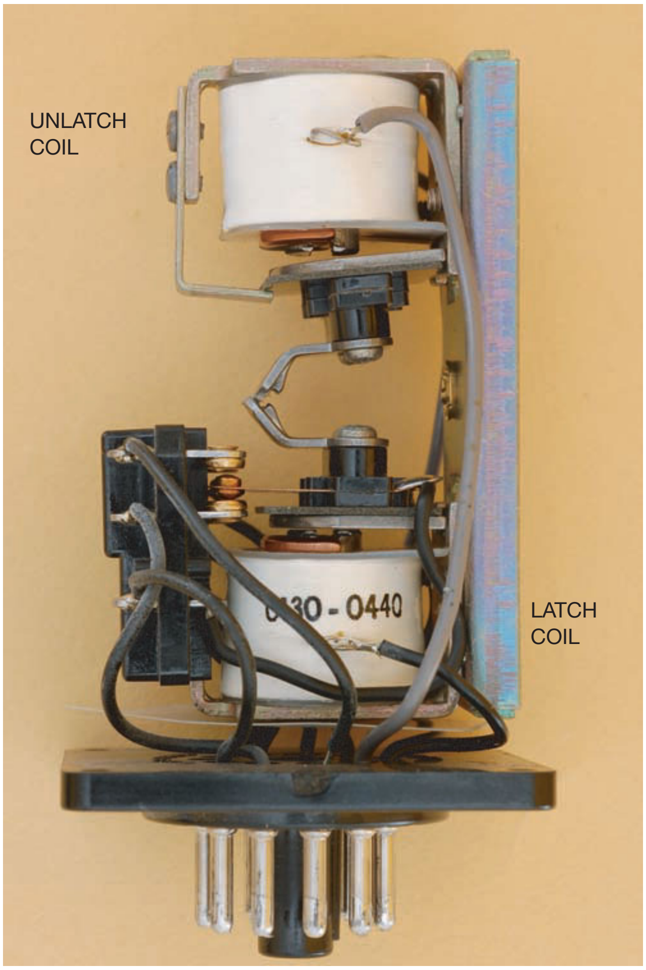


Figure 5–34 Latching relay. (Source: Delmar/Cengage Learning.)

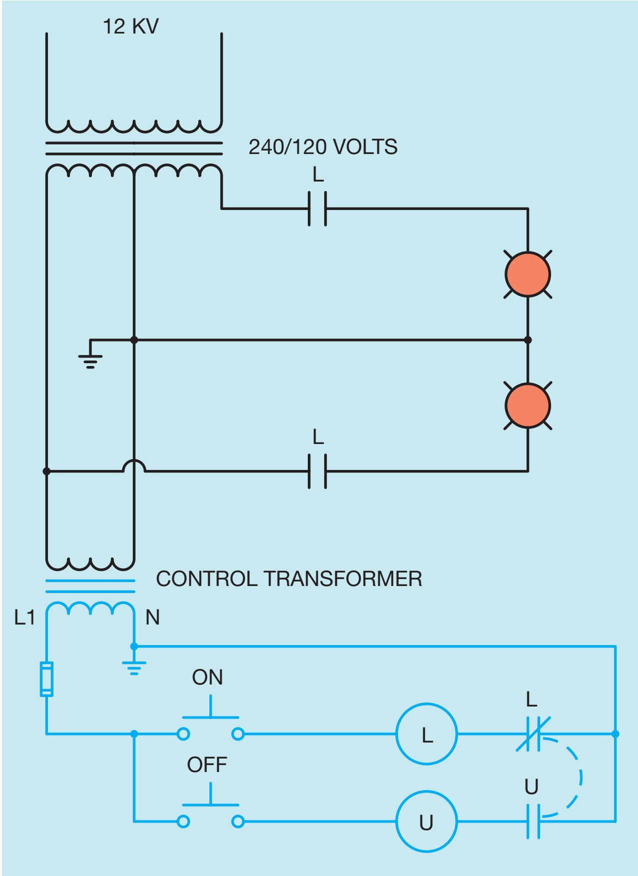


Figure 5–35 Latching type relays and contactors contain a latch and unlatch coil. (Source: Delmar/Cengage Learning.)

pitting caused by an arc when connection is made or broken. The disadvantage of mercury relays is that they contain mercury. Mercury is a toxic substance that has been shown to cause damage to the nervous system and kidneys. Mercury is banned in some European countries.

Mercury relays must be mounted vertically instead of horizontally. They are available in single-pole, double-pole, and three-pole configurations. A single-pole mercury relay is shown in Figure 5–37.

Motor Starters

Motor starters are contactors with the addition of an overload relay (Figure 5–38). Since they are intended to control the operation of motors, motor starters are rated in horsepower. Magnetic motor starters are available in different sizes. The size of starter required is determined by the horsepower and voltage of the motor it is intended to control. There are two standards that are used to determine the size of starter needed: NEMA and IEC. Figure 5–39 shows the NEMA size starters needed for normal starting duty. The capacity of the starter is determined by the size of its load or power contacts and the wire cross-sectional area that can be connected to the starter. The size of the load contacts is reduced when the voltage is doubled, because the current is halved for the same power rating ($P = E \times I$).

The number of *poles* refers to the load contacts and does not include the number of control or auxiliary contacts. Three-pole starters are used to control three-phase motors, and two-pole starters are used for single-phase motors.

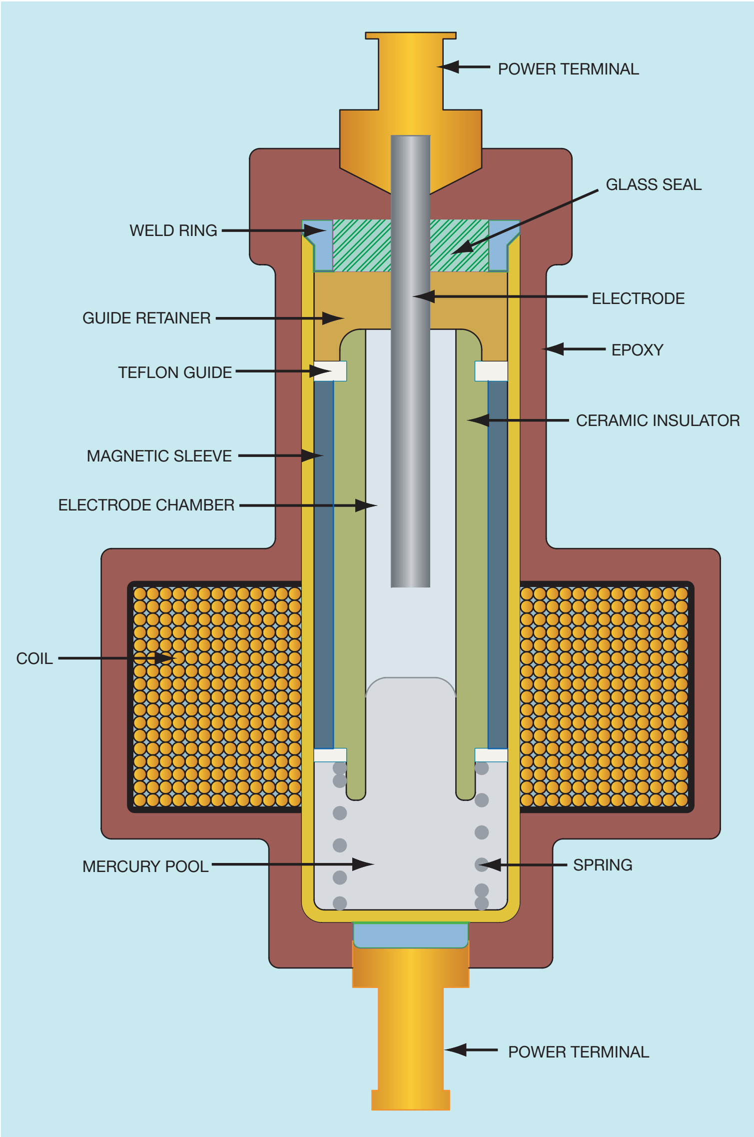


Figure 5–36 Diagram of a mercury relay. (Source: Delmar/Cengage Learning.)

Figure 5–37 Single-pole mercury relay. (Source: Delmar/Cengage Learning.)

NEMA and IEC

NEMA is the acronym for National Electrical Manufacturers Association. Likewise, IEC is the acronym for International Electrotechnical Commission. The IEC establishes standards and ratings for different types of equipment just as NEMA does. The IEC, however, is more widely used throughout Europe than in the United States. Many equipment manufacturers are now beginning to specify IEC standards for their products produced in the United States, also. The main reason is that much of the equipment produced in the United States is also marketed in Europe. Many European companies will not purchase equipment that is not designed with IEC standard equipment.

Although the IEC uses some of the same ratings as similar NEMA rated equipment, there is often a vast difference in the physical characteristics of the two. Two sets of load contacts are shown in Figure 5–40. The load contacts on the left are employed in a NEMA rated 00 motor starter. The load contacts on the right are used in an equivalent IEC rated 00 motor starter.

Figure 5–38 A motor starter is a contactor combined with an overload relay. (Courtesy Square D Company.)

Notice that the surface area of the NEMA rated contacts is much larger than the IEC rated contacts. This permits the NEMA rated starter to control a much higher current than the IEC starter. In fact, the IEC starter contacts rated equivalent to NEMA 00 contacts are smaller than the contacts of a small eight-pin control relay (Figure 5–41). Due to the size difference in contacts between NEMA and IEC rated starters, many engineers and designers of control systems specify an increase of one to two sizes for IEC rated equipment than would be necessary for NEMA rated equipment. A table of the ratings for IEC starters is shown in Figure 5–42.

Although motor starters basically consist of a contactor and overload relay mounted together, most contain auxiliary contacts. Many manufacturers make auxiliary contacts that can be added to a starter or contactor (Figure 5–43). Adding auxiliary contacts can often reduce the need for control relays to perform part of the circuit logic. In the circuit shown in Figure 5–44, motor #1 must be started before motors #2 or #3. This is accomplished by placing normally open contacts in series with starter coils M2 and M3. In the circuit shown in Figure 5–44A, the coil of a control relay has been connected in parallel with motor starter coil M1. In this way, control relay CR will operate in conjunction with motor starter coil M1. The two normally open CR contacts prevent motors #2 and #3 from starting until motor #1 is running. In the circuit shown in Figure 5–44B, it is assumed that two auxiliary contacts have been added to motor starter M1. The two new auxiliary contacts can replace the two normally open CR contacts, eliminating the need for control relay CR. A motor starter with additional auxiliary contacts is shown in Figure 5–45.

Motor Control Centers

Motor starters are often grouped with other devices such as circuit breakers, fuses, disconnects, and control transformers. This set of equipment is referred to as a combination starter. These components are often contained inside one enclosure (Figure 5–46).

Motor control centers employ the use of combination starters mounted in special enclosures designed to plug into central buss bars that supply power for several motors. The enclosure for this type of combination starter is often referred to as a module, cubicle, or can, Figure 5–47. They are designed to be inserted into a motor control center (MCC), as shown in Figure 5–48. Connection to individual modules is generally made with terminal strips located inside the module. Most manufacturers provide some means of removing the entire terminal strip without having to remove each individual wire. If a starter should fail, this permits rapid installation of a new starter. The defective starter can then be serviced at a later time.

CAUTION:

By necessity, motor control centers have very low impedance and can produce extremely large fault currents. It is estimated that the typical MCC can deliver enough energy in an arc-fault condition to kill a person thirty feet away. For this reason, many industries now require electricians to wear full protection (flame retardant clothing, face shield, ear plugs, and hard hat) when opening the door on a combination starter or energizing the unit. When energizing the starter, always stand to the side of the unit and not directly in front of it. In a direct short condition, it is possible for the door to be blown off or open.

		Maximum Horsepower Rating—Nonplugging and Nonjogging Duty				Maximum Horsepower Rating—Nonplugging and Nonjogging Duty	
NEMA Size	Load Volts	Single Phase	Poly Phase	NEMA Size	Load Volts	Single Phase	Poly Phase
00	115	½	. . .	3	115	7½	. . .
	200	. . .	1½		200	. . .	25
	230	1	1½		230	15	30
	380	. . .	1½		380	. . .	50
	460	. . .	2		460	. . .	50
	575	. . .	2		575	. . .	50
0	115	1	. . .	4	200	. . .	40
	200	. . .	3		230	. . .	50
	230	2	3		380	. . .	75
	380	. . .	5		460	. . .	100
	460	. . .	5		575	. . .	100
	575	. . .	5				
1	115	2	. . .	5	200	. . .	75
	200	. . .	7½		230	. . .	100
	230	3	7½		380	. . .	150
	380	. . .	10		460	. . .	200
	460	. . .	10		575	. . .	200
	575	. . .	10				
*1P	115	3	. . .	6	200	. . .	150
	230	5	. . .		230	. . .	200
					380	. . .	300
					460	. . .	400
					575	. . .	400
2	115	3	. . .	7	230	. . .	300
	200	. . .	10		460	. . .	600
	230	7½	15		575	. . .	600
	380	. . .	25	8	230	. . .	450
	460	. . .	25		460	. . .	900
	575	. . .	25		575	. . .	900

Tables are taken from NEMA Standards.
*1¾, 10 hp is available.

Figure 5–39 Motor starter sizes and ratings. (Source: Delmar/Cengage Learning.)

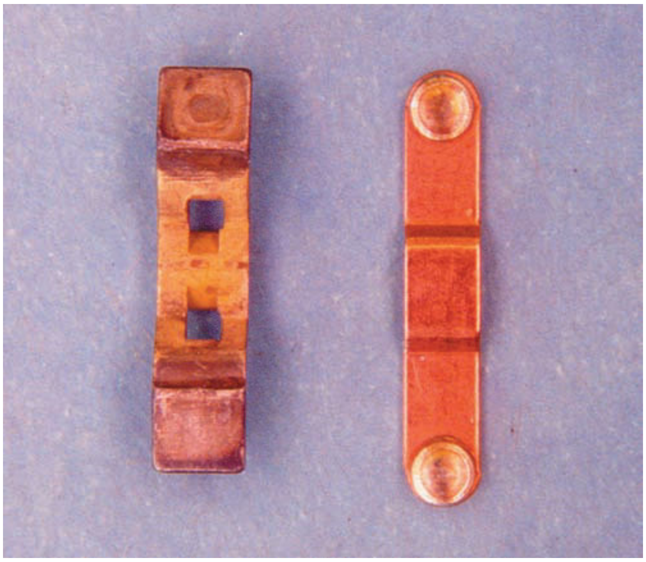


Figure 5–40 The load contacts on the left are NEMA size 00. The load contacts on the right are IEC size 00. (Source: Delmar/Cengage Learning.)

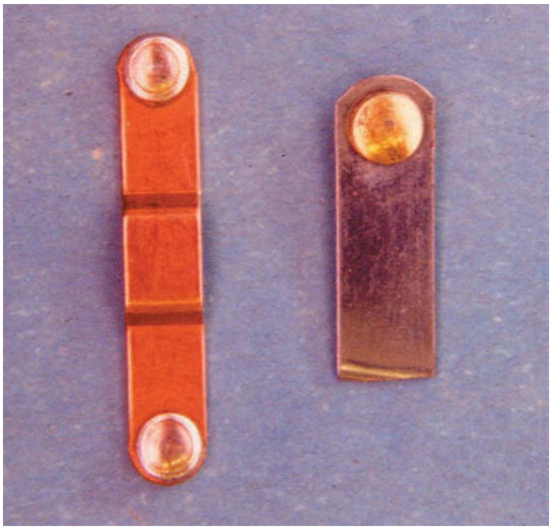


Figure 5–41 The load contacts of an IEC 00 starter shown on the left are smaller than the auxiliary contacts of an eight-pin control relay shown on the right. (Source: Delmar/Cengage Learning.)

Current Requirements

When the coil of an alternating current relay or contactor is energized, it will require more current to pull the armature in than to hold it in. The reason for this is the change of inductive reactance caused by the air gap (Figure 5–49). When the relay is turned off, a large air gap exists between the metal of the stationary pole piece and the armature. This air gap causes a poor magnetic circuit, and the inductive reactance (X_L) has a low ohmic value. Although the wire used to make the coil does have some resistance, the main current limiting factor of an inductor is inductive reactance. After the coil is energized and the armature makes contact with the stationary pole piece, there is a very small air gap between the armature and pole piece. This small air gap permits a better magnetic circuit, which increases the inductive reactance, causing the current to decrease. If dirt or some other foreign matter should prevent the armature from making a seal with the stationary pole piece, the coil current will remain higher than normal, which can cause overheating and eventual coil burnout.

Direct current relays and contactors depend on the resistance of the wire used to construct the coil to limit current flow. For this reason, the coils of DC relays and contactors will exhibit a higher resistance than coils of AC relays. Large direct current contactors are often equipped with two coils instead of one (Figure 5–50). When the contactor is energized, the coils are connected in parallel to produce a strong magnetic field in the pole piece. A strong field is required to provide the attraction needed to attract the armature. Once the armature has been attracted, a much weaker magnetic field can hold the armature in place. When the armature closes, a switch disconnects one of the coils, reducing the current to the contactor.

IEC MOTOR STARTERS (60 HZ)

SIZE	MAX AMPS	MOTOR VOLTAGE	MAX. HORSEPOWER SINGLE PHASE	MAX. HORSEPOWER THREE PHASE
A	7	115	1/4	
		200		1 1/2
		230	1/2	1 1/2
		460		3
		575		5
B	10	115	1/2	
		200		2
		230	1	2
		460		5
		575		7 1/2
C	12	115	1/2	
		200		3
		230	2	3
		460		7 1/2
		575		10
D	18	115	1	
		200		5
		230	3	5
		460		10
		575		15
E	25	115	2	
		200		5
		230	3	7 1/2
		460		15
		575		20
F	32	115	2	
		200		7 1/2
		230	5	10
		460		20
		575		25
G	37	115	3	
		200		7 1/2
		230	5	10
		460		25
		575		30
H	44	115	3	
		200		10
		230	7 1/2	15
		460		30
		575		40
J	60	115	5	
		200		15
		230	10	20
		460		40
		575		40
K	73	115	5	
		200		20
		230	10	25
		460		50
		575		50
L	85	115	7 1/2	
		200		25
		230	10	30
		460		60
		575		75
M	105	115	10	
		200		30
		230	10	40
		460		75
		575		100
N	140	115	10	
		200		40
		230	10	50
		460		100
		575		125
P	170	115		
		200		50
		230		60
		460		125
		575		125
R	200	115		
		200		60
		230		75
		460		150
		575		150
S	300	115		
		200		75
		230		100
		460		200
		575		200
T	420	115		
		200		125
		230		125
		460		250
		575		250
U	520	115		
		200		150
		230		150
		460		350
		575		250
V	550	115		
		200		150
		230		200
		460		400
		575		400
W	700	115		
		200		200
		230		250
		460		500
		575		500
X	810	115		
		200		250
		230		300
		460		600
		575		600
Z	1215	115		
		200		450
		230		450
		460		900
		575		900

Figure 5–42 IEC motor starters rated by size, horsepower, and voltage for 60 Hz circuits. (Source: Delmar/Cengage Learning.)

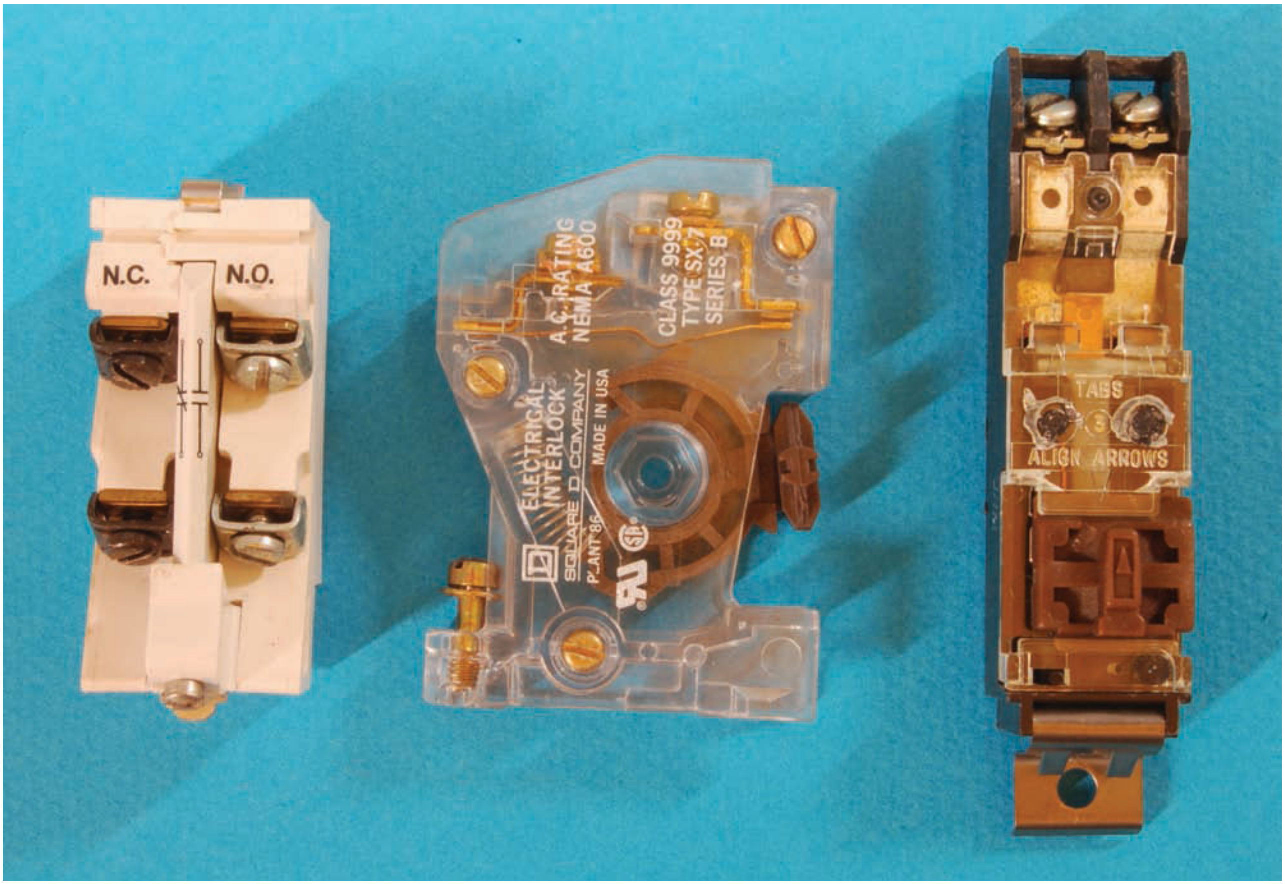


Figure 5–43 Auxiliary contact sets can be added to motor starters and contractors. (Source: Delmar/Cengage Learning.)

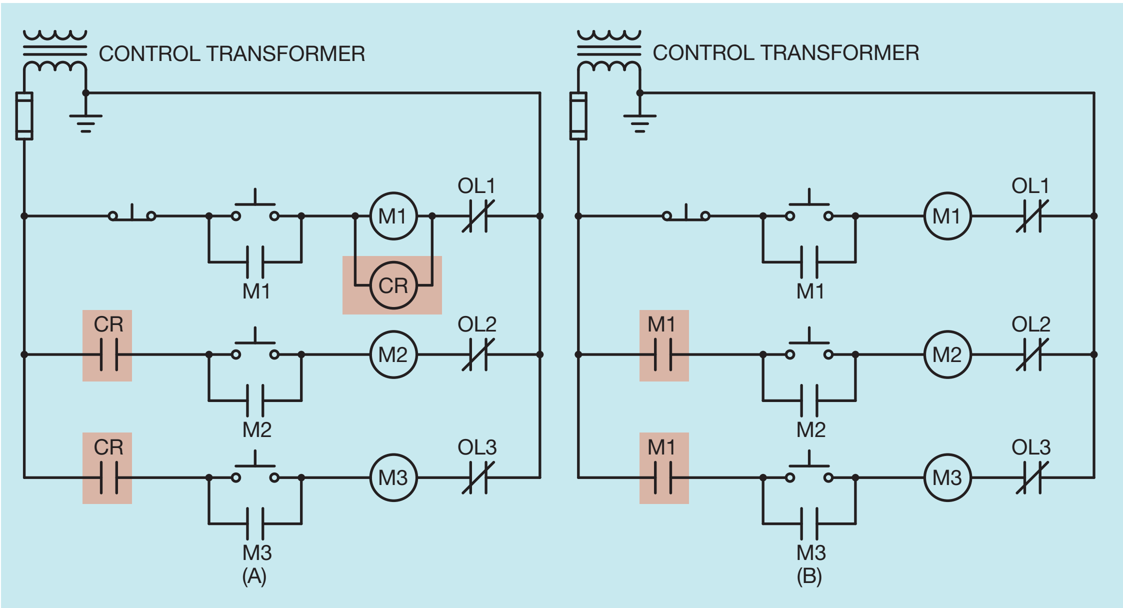


Figure 5–44 Control relays can sometimes be eliminated by adding auxiliary contacts to a motor starter. (Source: Delmar/Cengage Learning.)

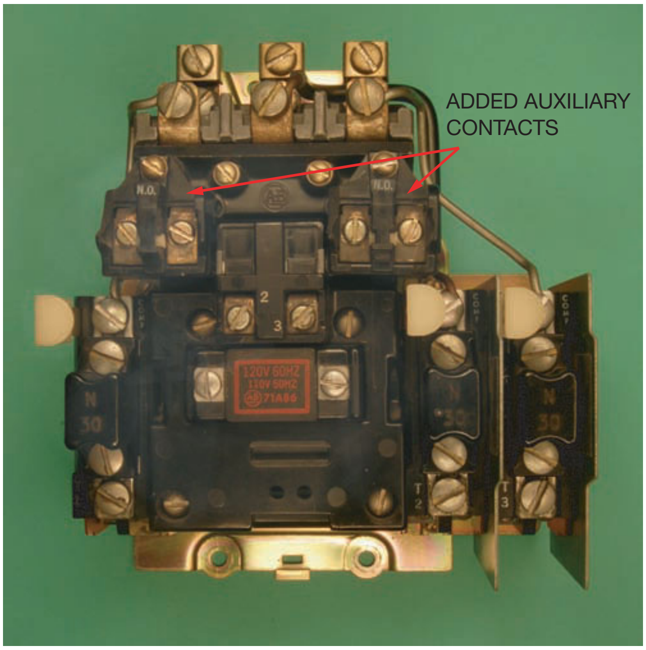


Figure 5–45 Motor starter with additional auxiliary contacts. (Source: Delmar/Cengage Learning.)

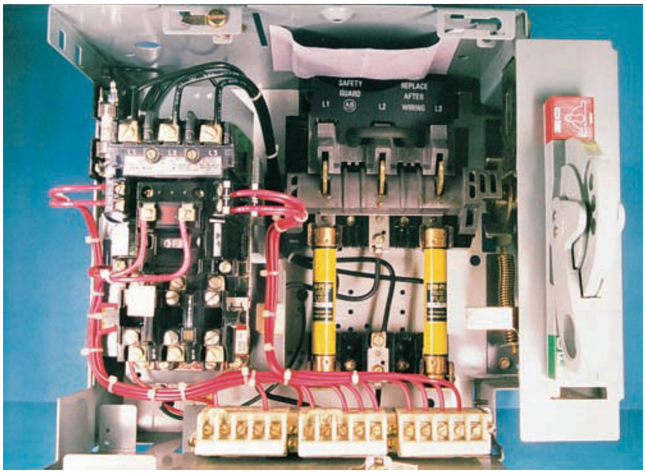


Figure 5–47 Combination starter with fused disconnect intended for use in a motor control center (MCC). Note that only two fuses are used in this module. Delta connected power systems with one phase grounded do not require a fuse in the grounded conductor. (Source: Delmar/Cengage Learning.)

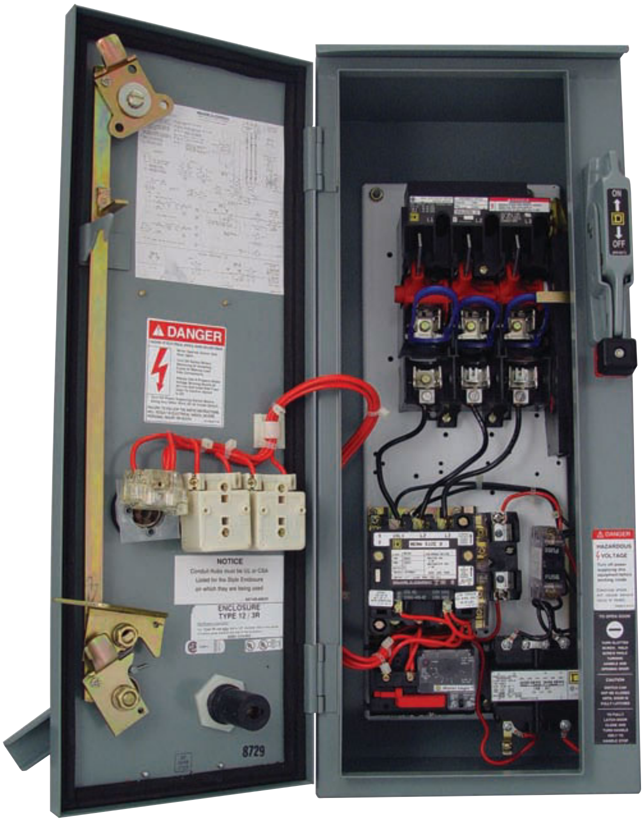


Figure 5–46 A combination starter with fused disconnect, control transformer, push buttons, and motor starter. (Courtesy Square D Company.)

Figure 5–48 Motor control center. (Courtesy Cutler Hammer, Eaton Corp.)

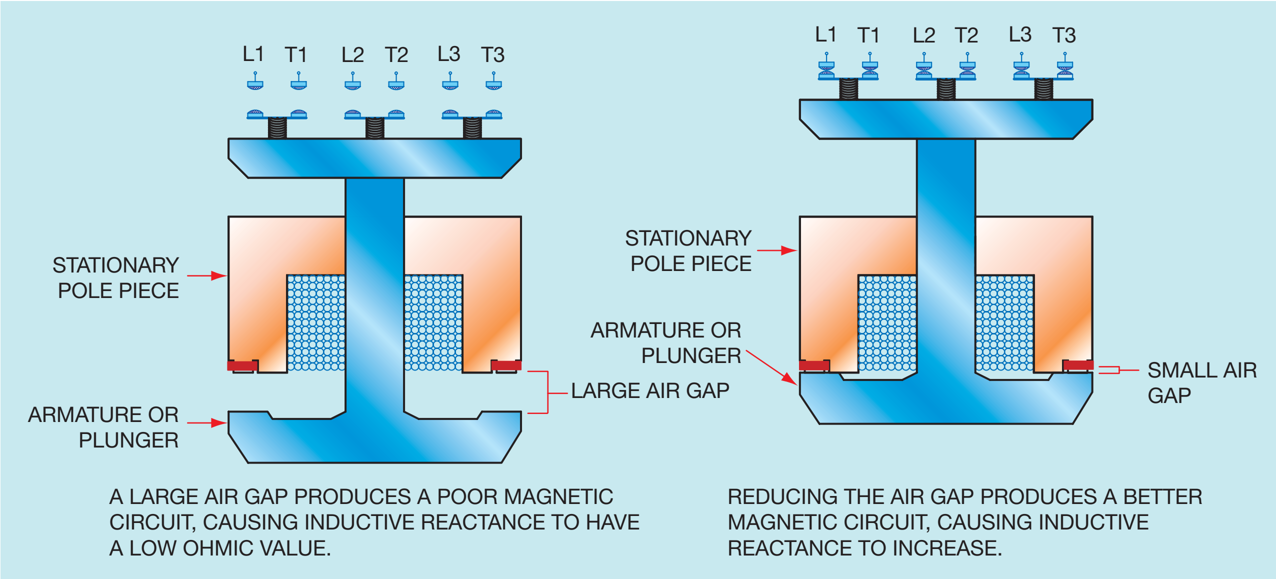


Figure 5–49 The air gap determines the inductive reactance of the solenoid. (Source: Delmar/Cengage Learning.)

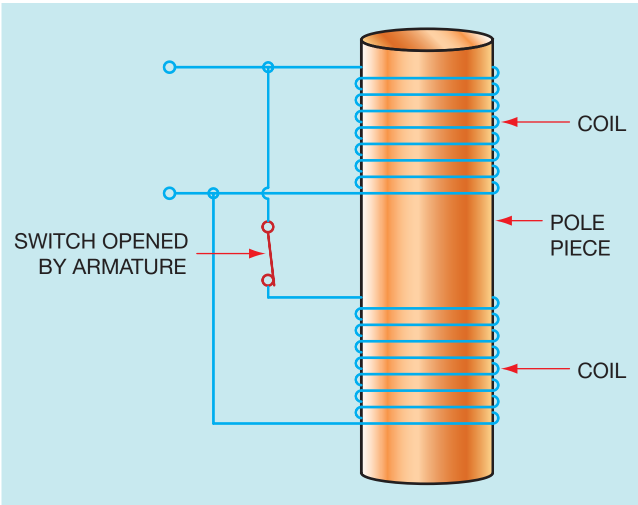


Figure 5–50 Direct current contactors often contain two coils. (Source: Delmar/Cengage Learning.)

Review Questions

1. Explain the difference between clapper type contacts and bridge type contacts.
2. What is the advantage of bridge type contacts over clapper type contacts?
3. Explain the difference between auxiliary contacts and load contacts.
4. What type of electronic device is used to connect the load to the line in a solid state relay used to control an alternating current load?
5. What is optoisolation and what is its main advantage?
6. What pin numbers are connected to the coil of an eight-pin control relay?

7. An eleven-pin control relay contains three sets of single-pole double-throw contacts. List the pin numbers by pairs that can be used as normally open contacts.
8. What is the purpose of the shading coil?
9. Refer to the circuit shown in Figure 5–29. Is the thermostat contact normally open, normally closed, normally closed held open, or normally open held closed?
10. What is the difference between a motor starter and a contactor?
11. A 150-horsepower motor is to be installed on a 480 volt three-phase line. What is the minimum size NEMA starter that should be used for this installation?
12. What is the minimum size IEC starter rated for the motor described in question 11?
13. When energizing or de-energizing a combination starter, what safety precaution should always be taken?
14. What is the purpose of “coil clearing contacts”?
15. Refer to the circuit shown in Figure 5–29. In this circuit, contactor HR is equipped with five contacts. Three are load contacts and two are auxiliary contacts. From looking at the schematic diagram, how is it possible to identify which contacts are the load contacts and which are the auxiliary contacts?

CHAPTER 6

THE CONTROL TRANSFORMER

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the use of control transformers in a control circuit.
- Connect a control transformer for operation on a 240 or 480 volt system.

Most industrial motors operate on voltages that range from 240 to 480 volts. Magnetic control systems, however, generally operate on 120 volts. A control transformer is used to step the 240 or 480 volts down to 120 volts to operate the control system. There is really nothing special about a control transformer except that most of them are made with two primary windings and one secondary winding. Each primary winding is rated at 240 volts, and the secondary winding is rated at 120 volts. This means there is a turns ratio of 2:1 (2 to 1) between each primary winding and the secondary winding. For example, assume that each primary winding contains 200 turns of wire and the secondary winding contains 100 turns. There are two turns of wire in each primary winding for every one turn of wire in the secondary.

One of the primary windings of the control transformer is labeled H1 and H2. The other primary winding is labeled H3 and H4. The secondary winding is labeled X1 and X2. If the transformer is to be used to step 240 volts down to 120 volts, the two primary windings are connected parallel to each other as shown in Figure 6–1. Notice that in Figure 6–1 the H1 and H3

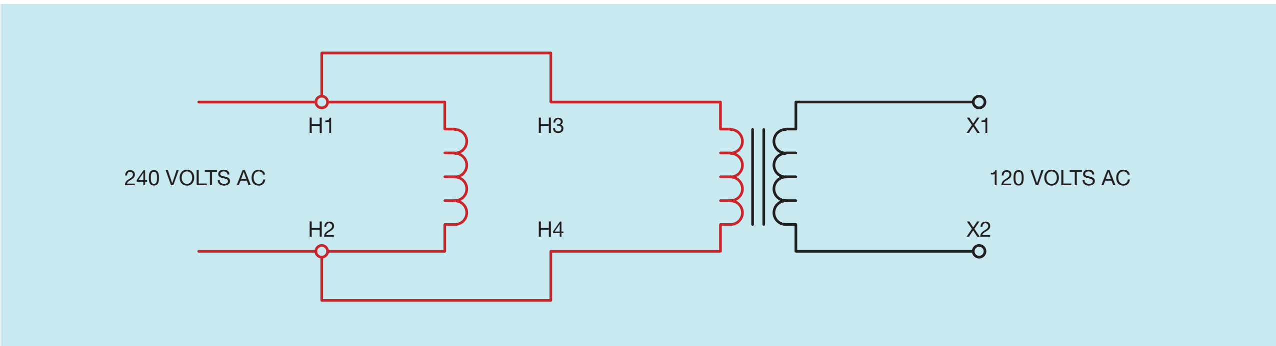


Figure 6–1 Primaries connected in parallel for 240 volt operation. (Source: Delmar/Cengage Learning.)

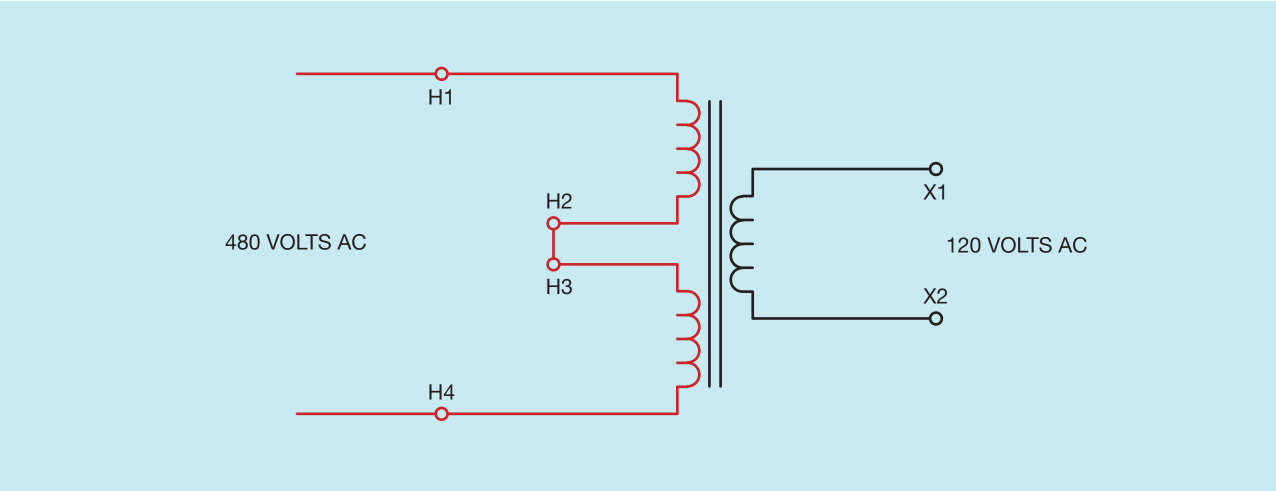


Figure 6–2 Primaries connected in series for 480 volt operation. (Source: Delmar/Cengage Learning.)

leads are connected together, and the H2 and H4 leads are connected together. Since the voltage applied to each primary winding is the same, the effect is the same as having only one primary winding with 200 turns of wire in it. This means that when the transformer is connected in this manner, the turns ratio is 2:1. When 240 volts are connected to the primary winding, the secondary voltage is 120 volts.

If the transformer is to be used to step 480 volts down to 120 volts, the primary windings are connected in series as shown in Figure 6–2. With the windings connected in series, the primary winding now has a total of 400 turns of wire, which makes a turns ratio of 4:1. When 480 volts is connected to the primary winding, the secondary winding has an output of 120 volts.

Control transformers generally have screw terminals connected to the primary and secondary leads. The H2 and H3 leads are crossed to make connection of the primary winding easier, Figure 6–3. For example, if the transformer is to be connected for 240 volt operation, the two primary windings must be connected parallel to each other as shown in Figure 6–1. This connection can be made on the transformer by using one metal link to connect leads H1 and H3, and another metal link to connect H2 and H4 (Figure 6–4).

If the transformer is to be used for 480 volt operation, the primary windings must be connected in series as shown in Figure 6–2. This connection can be made on the control transformer by using a metal link

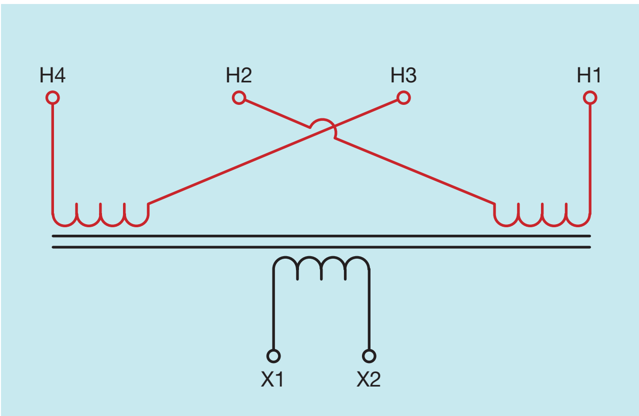


Figure 6–3 Primary leads are crossed. (Source: Delmar/Cengage Learning.)

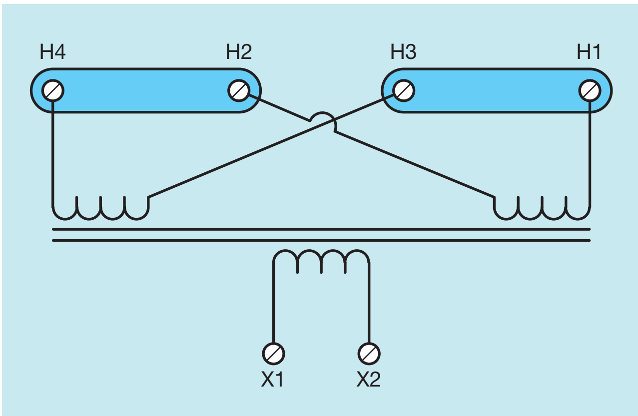


Figure 6–4 Metal links used to make a 240 volt connection. (Source: Delmar/Cengage Learning.)

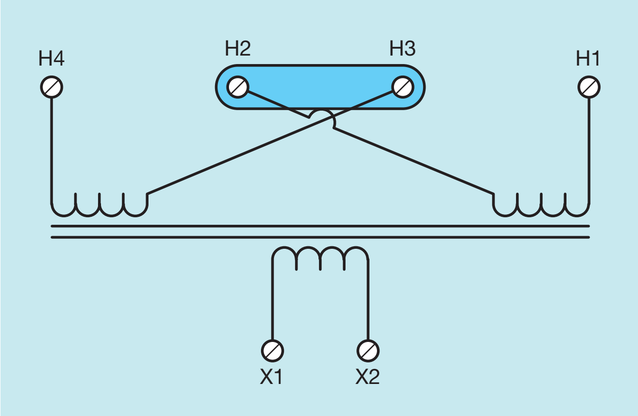


Figure 6–5 Metal link used to make a 480 volt connection. (Source: Delmar/Cengage Learning.)

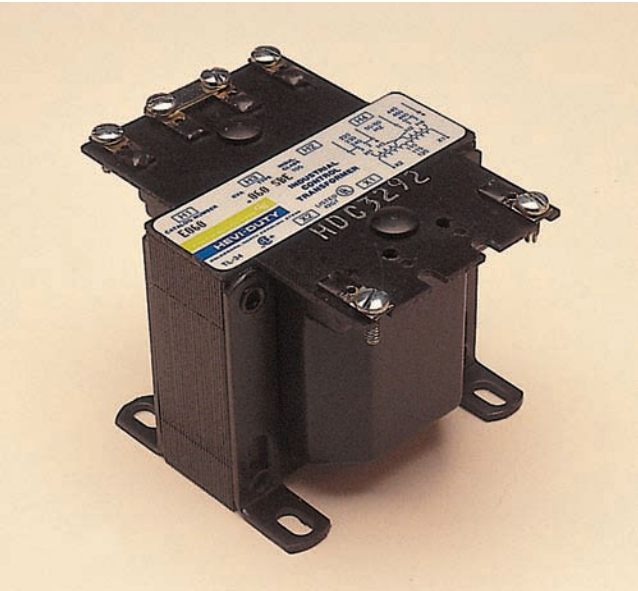


Figure 6–6 Control transformer. (Courtesy McKenzi and Dickerson.)

to connect H2 and H3 as shown in Figure 6–5. A typical control transformer is shown in Figure 6–6.

Some control transformers contain a multi-tapped primary instead of two separate windings (Figure 6–7). The transformer in this example is designed to step voltages of 480, 277, 240, or 208 down to 120.

Power Rating

The power rating of control transformers generally ranges from 0.75 kilovolt-amperes, or 75 volt-amperes, to 1 kilovolt-ampere, or 1000 volt-ampere. The rating

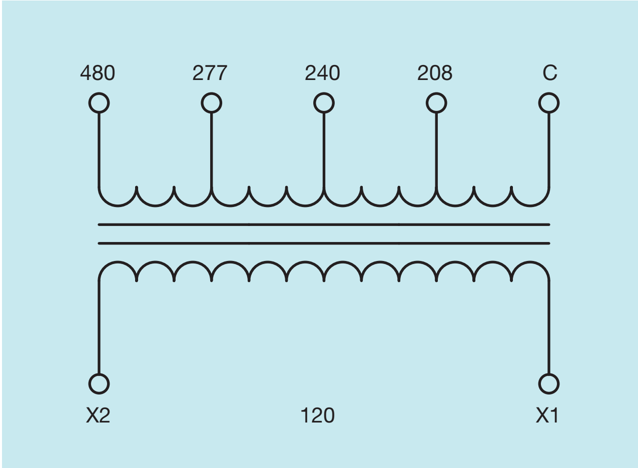


Figure 6–7 Control transformer with a multi-tapped primary winding. (Source: Delmar/Cengage Learning.)

is indicated in volt-amperes, not watts, because transformers generally supply power to operate inductive devices such as the coils of relays and motor starters (Figure 6–8). The volt-ampere rating indicates the amount of current the transformer can supply to operate control devices. To determine the maximum output current of a transformer, divide the volt-ampere rating by the secondary voltage. The transformer shown in Figure 6–8 has a power rating of 250 volt-amperes. If the secondary voltage is 120 volts, the maximum secondary current would be 2.08 amperes.

$$I = \frac{VA}{E}$$

$$I = \frac{250}{120}$$

$$I = 2.08 \text{ A}$$

A control transformer intended to operate a single motor starter may have a rating of 75 to 100 volt-amperes. Transformers intended to supply power to an entire relay cabinet will have much higher ratings, depending on the number of devices and their current requirements.

Grounded and Floating Control Systems

One side of the secondary winding of a control transformer is often grounded (Figure 6–9). When this is done, the control system, is referred to as a *grounded system.* Many industries prefer to ground the control

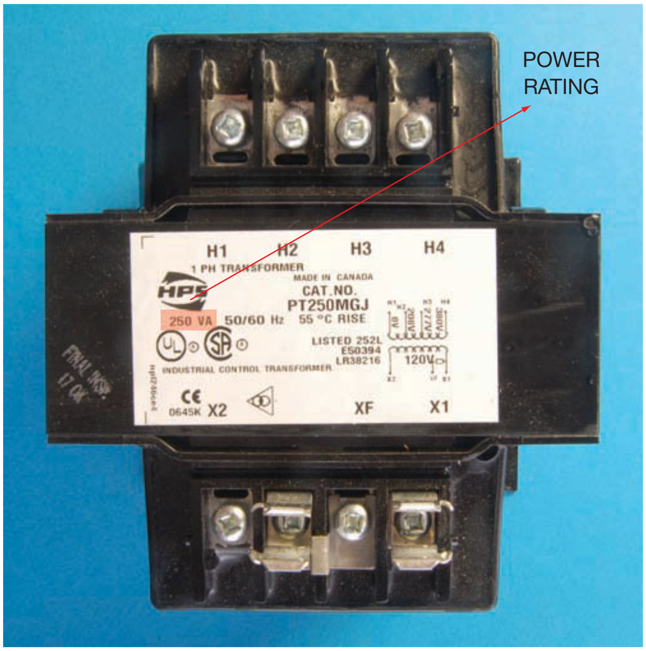


Figure 6–8 The power rating of a transformer is listed in volt-amperes. (Source: Delmar/Cengage Learning.)

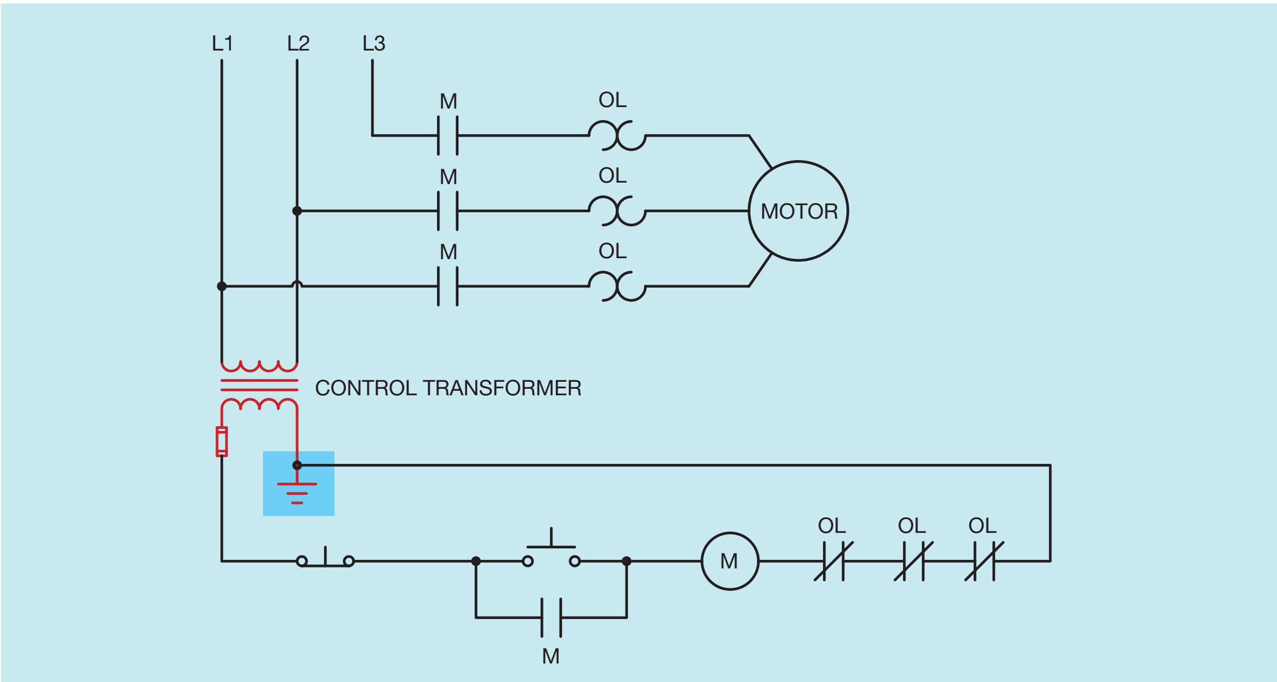


Figure 6–9 One side of the transformer has been grounded. (Source: Delmar/Cengage Learning.)

system, and it is a very common practice. Some technicians believe that it is an aid when troubleshooting a problem. Grounding one side of the control transformer permits one lead of a voltmeter to be connected to any grounded point and the other voltmeter lead to be used to test voltage at various locations throughout the circuit (Figure 6–10).

However, it is also a common practice to not ground one side of the control transformer. This is generally referred to as a *floating system.* If one voltmeter probe were to be connected to a grounded point, the meter reading would be erroneous or meaningless since there is not a complete circuit (Figure 6–11). High impedance voltmeters would probably indicate some amount of voltage caused by the capacitance of the ground and induced voltage produced by surrounding magnetic fields. These are generally referred to as *ghost voltages.* A low impedance meter such as a plunger type voltage tester would indicate no voltage. Accurate voltage measurement can be made in a float control system, however, by connecting one voltmeter probe directly to one side of the control transformer (Figure 6–12). Since both grounded and floating control systems are common, both will be illustrated throughout this text.

Transformer Fusing

Control transformers are generally protected by fuses or circuit breakers. Protection can be placed on the primary or secondary side of the transformer, and some industries prefer protection on both sides. NEC Section 430.72(C) lists requirements for the protection of transformers employed in motor control circuits. This section basically states that control transformers that have a primary current of less than 2 amperes shall be protected by an overcurrent device set at not more than 500% of the rated primary current. This large percentage is necessary because of the high in-rush current associated with transformers. To determine the rated current of the transformer, divide the volt-ampere rating of the transformer by the primary voltage.

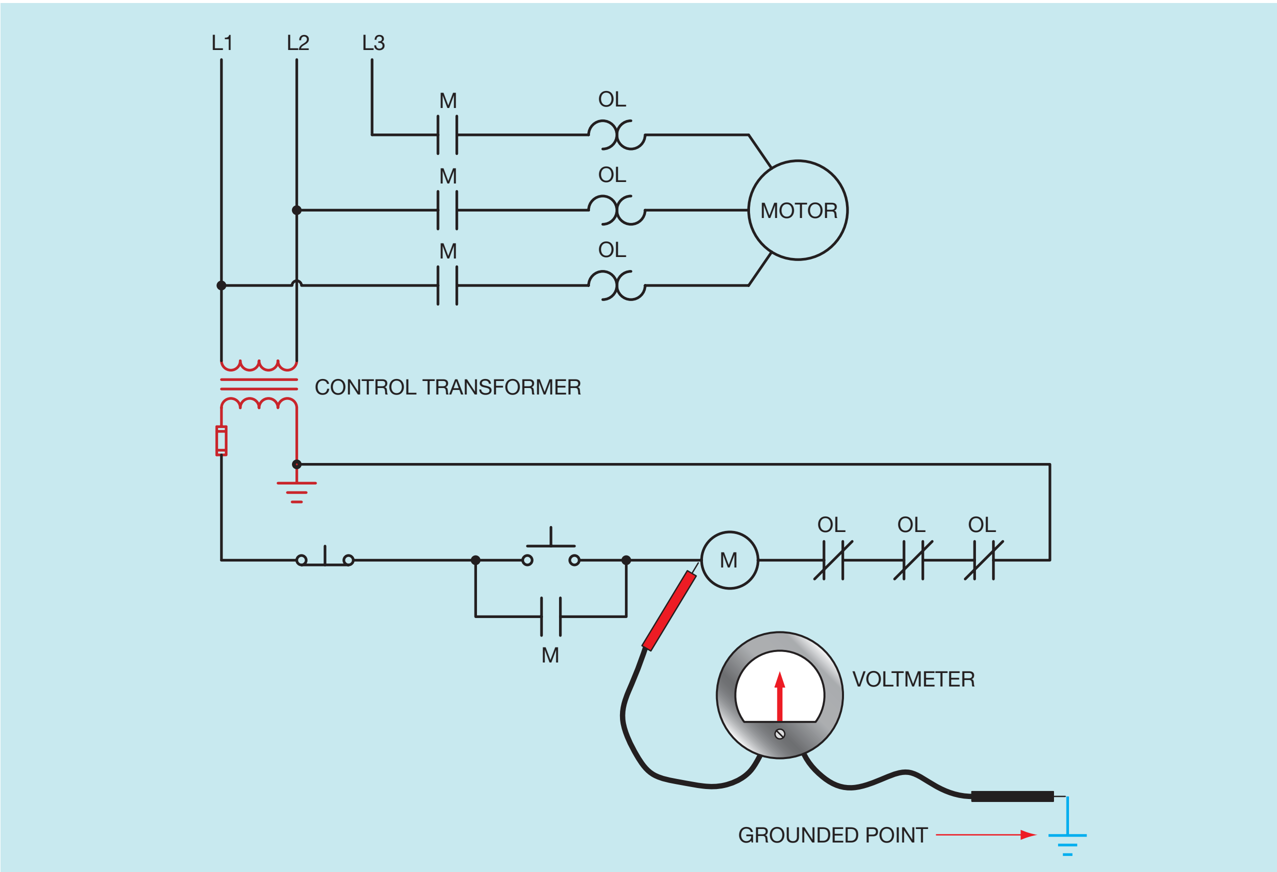


Figure 6–10 Voltage can be measured by connecting one meter probe to any grounded point. (Source: Delmar/Cengage Learning.)

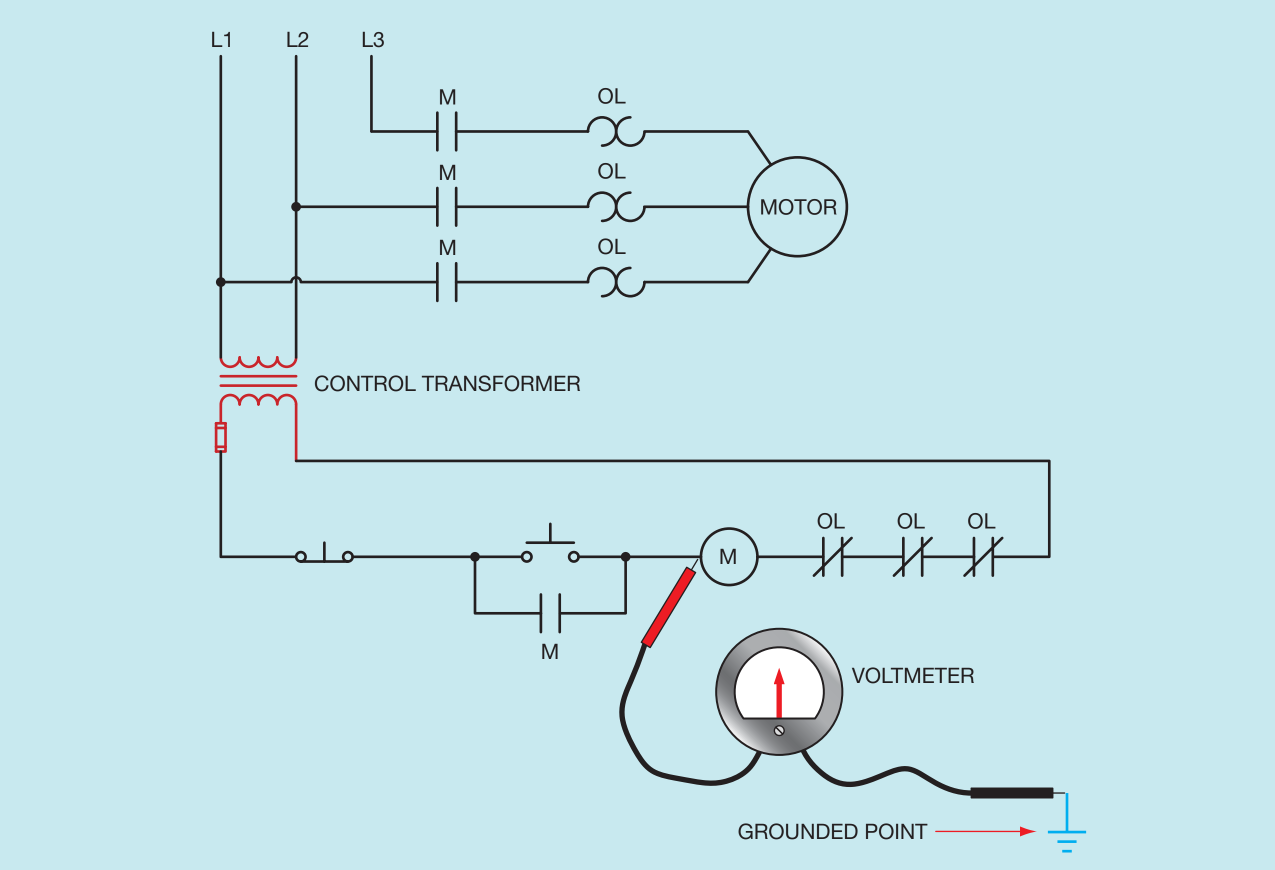


Figure 6–11 Floating control systems do not ground one side of the control transformer. Connecting a voltmeter probe to a grounded point would provide meaningless readings because a complete circuit does not exist. (Source: Delmar/Cengage Learning.)

EXAMPLE:

What is the maximum fuse size permitted to protect the primary winding of a control transformer rated at 300 volt-amperes and connected to 240 volts?

$$I = \frac{VA}{E}$$

$$I = \frac{300}{240}$$

$$I = 1.25 \text{ A}$$

$$\text{Fuse size} = 1.25 \times 5$$

$$\text{Fuse size} = 6.25 \text{ A}$$

NEC Section 240.6 indicates that a standard fuse size is 6 amperes. A 6 ampere fuse would be used.

NEC Section 430.72(C)(2) states that fuse protection in accordance with 450.3 is permitted also. This section states that primary protection for transformers rated 600 volts or less is determined in NEC Table 430.3(B). The table indicates a rating of 300% of the rated current.

The secondary fuse size can also be determined from NEC Table 450.3(B). The table indicates a rating of 167% of the rated secondary current for fuses protecting a transformer secondary with a current of less than 9 amperes. Assuming a control voltage of 120 volts, the rated secondary current of the transformer in the previous example would be 2.5 amperes (300/120). The fuse size would be:

$$2.5 \times 1.67 = 4.175 \text{ A}$$

The nearest standard fuse size listed in 240.6 without going over this value is 3 amperes. The secondary fuse

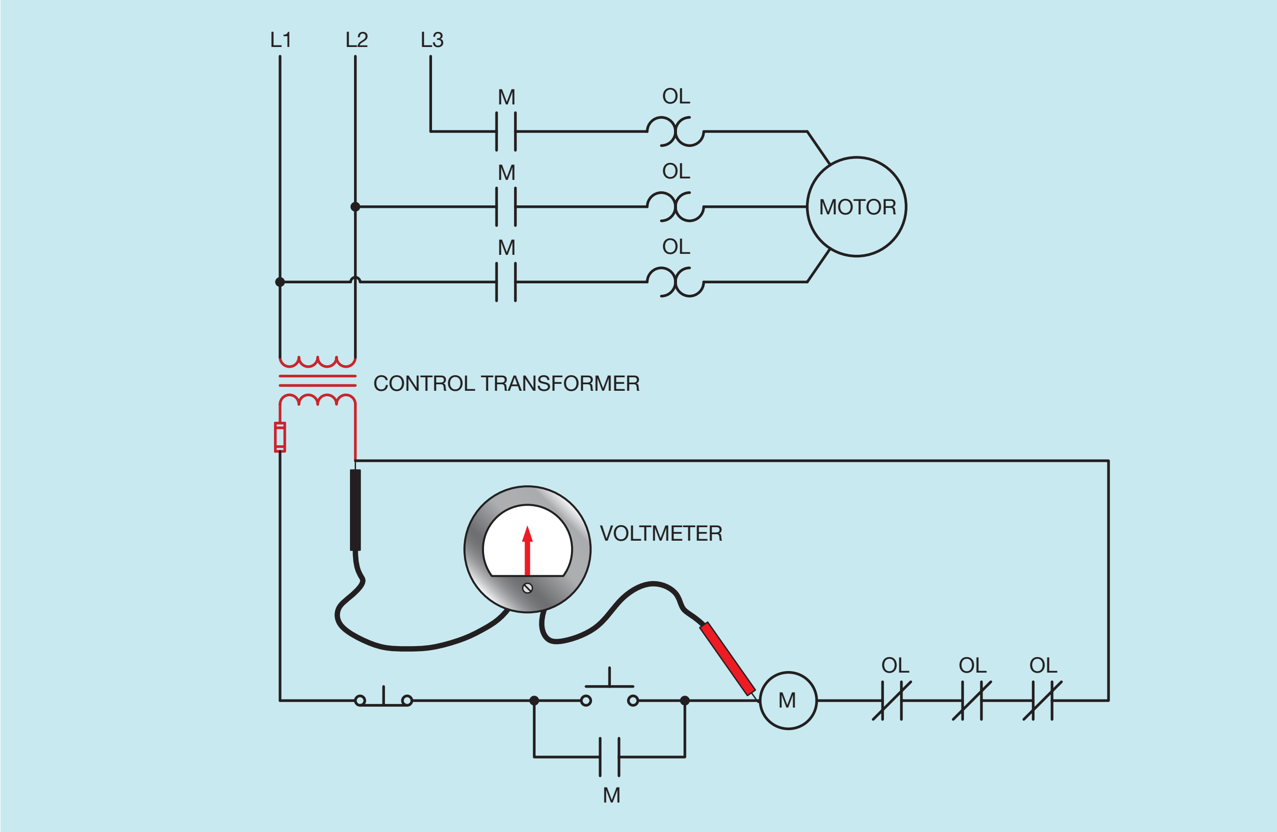


Figure 6–12 Connecting one meter probe directly to one side of the transformer will provide accurate readings on a floating control system. (Source: Delmar/Cengage Learning.)

size can be set at a lower percentage of the rated current because the secondary does not experience the high in-rush current of the primary. Since primary and secondary fuse protection is common throughout industry, control circuits presented in this text will illustrate both.

Review Questions

1. What is the operating voltage of most magnetic control systems?
2. How many primary windings do control transformers have?
3. How are the primary windings connected when the transformer is to be operated on a 240 volt system?
4. How are the primary windings connected when the transformer is to be operated on a 480 volt system?
5. Why are two of the primary leads crossed on a control transformer?
6. You are an electrician working in an industrial plant. You are building a motor control cabinet that contains six motor starters and six pilot lamps. All control components operate on 120 volts AC. Two of the motor starters have coil currents of 0.1 amperes each and four have coil currents of 0.18 amperes each. The six pilot lamps are rated at 5 watts each. The supply room has control transformers with the following rating (in volt-amperes): 75, 100, 150, 250, 300, and 500. Which of the available control transformers should you choose to supply the power for all the control components in the cabinet? (Choose the smallest size that will supply the power needed.)

CHAPTER 7
TIMING RELAYS

OBJECTIVES

After studying this chapter, the student will be able to:

- Identify the primary types of timing relays.
- Explain the basic steps in the operation of the common timing relays.
- List the factors that affect the selection of a timing relay for a particular use.
- List applications of several types of timing relays.
- Draw simple circuit diagrams using timing relays.
- Identify on- and off-delay timing wiring symbols.

Time delay relays can be divided into two general classifications: the on-delay relay, and the off-delay relay. The on-delay relay is often referred to as DOE, which stands for "Delay On Energize." The off-delay relay is often referred to as DODE, which stands for "Delay On De-Energize."

Timer relays are similar to other control relays in that they use a coil to control the operation of some number of contacts. The difference between a control relay and a timer relay is that the contacts of the timer relay delay changing their position when the coil is energized or de-energized. When power is connected to the coil of an on-delay timer, the contacts delay changing position for some period of time. For this example, assume that the timer has been set for a delay of 10 seconds. Also assume that the contact is normally open. When voltage is connected to the coil of the on-delay timer, the contacts will remain in the open position for 10 seconds and then close. When voltage is removed and the coil is de-energized, the contact will immediately change back to its normally open position. The contact symbols for an on-delay relay are shown in Figure 7–1.

The operation of the off-delay timer is the opposite of the operation of the on-delay timer. For this example, again assume that the timer has been set for a delay of 10 seconds, and also assume that the contact is normally open. When voltage is applied to the coil of the off-delay timer, the contact will change immediately from open to closed. When the coil is de-energized, however, the contact will remain in the closed position for 10 seconds before it reopens. The contact symbols for an off-delay relay are shown in Figure 7–2. Time-delay relays can have normally open, normally closed, or a combination of normally open and normally closed contacts.

Although the contact symbols shown in Figures 7–1 and 7–2 are standard NEMA symbols for on-delay and off-delay contacts, some control schematics may use a different method of indicating timed contacts. The abbreviations TO and TC are used with some control schematics to indicate a time-operated contact. *TO stands for time opening, and TC stands for time closing*. If these abbreviations are used with standard contact symbols, their meaning can be confusing. Figure 7–3 shows a standard normally open contact symbol with the abbreviation TC written beneath it. This contact must be connected to an on-delay relay if it is to be time delayed when closing. Figure 7–4 shows the same contact with the abbreviation TO beneath it. If this contact is to be time delayed when opening, it must be operated by an off-delay timer. These abbreviations can also be used with standard NEMA symbols as shown in Figure 7–5.

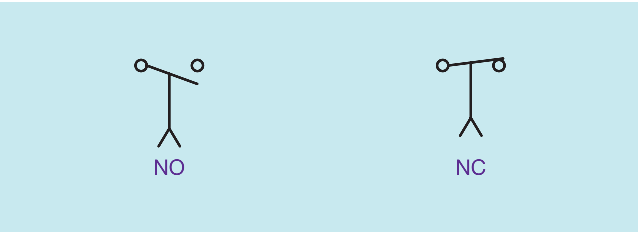


Figure 7–1 On-delay normally open and normally closed contacts. (Source: Delmar/Cengage Learning.)

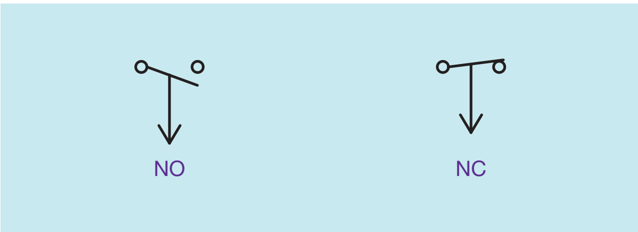


Figure 7–2 Off-delay normally open and normally closed contacts. (Source: Delmar/Cengage Learning.)

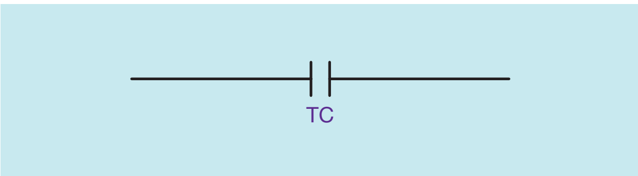


Figure 7–3 Time closing contact. (Source: Delmar/Cengage Learning.)

Pneumatic Timers

Pneumatic, or air timers, operate by restricting the flow of air through an orifice to a rubber bellows or diaphragm. Figure 7–6 illustrates the principle of operation of a simple bellows timer. If rod "A" pushes against the end of the bellows, air is forced out of the bellows through the check valve as the bellows contracts. When the bellows is moved back, contact TR changes from an open to a closed contact. When rod "A" is pulled away from the bellows, the spring tries to return the bellows to its original position. Before the bellows can be returned to its original position, however, air must enter the bellows through the air inlet port. The rate at which the air is permitted to enter the bellows is controlled by the needle valve. When the bellows returns to its original position, contact TR returns to its normally open position.

Pneumatic timers are popular throughout industry because they have the following characteristics:

A. They are unaffected by variations in ambient temperature or atmospheric pressure.

B. They are adjustable over a wide range of time periods.

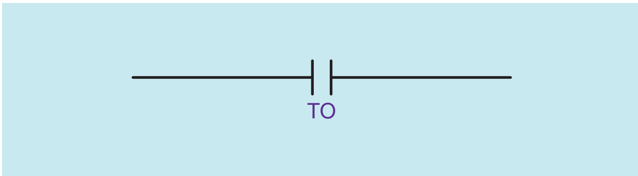


Figure 7–4 Time opening contact. (Source: Delmar/Cengage Learning.)

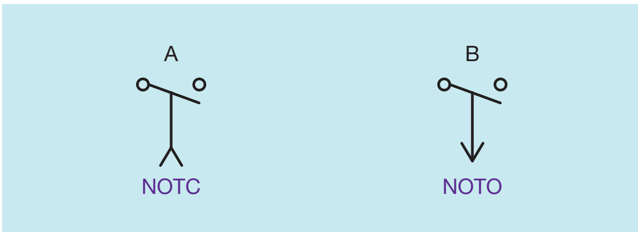


Figure 7–5 Contact A is an on-delay contact with the abbreviation NOTC (normally open time closing). Contact B is an off-delay contact with the abbreviation NOTO (normally open time opening). (Source: Delmar/Cengage Learning.)

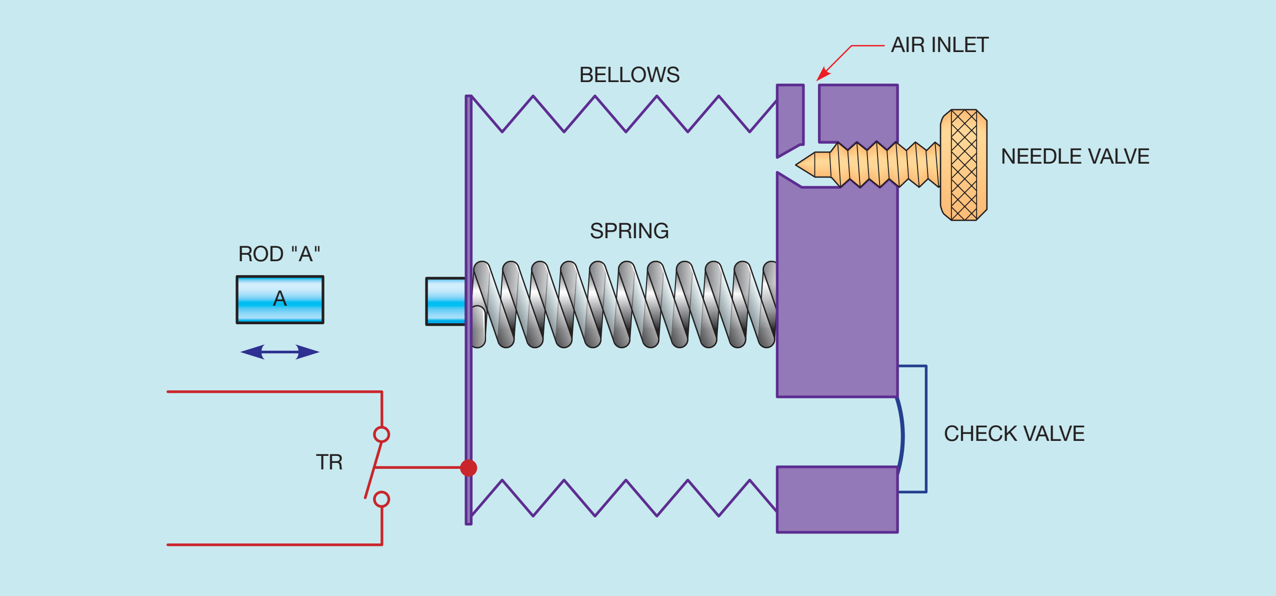


Figure 7–6 Bellows-operated pneumatic timer. (Source: Delmar/Cengage Learning.)

C. They have good repeat accuracy.

D. They are available with a variety of contact and timing arrangements.

Some pneumatic timers are designed to permit the timer to be changed from on-delay to off-delay, and the contact arrangement to be changed to normally opened or normally closed (Figure 7–7). This type of flexibility is another reason for the popularity of pneumatic timers.

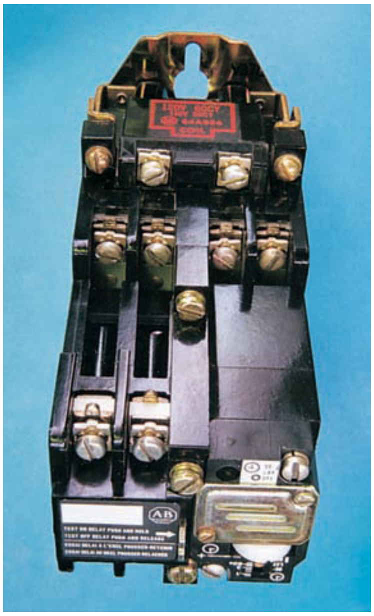


Figure 7–7 Pneumatic timer. (Courtesy Allen-Bradley, a Rockwell International Company.)

Many timers are made with contacts that operate with the coil as well as time delayed contacts. When these contacts are used, they are generally referred to as *instantaneous contacts* and indicated on a schematic diagram by the abbreviation INST. printed below the contact (Figure 7–8). These instantaneous contacts change their positions immediately when the coil is energized and change back to their normal positions immediately when the coil is de-energized.

Clock Timers

Another timer frequently used is the clock timer (Figure 7–9). Clock timers use a small AC synchronous motor similar to the motor found in a wall clock to provide the time measurement for the timer. The length of time of one clock timer may vary greatly from the length

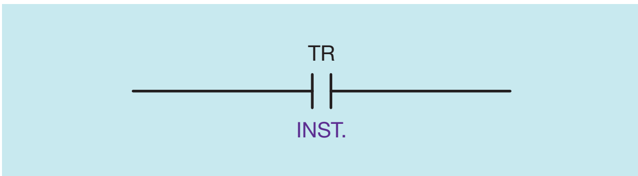


Figure 7–8 Normally open instantaneous contact of a timer relay. (Source: Delmar/Cengage Learning.)

Figure 7–9 Clock driven timer. (Source: Delmar/Cengage Learning.)

of time of another. For example, one timer may have a full range of 0 to 5 seconds and another timer may have a full range of 0 to 5 hours. The same type of timer motor could be used with both timers. The gear ratio connected to the motor would determine the full range of time for the timer. Some advantages of clock timers are:

A. They have extremely high repeat accuracy.

B. Readjustment of the time setting is simple and can be done quickly. Clock timers are generally used when the machine operator must make adjustments to the time length.

Motor-Driven Timers

When a process has a definite on and off operation, or a sequence of successive operations, a motor-driven timer is generally used (Figure 7–10 and Figure 7–11). A typical application of a motor-driven timer is to control laundry washers where the loaded motor is run for a given period in one direction, reversed, and then run in the opposite direction.

Generally, this type of timer consists of a small, synchronous motor driving a cam-dial assembly on a common shaft. A motor-driven timer successively closes and opens switch contacts, which are wired in circuits to energize control relays or contactors to achieve desired operations.

Min. Time Delay: 0.05 second

Max. Time Delay: 3 minutes

Minimum Reset Time: 0.75 second

Accuracy: 610 percent of setting

Contact Ratings:

AC

6.0 A, 115 V
3.0 A, 230 V
1.5 A, 460 V
1.2 A, 550 V

DC

1.0 A, 115 V
0.25 A, 230 V

Operating Coils: Coils can be supplied for voltages and frequencies upto 600 volts, 60 hertz AC and 250 volts DC

Types of Contact: One normally open and one normally closed. Cadmium silver alloy contacts.

Figure 7–10 Typical specifications. (Source: Delmar/Cengage Learning.)

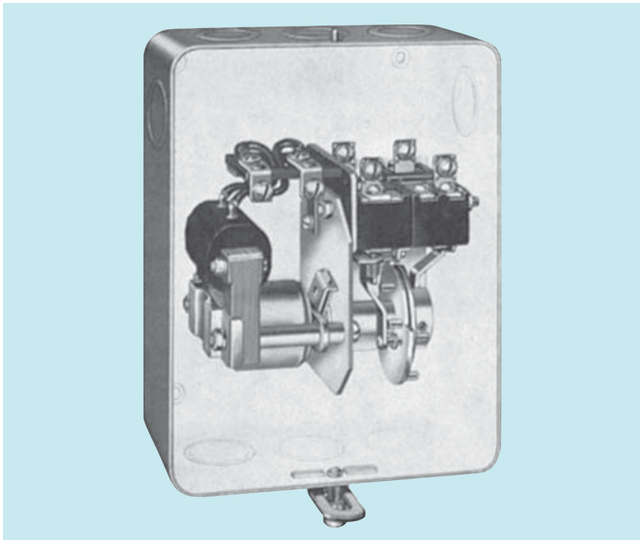


Figure 7–11 Motor-driven process timer. Often referred to as a cam timer. (Courtesy Allen-Bradley, a Rockwell International Company.)

Capacitor Time Limit Relay

Assume that a capacitor is charged by connecting it momentarily across a DC line, and then the capacitor direct current is discharged through a relay coil. The

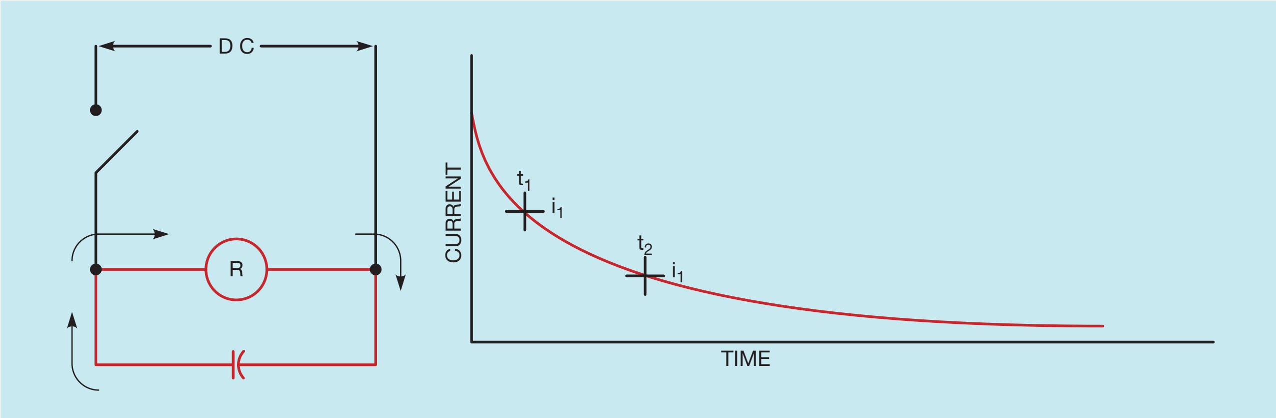


Figure 7–12 Charged capacitor discharging through a relay coil. The graph at the right illustrates the current decrease in the coil. (Source: Delmar/Cengage Learning.)

current induced in the coil will decay slowly, depending on the relative values of capacitance, inductance, and resistance in the discharge circuit.

If a relay coil and a, capacitor are connected parallel to a DC line (Figure 7–12), the capacitor is charged to the value of the line voltage and a current appears in the coil. If the coil and capacitor combination is now removed from the line, the current in the coil will start to decrease along the curve shown in Figure 7–12.

If the relay is adjusted so that the armature is released at current i_1, a time delay of t_1 is obtained. The time delay can be increased to a value of t_2 by adjusting the relay so that the armature will not be released until the current is reduced to a value of i_2. Figure 7–13 shows a relay used for this type of time control.

A potentiometer is used as an adjustable resistor to vary the time. This resistance-capacitance (RC) theory is used in industrial electronic and solid-state controls also. This timer is highly accurate and is used in motor acceleration control and in many industrial processes.

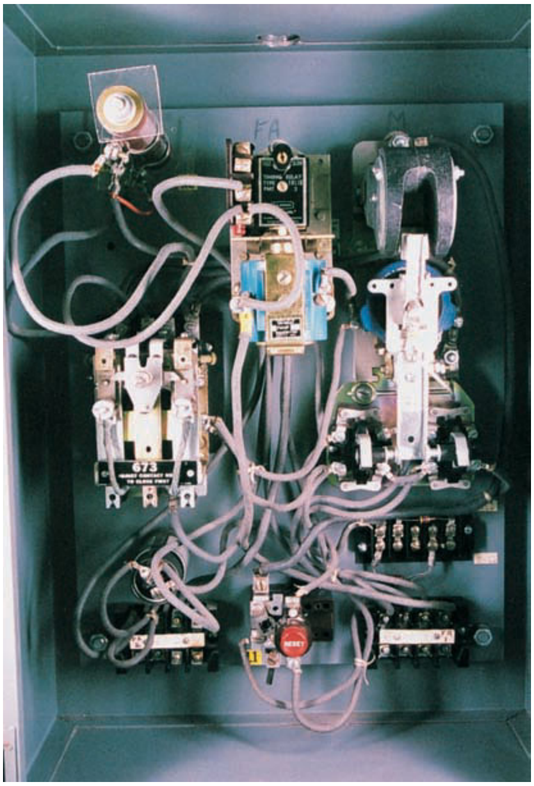


Figure 7–13 Capacitor timer limit controller. (Generally used with direct current control systems.) (Source: Delmar/Cengage Learning.)

Electronic Timers

Electronic timers use solid-state components to provide the time delay desired. Some of these timers use an RC time constant to obtain the time base and others use quartz clocks as the time base (Figure 7–14). RC time constants are inexpensive and have good repeat times. The quartz timers, however, are extremely accurate and can often be set for 0.1 second times. These timers are generally housed in a plastic case and are designed to be plugged into some type of socket. An electronic timer that is designed to be plugged into a standard eight-pin tube socket is shown in Figure 7–15. The length of the time delay can be set by adjusting the control knob shown on top of the timer.

Eight-pin electron timers similar to the one shown in Figure 7–15 are intended to be used as on-delay

Figure 7–14 Digital clock timer. (Source: Delmar/Cengage Learning.)

Figure 7–15 Electronic timer. (Source: Delmar/Cengage Learning.)

timers only. Many electronic timers are designed to plug into an eleven-pin tube socket (Figure 7–16) and are more flexible. Two such timers are shown in Figure 7–17A and Figure 7–17B. Either of these timers can be used as an on-delay timer, an off-delay timer, a pulse timer, or as a one-shot timer. Pulse timers

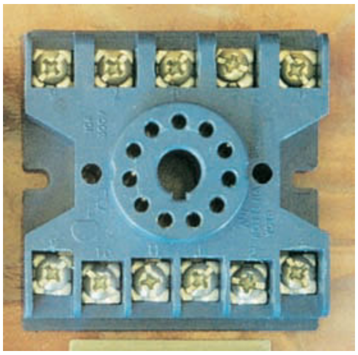


Figure 7–16 Eleven-pin tube sockets. (Source: Delmar/Cengage Learning.)

continually turn on and off at regular intervals. A timing period chart for a pulse timer set for a delay of 1 second is shown in Figure 7–18. A one-shot timer will operate for one time period only. A timing period chart for a one shot timer set for 2 seconds is shown in Figure 7–19.

Most electronic timers can be set for a wide range of times. The timer shown in Figure 7–17A uses a thumbwheel switch to enter the timer setting. The top selector switch can be used to set the full range value from 9.99 seconds to 999 minutes. This timer has a range from 0.01 second to 999 minutes (16 hrs. 39 min.). The timer shown in Figure 7–17B can be set for a range of 0.01 second to 100 hours by adjusting the range and units settings on the front of the timer. Most electronic timers have similar capabilities.

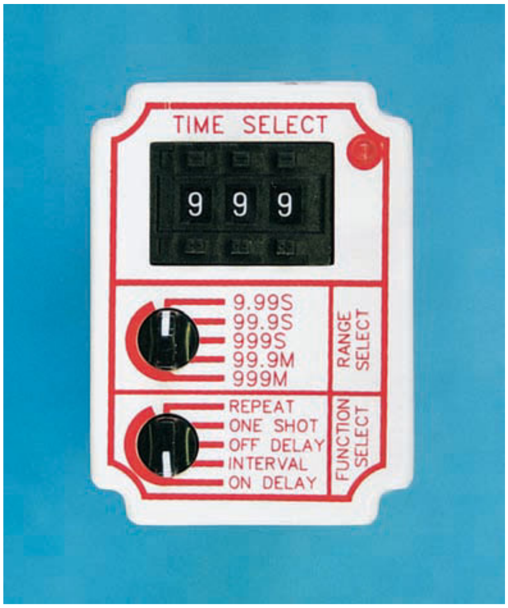


Figure 7–17A Dayton electronic timer. (Source: Delmar/Cengage Learning.)

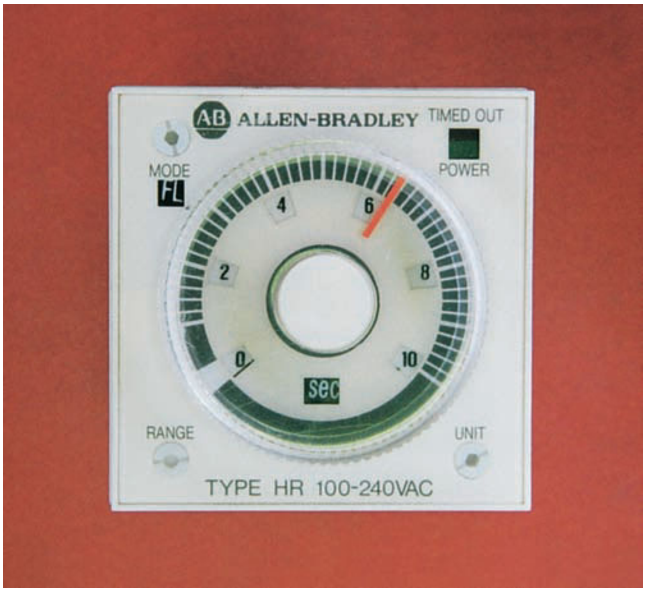


Figure 7–17B Allen-Bradley electronic timer. (Source: Delmar/Cengage Learning.)

Connecting Eleven-Pin Timers

Connecting eleven-pin timers into a circuit is generally a little more involved than simply connecting the coil to power. The manufacturer's instructions should always be consulted before trying to connect one of these timers. Although most electronic timers are similar in how they are connected, there are differences. The pin connection diagram for the timer shown in Figure 7–17A is shown in Figure 7–20. Notice that a normally open push-button switch is shown across terminals 5 and 6. This switch is used to start the action of the timer when it is set to function as an off-delay timer or as a one-shot timer. The reason for this is that when the timer is to function as an off-delay timer, power must be applied to the timer at all times to permit the internal timing circuit to operate. If power is removed, the internal timer cannot function. The start switch is actually used to initiate the operation of the timer when it is set to function in the off-delay mode. Recall the logic of an off-delay timer: *When the coil is energized,*

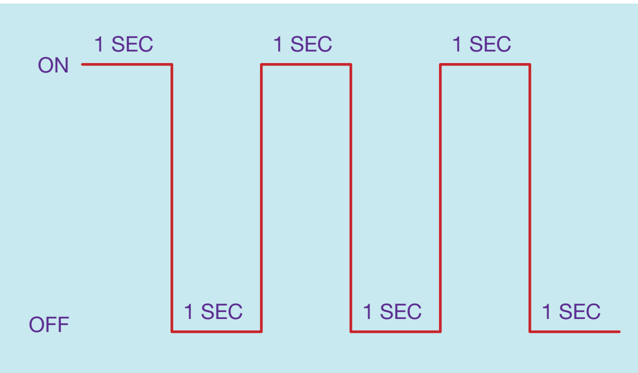


Figure 7–18 Timing chart for a pulse timer. (Source: Delmar/Cengage Learning.)

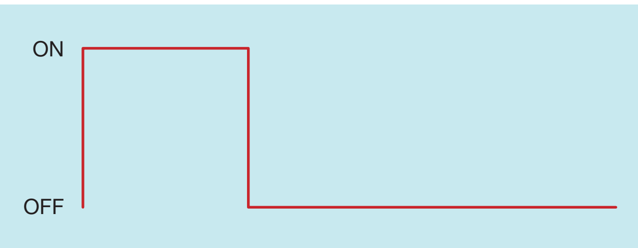


Figure 7–19 Timing chart for a one shot timer. (Source: Delmar/Cengage Learning.)

Figure 7–20 Pin connection diagram for Dayton timer. (Source: Delmar/Cengage Learning.)

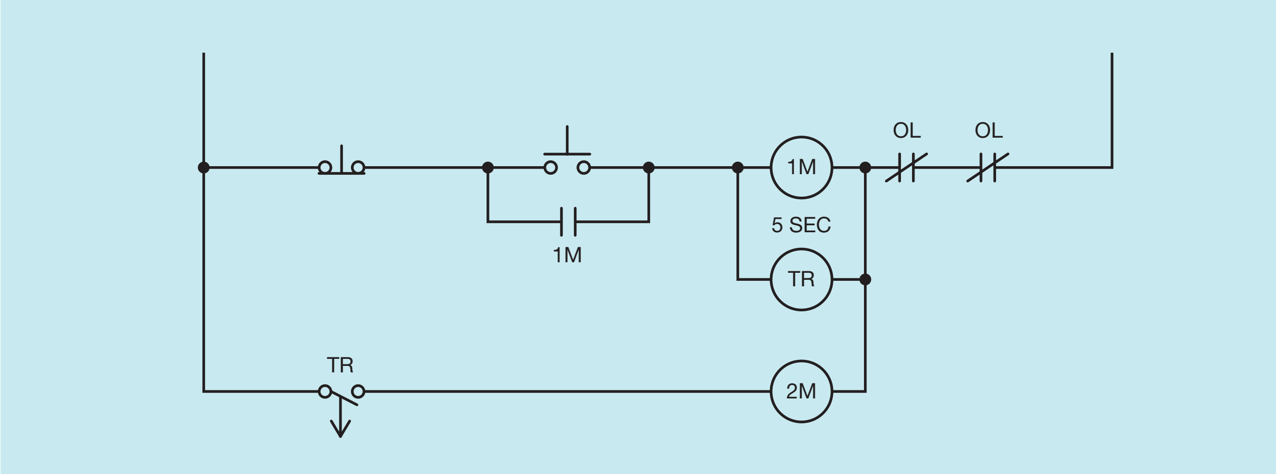


Figure 7–21 Off-delay timer circuit using a pneumatic timer. (Source: Delmar/Cengage Learning.)

the contacts change position immediately. When the coil is de-energized, the contacts delay returning to their normal position. According to the pin chart shown in Figure 7–20, pins 2 and 10 connect to the coil of the timer. To use this timer in the off-delay mode, power must be connected to pins 2 and 10 at all times. Shorting pins 5 and 6 together causes the timed contacts to change position immediately. When the short circuit between pins 5 and 6 is removed, the time sequence begins. At the end of the preset time period, the contacts will return to their normal position.

If electronic off-delay timers are to replace pneumatic off-delay timers in a control circuit, it is generally necessary to modify the circuit. For example, in the circuit shown in Figure 7–21, it is assumed that starters 1M and 2M control the operation of two motors, and timer TR is a pneumatic off-delay timer. When the start button is pressed, two motors start at the same time. The motors will continue to operate until the stop button is pressed, which causes motor #1 to stop running immediately. Motor #2, however, will continue to run for a period of 5 seconds before stopping.

Now assume that the pneumatic off-delay timer is to be replaced with an electronic off-delay timer (Figure 7–22). In this circuit, notice that the coil of the timer is connected directly across the incoming power, which permits it to remain energized at all times. In the circuit shown in Figure 7–21, the timer actually operates with starter 1M. When coil 1M energizes, timer TR energizes at the same time. When coil 1M de-energizes, timer TR de-energizes also. For this reason, a normally open auxiliary contact on starter 1M will be used to control the operation of the electronic off-delay timer. In the circuit shown in Figure 7–22 a set of normally open 1M contacts is connected to pins 5 and 6 of the timer. When coil 1M energizes, contact 1M closes and shorts pins 5 and 6, causing the normally open TR contacts to close and energize starter coil 2M. When coil 1M is de-energized, the contacts reopen and timer TR begins timing. After 5 seconds, contacts TR reopen and de-energize starter coil 2M.

All electronic timers are similar, but there are generally differences in how they are to be connected. The connection diagram for the timer shown in Figure 7–17B is shown in Figure 7–23. Notice that this timer contains RESET, START, and GATE pins. Connecting pin 2 to pin 5 activates the GATE function, which interrupts or suspends the operation of the internal clock. Connecting pin 2 to pin 6 activates the START function, which operates in the same manner as the timer shown in Figure 7–17A. Connecting pin 2 to pin 5 activates the RESET function, which resets the internal clock to zero. If this timer were to be used in the circuit shown in Figure 7–22, it would have to be modified as shown in Figure 7–24 by connecting the 1M normally open contact to pins 2 and 6 instead of pins 5 and 6.

Construction of a Simple Electronic Timer

The schematic for a simple on-delay timer is shown in Figure 7–25. The timer operates as follows: When switch S1 is closed, current flows through resistor RT

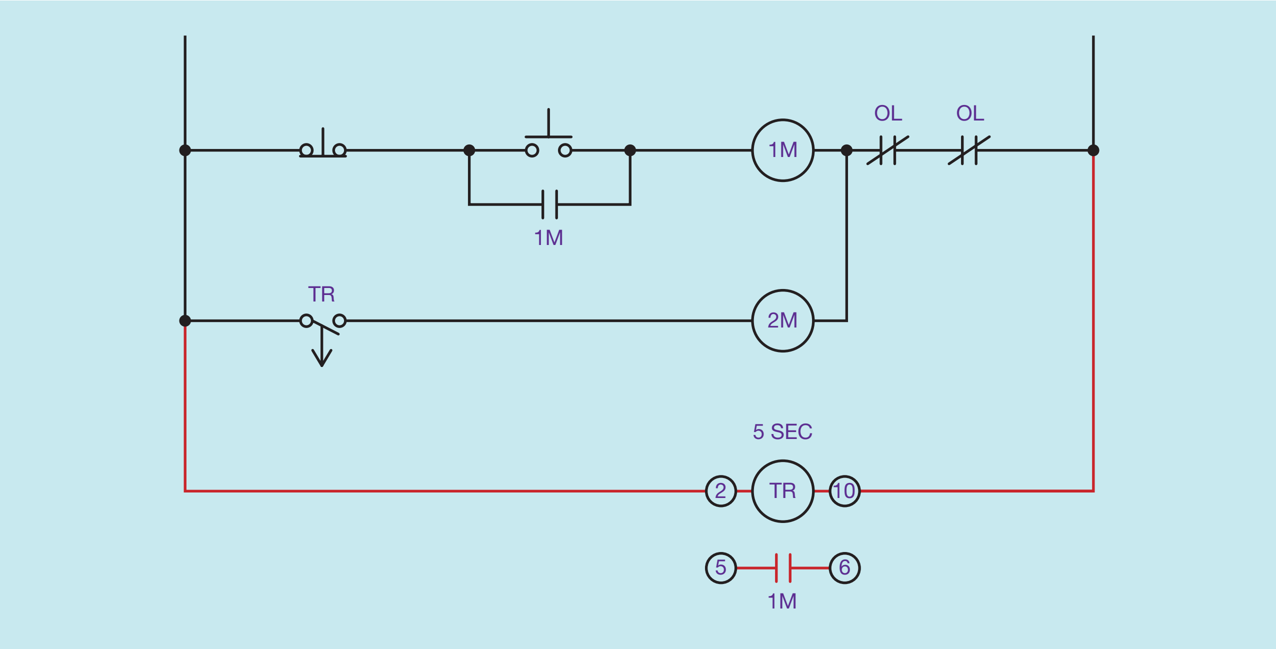


Figure 7–22 Modifying the circuit for an electronic off-delay timer. (Source: Delmar/Cengage Learning.)

and begins charging capacitor C1. When capacitor C1 has been charged to the trigger value of the unijunction transistor, the UJT turns on and discharges capacitor C1 through resistor R2 to ground. The sudden discharge of capacitor C1 causes a spike voltage to appear across resistor R2. This voltage spike travels through capacitor C2 and fires the gate of the silicon-controlled rectifier (SCR). When the SCR turns on, current is provided to the coil of relay K1.

Resistor R1 limits the current flow through the UJT. Resistor R3 is used to keep the SCR turned off until the UJT provides the pulse to fire the gate. Diode D1 is used to protect the circuit from the spike voltage produced by the collapsing magnetic field around coil K1 when the current is turned off.

By adjusting resistor RT, capacitor C1 can be charged at different rates. In this manner, the relay can be adjusted for time. Once the SCR has turned on, it will remain on until switch S1 is opened.

Programmable controllers, which will be discussed in Chapters 53 through 55, contain "internal" electronic timers. Most programmable controllers (PLCs) use a quartz-operated clock as the time base. When the controller is programmed, the timers can be set in time increments of 0.1 second. This, of course, provides very accurate time delays for the controller.

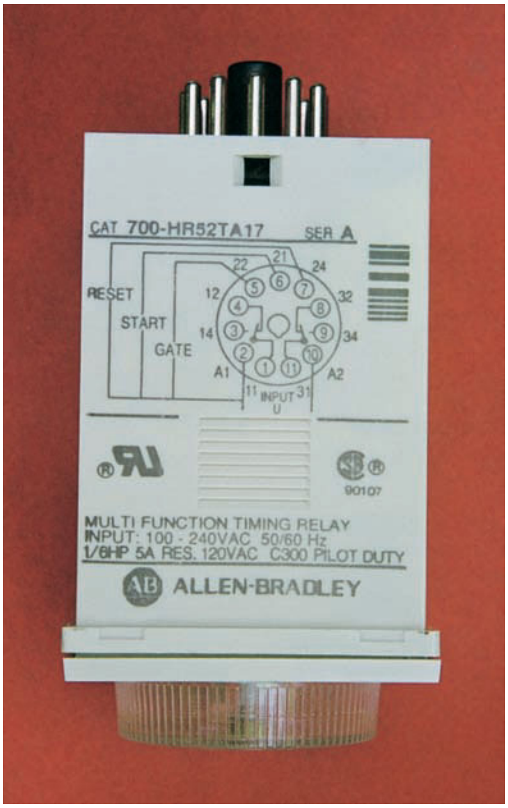


Figure 7–23 Pin connection diagram for Allen-Bradley timer. (Source: Delmar/Cengage Learning.)

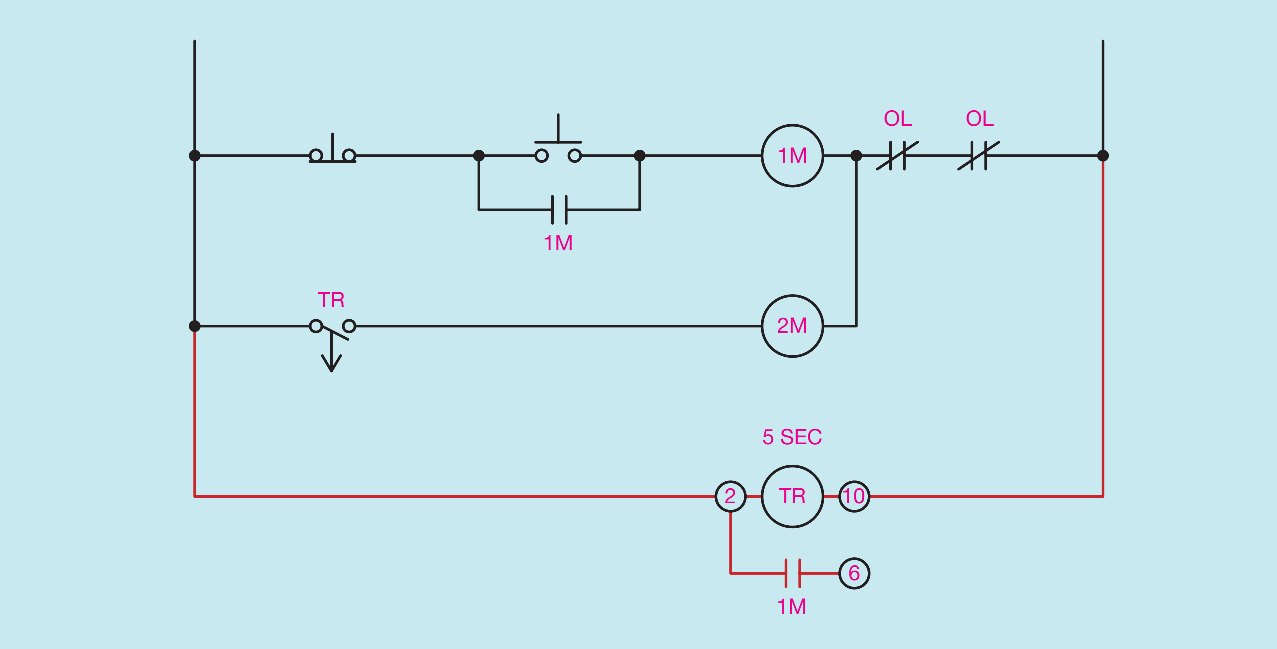


Figure 7–24 Replacing the Dayton timer with the Allen-Bradley timer. (Source: Delmar/Cengage Learning.)

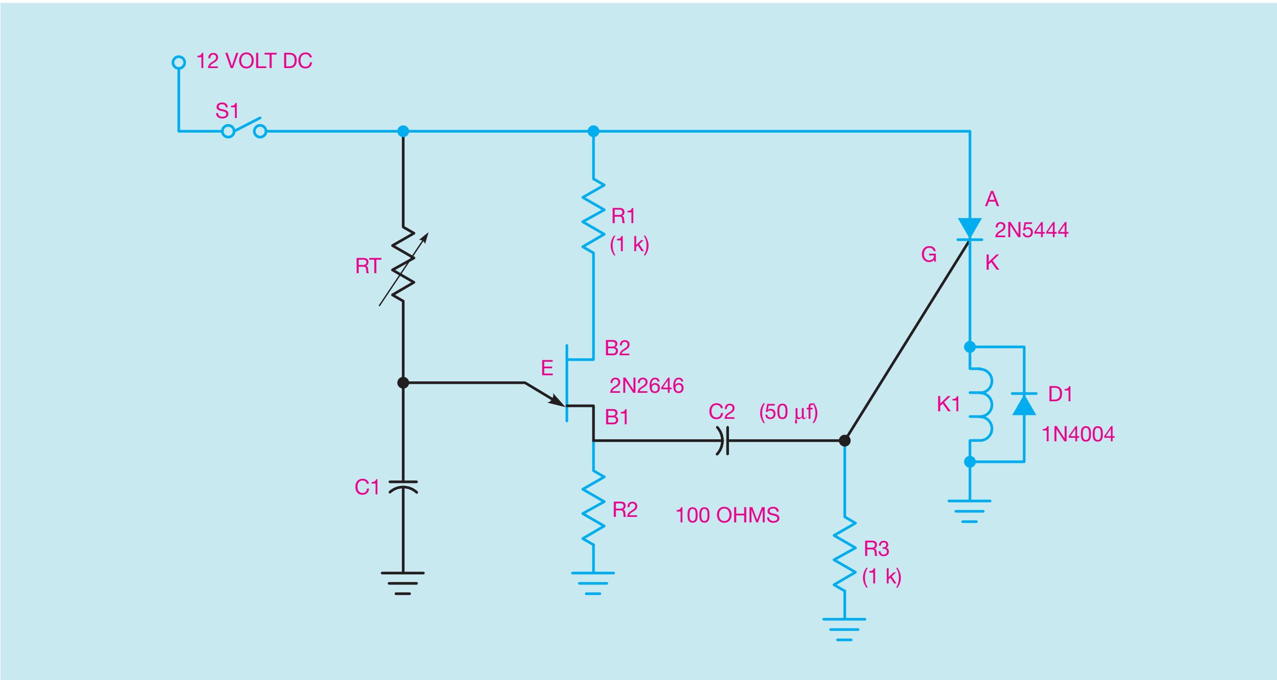


Figure 7–25 Schematic of electronic on-delay timer. (Source: Delmar/Cengage Learning.)

Review Questions

1. What are the two basic classifications of timers?
2. Explain the operation of an on-delay relay.
3. Explain the operation of an off-delay relay.
4. What are instantaneous contacts?
5. How are pneumatic timers adjusted?
6. Name two methods used by electronic timers to obtain their time base.

CHAPTER 8

PRESSURE SWITCHES AND SENSORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of high pressure switches.
- Describe the operation of low pressure switches.
- Discuss differential setting of pressure switches.
- Discuss pressure sensors that convert pressure to current for instrumentation purposes.

Pressure Switches

Pressure switches are found throughout industry in applications where it is necessary to sense the pressure of pneumatic or hydraulic systems. Pressure switches are available that can sense pressure changes of less than 1 psi (pound per square inch) or pressures over 15,000 psi. A diaphragm operated switch can sense small pressure changes at low pressure (Figure 8–1).

A metal bellows type switch can sense pressures up to 2000 psi. The metal bellows type pressure switch employs a metal bellows that expands with pressure (Figure 8–2). Although this switch can be used to sense a much higher pressure than the diaphragm type, it is not as sensitive in that it takes a greater change in pressure to cause the bellows to expand enough to active a switch. A piston type pressure switch can be used for pressures up to 15,000 psi (Figure 8–3).

Regardless of the method used to sense pressure, all pressure switches activate a set of contacts. The contacts may be either single pole or double pole depending on the application, and will be designed with some type of snap-action mechanism. Contacts cannot be permitted to slowly close or open. This would produce a bad connection and cause burning of the contacts as well as low voltage problems to the equipment they control. Some pressure switches are equipped with contacts large enough to connect a motor directly to the power line, and others are intended to control the operation of a relay coil. A line voltage type pressure switch is shown in Figure 8–4. Pressure switches of this type are often used to control the operation of well pumps and air compressors (Figure 8–5).

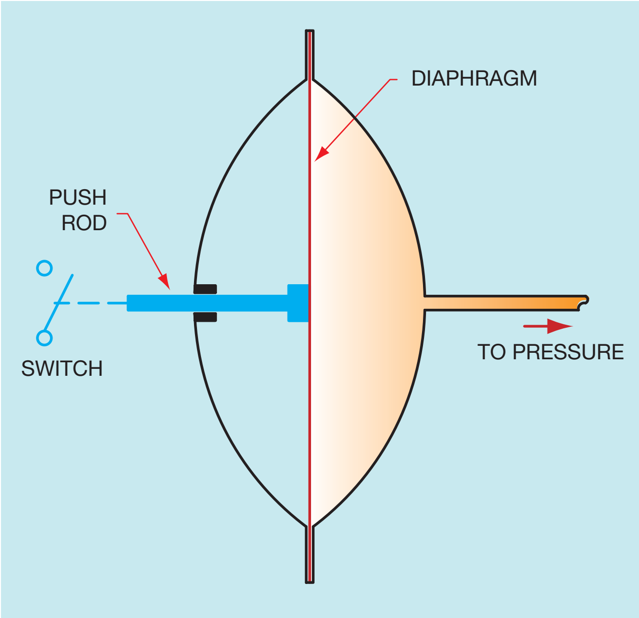


Figure 8–1 A diaphragm type pressure switch can sense small pressure changes at a low pressure. (Source: Delmar/Cengage Learning.)

Differential Pressure

Differential pressure is the difference in pressure between the cut-in or turn-on pressure and the cut-out or turn-off pressure. Most pressure switches provide a means for setting the pressure differential. In the example shown in Figure 8–5, a line voltage pressure switch controls the motor of a well pump. Typically, a pressure switch of this type would be set to cut in at about 30 psi and cut out at about 50 psi. The 20 pounds of differential pressure is necessary to prevent overworking the pump motor. Without differential pressure, the pump motor would continually turn on and off. This is what happens when a tank becomes waterlogged. An air space must be maintained in the tank to permit the pressure switch to function. The air space is necessary because air can be compressed, but a liquid cannot. If the tank becomes waterlogged, the pressure switch would turn on and off immediately each time a very small amount of water was removed from the tank. Pressure switch symbols are shown in Figure 8–6.

Typical Application

Pressure switches are used in many common industrial applications. A circuit that is used to turn off a motor and turn on a pilot warning light is shown in Figure 8–7. In this circuit, a pressure switch is connected to a control relay. If the pressure should become too great, the control relay will open a normally closed contact connected to a motor starter to stop the motor. A normally open PSCR (pressure switch control relay) contact will close and turn on a pilot light to indicate a high pressure condition. Notice that in this example circuit, the pressure switch needs both normally open and normally closed contacts. This is not a common contact arrangement for a pressure switch. To solve the problem, the pressure switch controls the action of a control relay. This is a very common practice in industrial control systems.

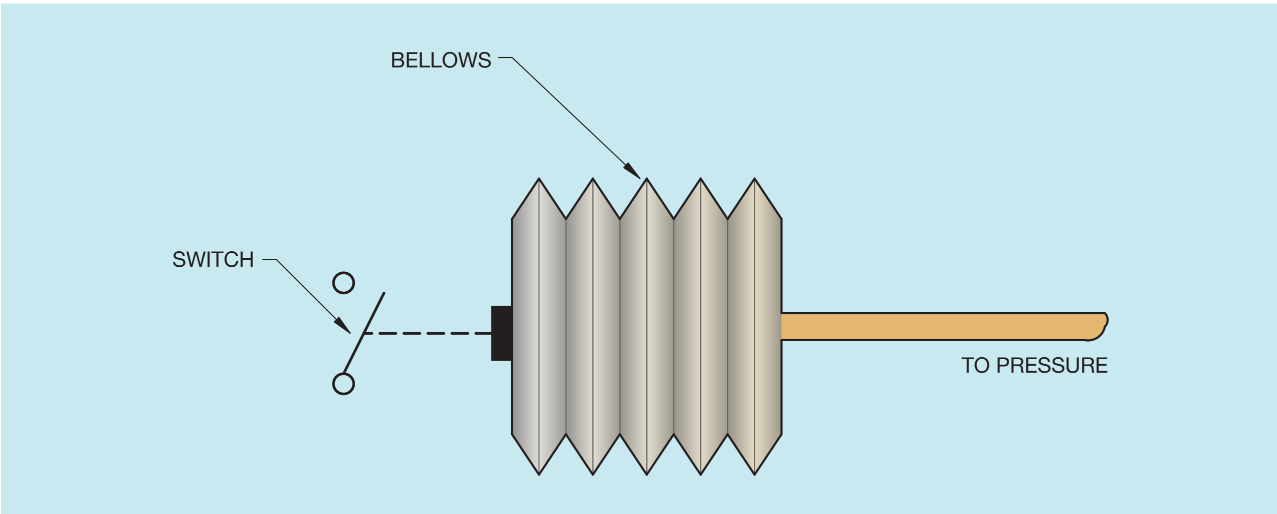


Figure 8–2 A metal bellows type pressure switch can be used for pressures up to 2000 psi. (Source: Delmar/Cengage Learning.)

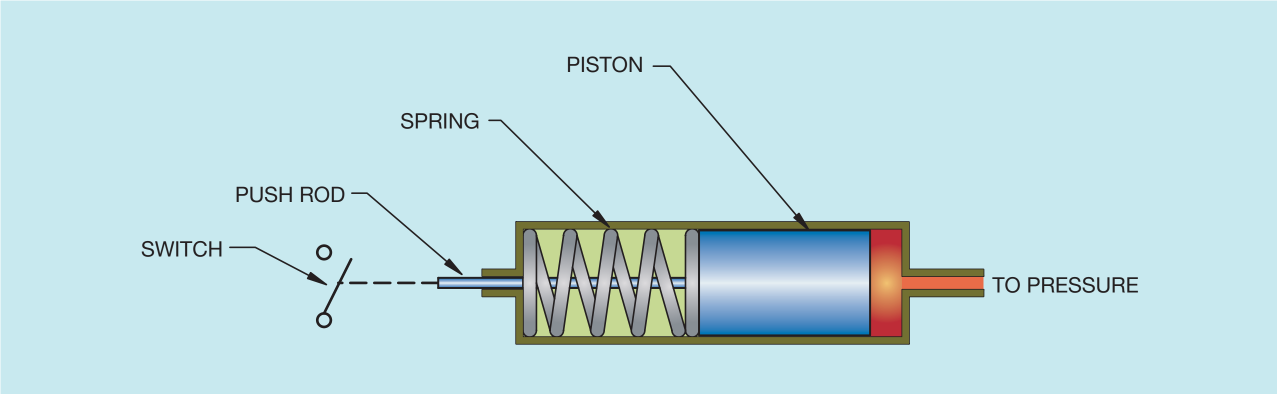


Figure 8–3 Piston type pressure switches can be used for pressures up to 15,000 psi. (Source: Delmar/Cengage Learning.)

Figure 8–4 Line voltage pressure switch. (Source: Delmar/Cengage Learning.)

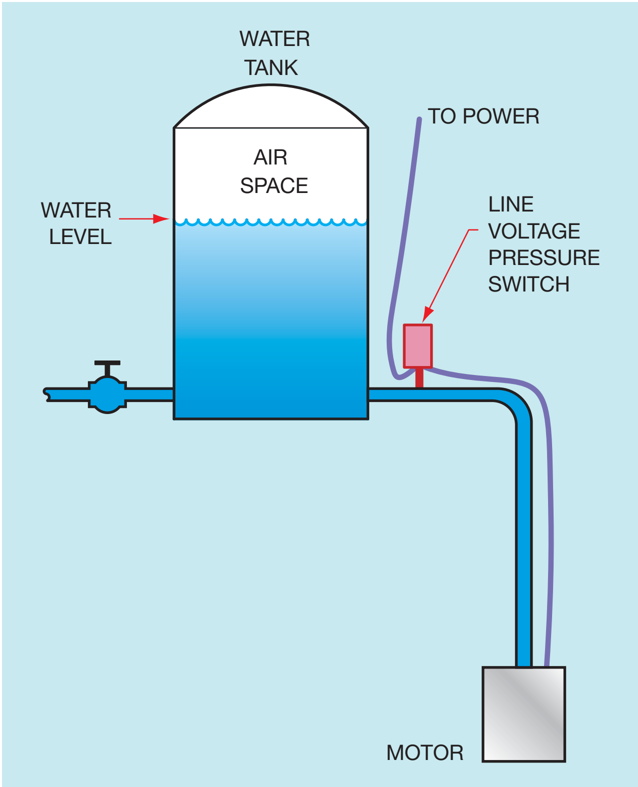


Figure 8–5 A line voltage pressure switch controls the operation of a pump motor. (Source: Delmar/Cengage Learning.)

Pressure Sensors

Pressure switches are not the only pressure sensing devices that an electrician is likely to encounter on the job, especially in an industrial environment. It is often necessary to know not only if the pressure has reached a certain level, but also to know the amount of pressure. Although sensors of this type are generally considered to be in the instrumentation field, an electrician should be familiar with some of the various types and how they operate.

Pressure sensors are designed to produce an output voltage or current that is dependent on the amount of pressure being sensed. Piezoresistive sensors are very popular because of their small size, reliability, and accuracy (Figure 8–8). These sensors are available in ranges from 0 to 1 psi and 0 to 30 psi. The sensing element is a silicon diaphragm integrated with an integrated circuit chip. The chip contains four implanted piezoresistors connected to form a bridge circuit (Figure 8–9). When pressure is applied to the diaphragm, the resistance of piezoresistors changes proportionally to the applied pressure, which changes the balance of the bridge. The voltage across V0 changes in proportion to the applied pressure (V0 = V4 − V2 [when referenced to V3]). Typical millivolt outputs and pressures are shown below:

$$1 \text{ psi} = 44 \text{ mV}$$

$$5 \text{ psi} = 115 \text{ mV}$$

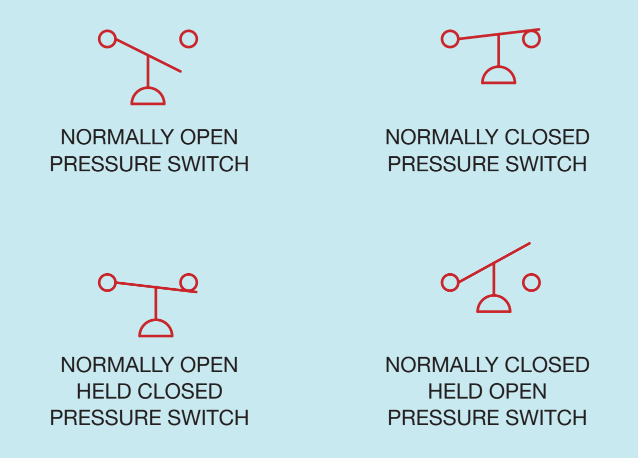


Figure 8–6 Pressure switch symbols. (Source: Delmar/Cengage Learning.)

$$15 \text{ psi} = 225 \text{ mV}$$
$$30 \text{ psi} = 315 \text{ mV}$$

Another type of piezoresistive sensor is shown in Figure 8–10. This particular sensor can be used to sense absolute, gage, or differential pressure. Units are available that can be used to sense vacuum. Sensors of this type can be obtained to sense pressure ranges of 0 to 1, 0 to 2, 0 to 5, 0 to 15, 0 to 30, and 0 to −15 (vacuum). The sensor contains an internal operational amplifier and can provide an output voltage proportional to the pressure. Typical supply voltage for this unit is 8 volts DC. The *regulated* voltage output for this unit is 1 to 6 volts. Assume for example that the sensor is intended to sense a pressure range of 0 to 5 psi. At 0 psi, the sensor would produce an output voltage of 1 volt. At 15 psi, the sensor would produce an output voltage of 6 volts.

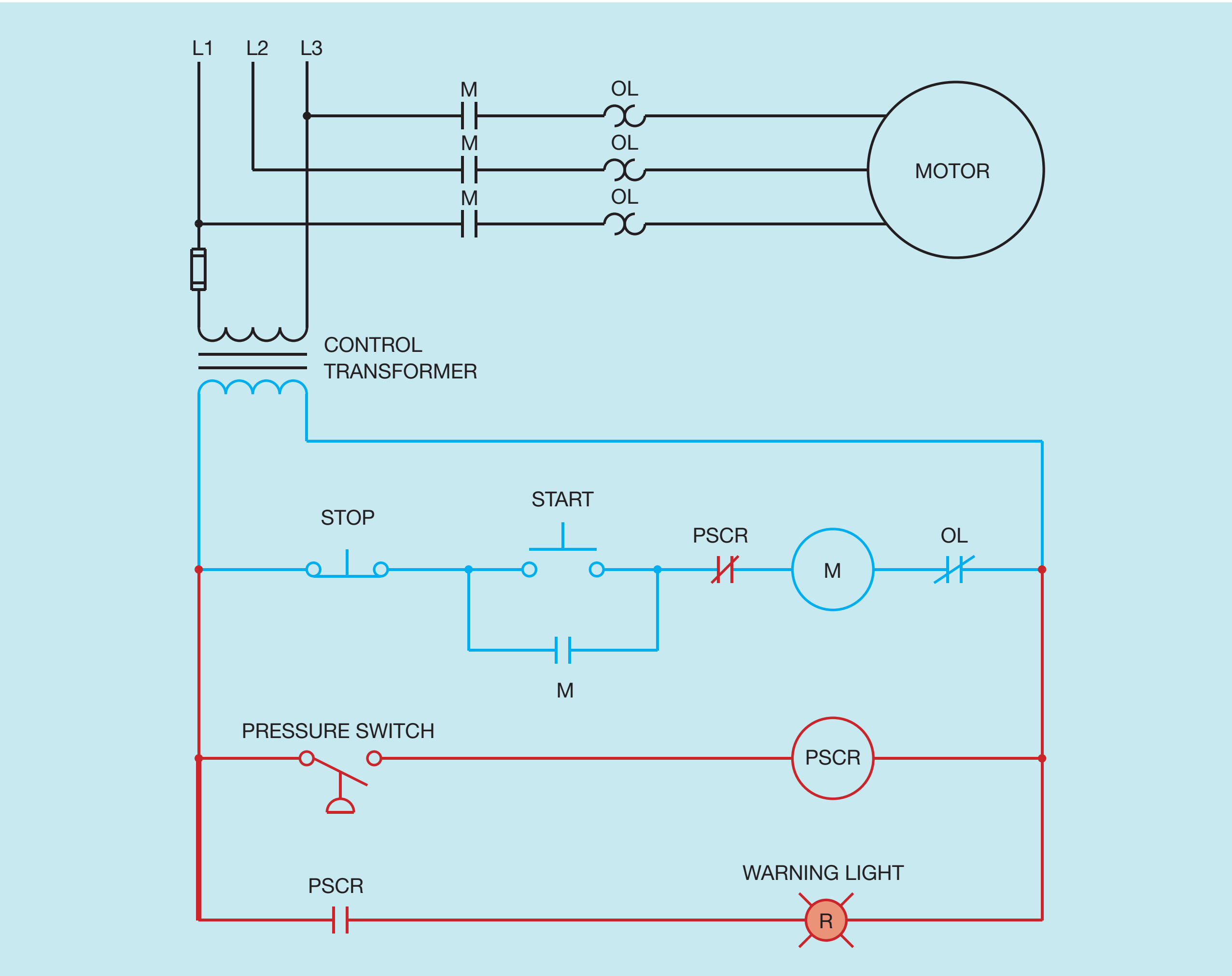


Figure 8–7 High pressure turns off the motor and turns on a warning light. (Source: Delmar/Cengage Learning.)

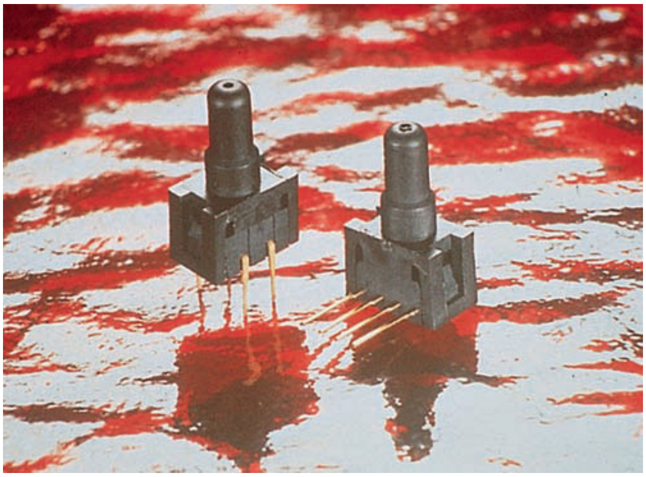


Figure 8–8 Piezoresistive pressure sensor. (Courtesy Honeywell's Micro Switch Division.)

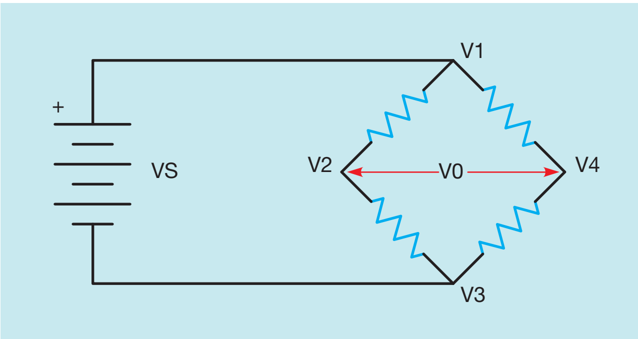


Figure 8–9 Piezoresistive bridge. (Source: Delmar/Cengage Learning.)

Figure 8–10 Differential pressure sensor. (Courtesy Honeywell's Micro Switch Division.)

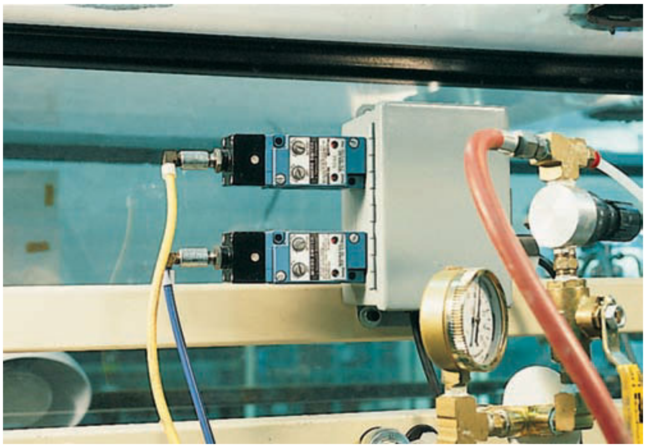


Figure 8–11 Pressure to current sensor for low pressures. (Courtesy Honeywell's Micro Switch Division.)

Figure 8–12 Pressure to current sensor for high pressure. (Courtesy Square D Company.)

Sensors can also be obtained that have a ratiometric output. The term *ratiometric* means that the output voltage will be proportional to the supply voltage. Assume that the supply voltage increases by 50% to 12 volts DC. The output voltage would increase by 50% also. The sensor would now produce a voltage of 1.5 volts at 0 psi and 9 volts at 15 psi.

Other sensors can be obtained that produce a current output of 4 to 20 milliamperes, instead of a regulated voltage output (Figure 8–11). One type of pressure to current sensor, which can be used to sense pressures as high as 250 psi, is shown in Figure 8–12.

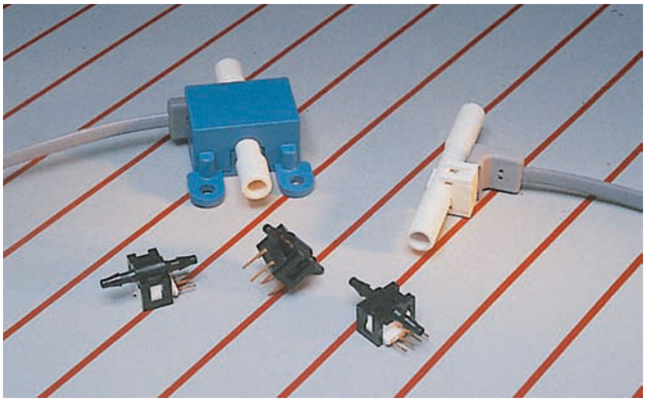


Figure 8–13 Flow-through pressure sensor. (Courtesy Honeywell's Micro Switch Division.)

This sensor can also be used as a set point detector to provide a normally open or normally closed output. Sensors that produce a proportional output current instead of voltage have fewer problems with induced noise from surrounding magnetic fields and with voltage drops due to long wire runs.

A flow-through pressure sensor is shown in Figure 8–13. This type of sensor can be placed in line with an existing system. In-line pressure sensors make it easy to add a pressure sensor to an existing system.

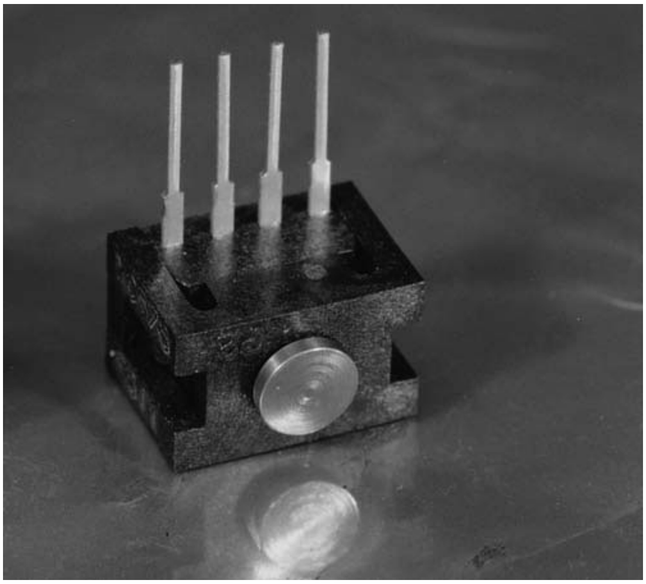


Figure 8–14 Force sensor. (Courtesy Honeywell's Micro Switch Division.)

Another device that is basically a pressure sensor is the force sensor (Figure 8–14). This sensor uses silicon piezoresistive elements to determine the amount of pressure to the sensing element.

Review Questions

1. What type of pressure switch is generally used to sense small changes in low pressure systems?
2. A pressure switch is set to cut in at a pressure of 375 psi and cut out at 450 psi. What is the pressure differential for this switch?
3. A pressure switch is to be installed on a system with pressures that can range from 1500 psi to 1800 psi. What type of pressure switch should be used?
4. A pressure switch is to be installed in a circuit that requires it to have three normally open contacts and one normally closed contact. The switch actually has one normally open contact. What must be done to permit this pressure switch to operate in this circuit?
5. What is a piezoresistor?
6. Refer to the circuit shown in Figure 8–7. If the pressure should become high enough for the pressure switch to close and stop the motor, is it possible to restart the motor before the pressure drops to a safe level?
7. Refer to the circuit shown in Figure 8–7. Assume that the motor is running and an overload occurs, causing the OL contact to open and disconnect coil M to stop the motor. What effect does the opening of the overload contact have on the pressure switch circuit?

CHAPTER 9
FLOAT SWITCHES

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of float switches.
- List the sequence of operation for sump pumping or tank filling.
- Draw wiring symbols for float switches.

A float switch is used when a pump motor must be started and stopped according to changes in the water (or other liquid) level in a tank or sump. Float switches are designed to provide automatic control of AC and DC pump motor magnetic starters and automatic direct control of light motor loads.

The operation of a float switch is controlled by the upward or downward movement of a float placed in a water tank. The float movement causes a rod-operated (Figure 9–1) or chain and counterweight (Figure 9–2) assembly to open or close electrical contacts. The float switch contacts may be either normally open or normally closed and may not be submerged. Float switches may be connected to a pump motor for tank or sump pumping operations or tank filling, depending on the contact arrangement.

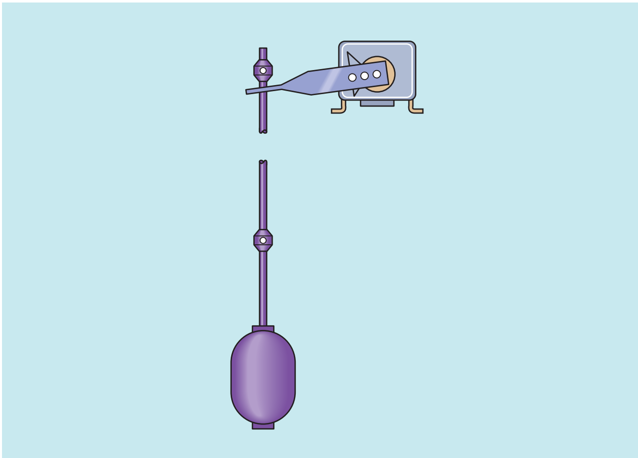


Figure 9–1 Rod-operated float switch. (Source: Delmar/Cengage Learning.)

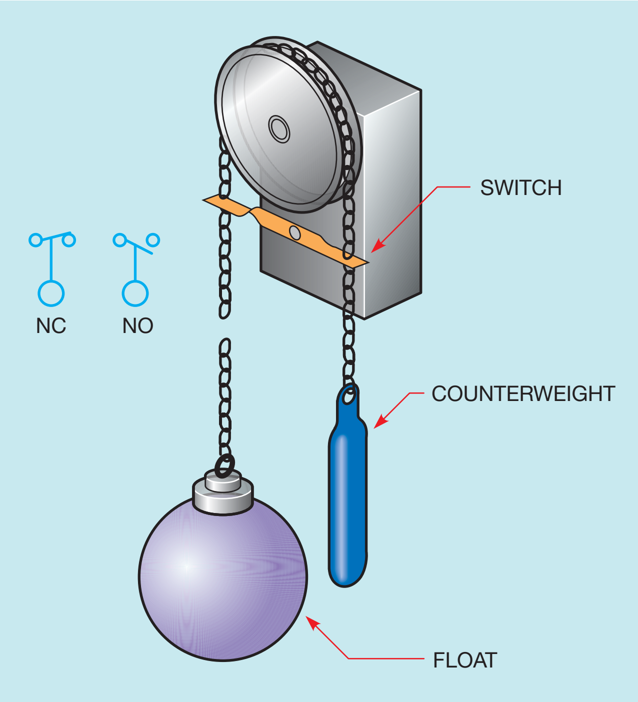


Figure 9–2 Chain-operated float switch with normally closed (NC) and normally open (NO) wiring symbols. (Source: Delmar/Cengage Learning.)

Mercury Bulb Float Switch

Another float switch that has become increasingly popular is the mercury bulb type of float switch. This type of float switch does not depend on a float rod or chain to operate. The mercury bulb switch appears as a rubber bulb connected to a conductor. A set of mercury contacts are located inside the bulb. When the liquid level is below the position of the bulb, it is suspended in a vertical position (Figure 9–3A). When the liquid level rises to the position of the bulb, it changes to a horizontal position (Figure 9–3B). This change of position changes the state of the contacts in the mercury switch.

Since the mercury bulb float switch does not have a differential setting as does the rod or chain type of float switch, it is necessary to use more than one mercury bulb float switch to control a pump motor. The differential level of the liquid is determined by suspending mercury bulb switches at different heights in the tank. Figure 9–4 illustrates the use of four mercury bulb type switches to operate two pump motors and provide a high liquid level alarm. The control

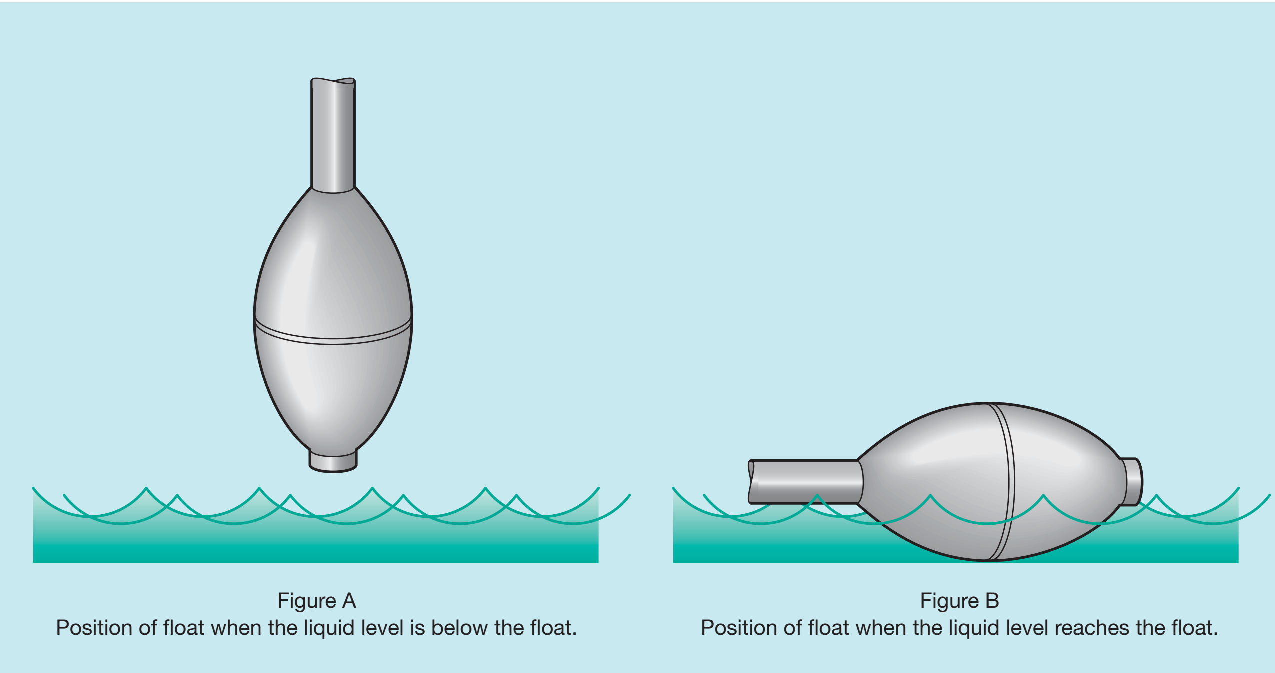


Figure 9–3 Mercury bulb type float switch. (Source: Delmar/Cengage Learning.)

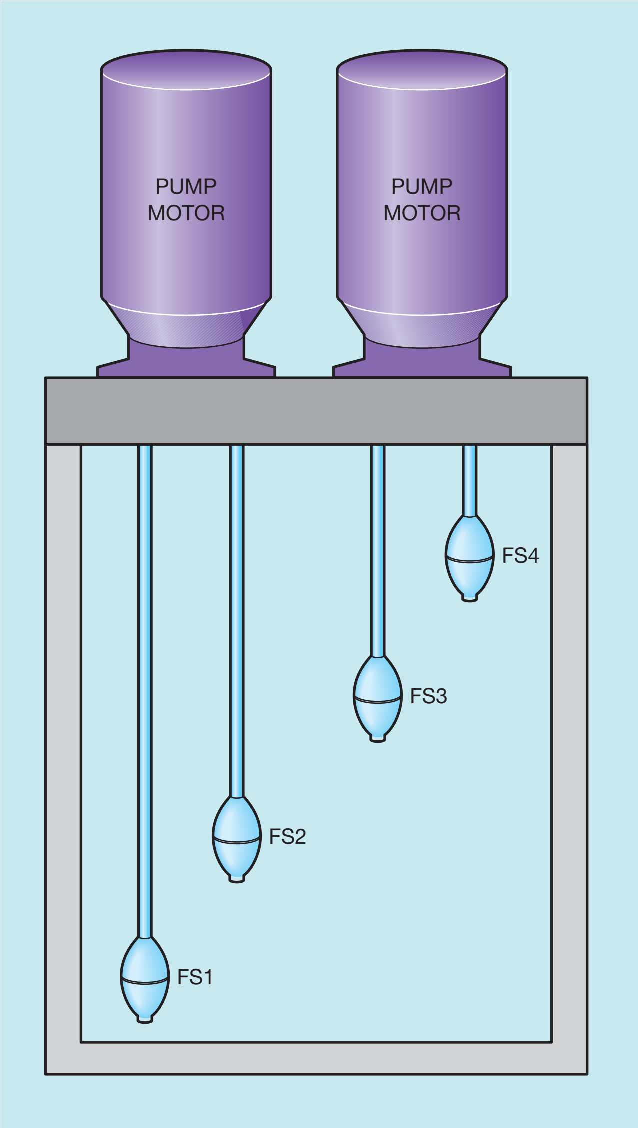


Figure 9–4 Float level is set by the length of the conductor. (Source: Delmar/Cengage Learning.)

circuit is shown in Figure 9–5. Float switch FS1 detects the lowest point of liquid level in the tank and is used to turn both pump motors off. Float switch FS2 starts the first pump when the liquid level reaches that height. If pump #1 is unable to control the level of the tank, float switch FS3 will start pump motor #2 if the liquid level should rise to that height. Float switch FS4 operates a warning light and buzzer to warn that the tank is about to overflow. A reset button can be used to turn off the buzzer, but the warning light will remain on until the water level drops below the level of float switch FS4.

The Bubbler System

Another method often used to sense liquid level is the bubbler system. This method does not employ the use of float switches. The liquid level is sensed by pressure switches (Figure 9–6). A great advantage of this system is that the pressure switches are located outside the tank, which makes it unnecessary to open the tank to service the system.

The bubbler system is connected to an air line, which is teed to a manifold and to another line that extends down into the tank. A hand valve is used to adjust the maximum air flow. The bubbler system operates on the principle that as the liquid level increases in the tank, it requires more air pressure to blow air through the line in the tank. For example, a 1-square-inch column of water 26.7 inches in height weighs 1 pound. Now assume a pipe with an inside area of 1 square inch is 10 feet in length. It would require a pressure of 4.494 psi to blow air through the pipe.

$$\frac{120 \text{ in.}}{26.7 \text{ psi}} = 4.494 \text{ lbs.}$$

If the water level was 7 feet in height it would require a pressure of only 3.146 psi.

Since the pressure required to bubble air through the pipe is directly proportional to the height of the liquid, the pressure switches provide an accurate measure of the liquid level. The pressure switches shown in Figure 9–6 could be used to control the two pump circuit previously discussed by replacing the float switches with pressure switches in the circuit shown in Figure 9–5.

Microwave Level Gauge

The microwave level gauge operates by emitting a high frequency signal of approximately 24 gigahertz into a tank and then measuring the frequency difference of the return signal that bounces off the product (Figure 9–7). A great advantage of the microwave level gauge is that no mechanical object touches or is inserted into the product. The gauge is ideal for measuring the level of turbulent, aerated, solids-laden, viscous,

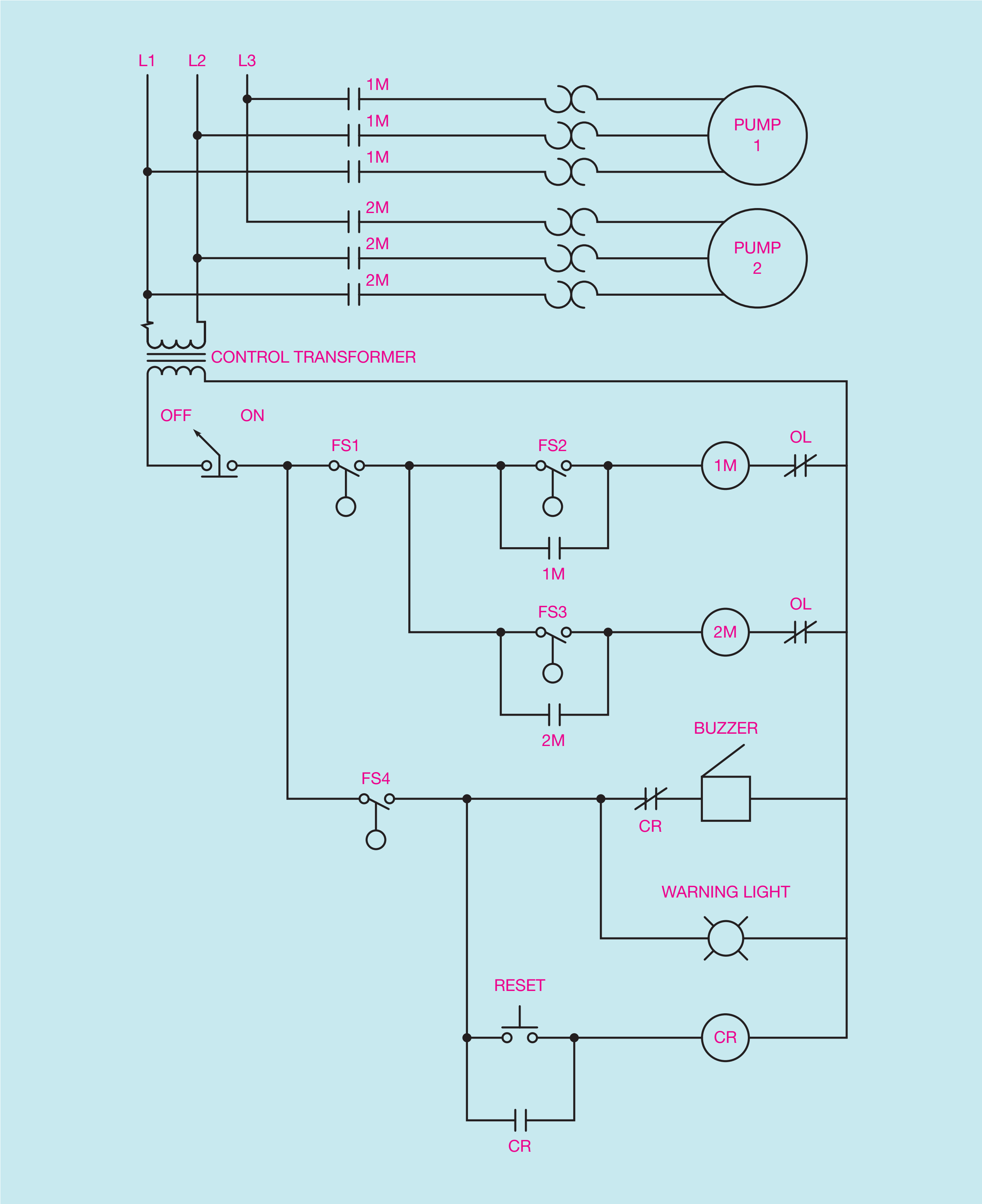


Figure 9–5 Two-pump control with high liquid level warning. (Source: Delmar/Cengage Learning.)

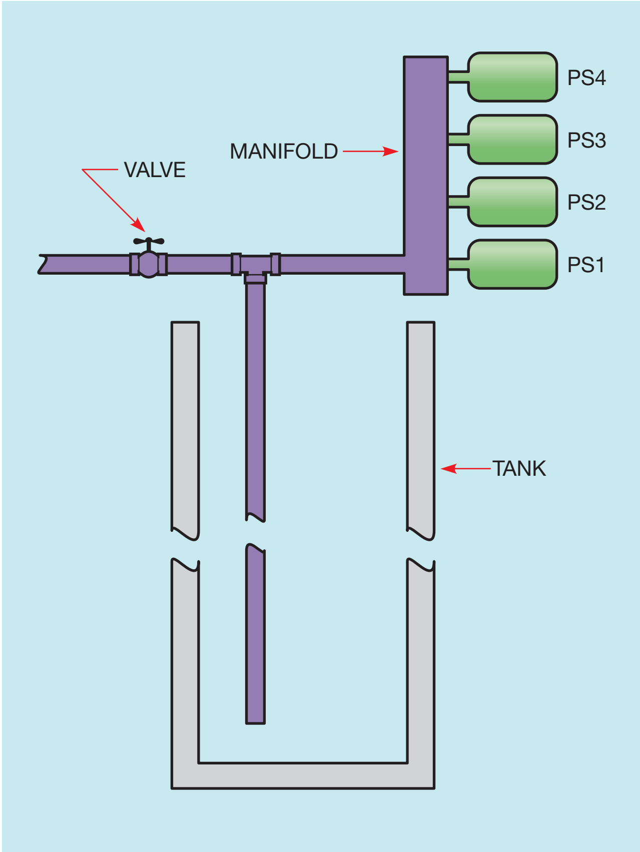


Figure 9–6 Bubbler system for detecting liquid level. (Source: Delmar/Cengage Learning.)

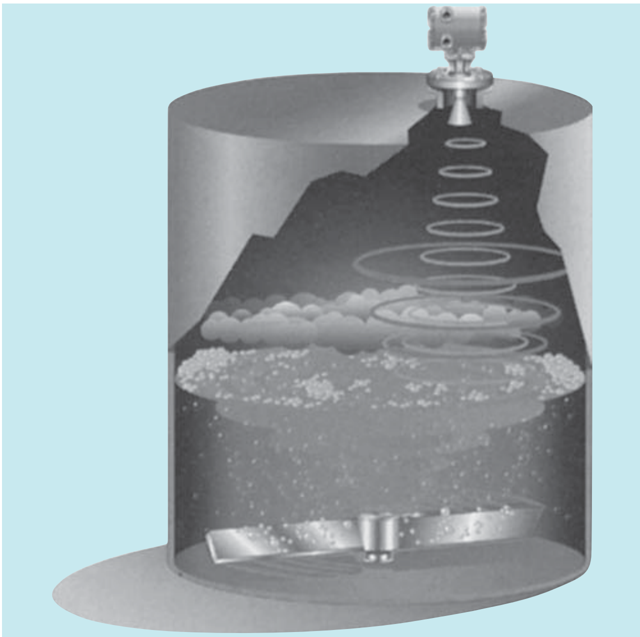


Figure 9–7 Operation of the microwave gauge. (Courtesy ©1998 Rosemount, Inc., used by permission.)

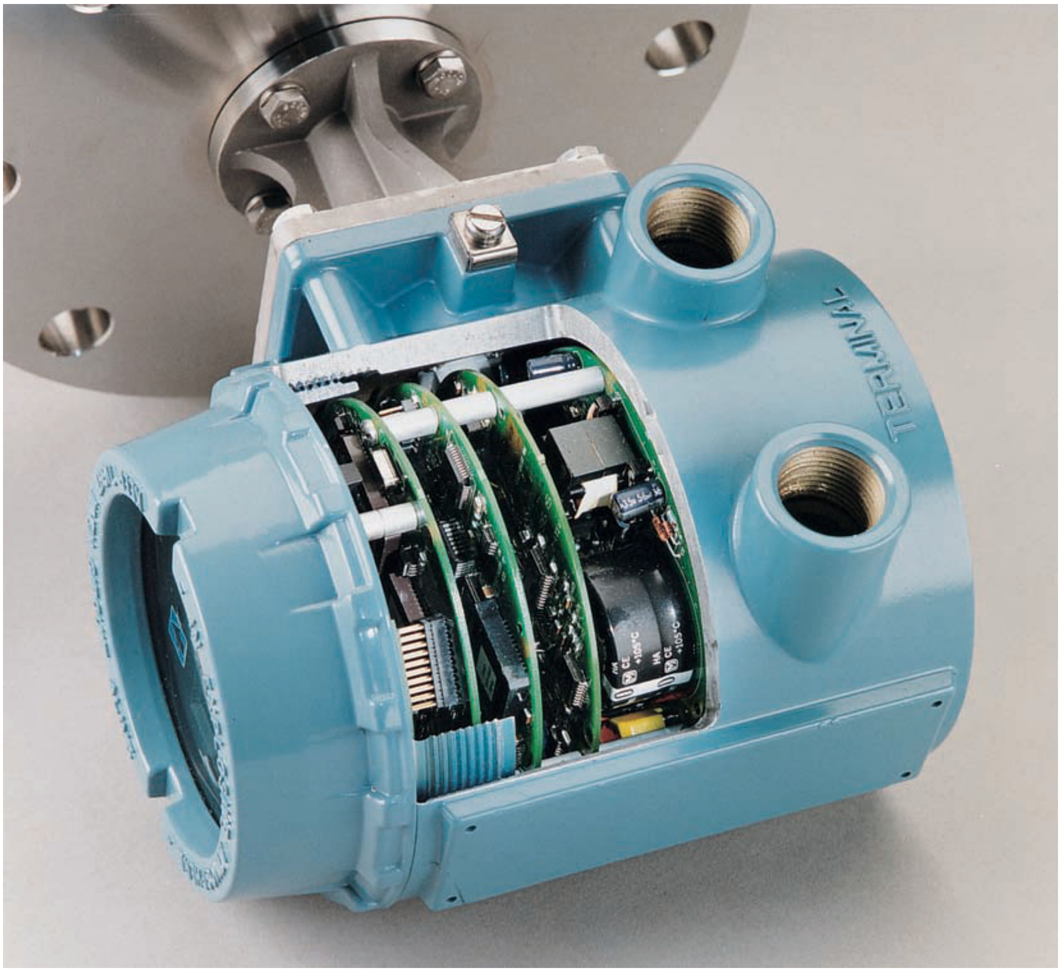


Figure 9–8 Cut-away view of a microwave level gauge. (Courtesy © 1998 Rosemount, Inc., used by permission.)

Figure 9–9 Microwave level gauge with meter. (Courtesy ©1998 Rosemount, Inc., used by permission.)

corrosive fluids. It also works well with pastes and slurries. A cut-away view of a microwave level gauge is shown in Figure 9–8.

The gauge shown in Figure 9–9 has a primary 4 to 20 milliampere analog signal. The gauge can accept one RTD (Resistance Temperature Detector) input signal. The gauge can be configured to display the level, calculated volume, or standard volume. A microwave level gauge with meter is shown in Figure 9–9.

Review Questions

1. Describe the sequence of operations required to (a) pump sumps and (b) fill tanks.
2. Draw the normally open and normally closed contact symbols for a float switch.
3. What type of float switch does not have a differential setting?
4. What is the advantage of the bubble type system for sensing liquid level?
5. Assume a pipe has an inside diameter of 1 square inch. How much air pressure would be required to bubble air though 25 feet of water?

CHAPTER 10

FLOW SWITCHES AND SENSORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of flow switches.
- Connect a flow switch in a circuit with other control components.
- Draw the NEMA symbols that represent a flow switch in a schematic diagram.
- Discuss the operation of different types of flow sensors.

Flow Switches

Flow switches are used to detect the movement of air or liquid through a duct or pipe. Air flow switches are often called *sail switches* because the sensor mechanism resembles a sail (Figure 10–1). The air flow switch is constructed from a snap-action micro switch. A metal arm is attached to the micro switch. A piece of thin metal or plastic is connected to the metal arm. The thin piece of metal or plastic has a large surface area and offers resistance to the flow of air. When a large amount of air flow passes across the sail, enough force is produced to cause the metal arm to operate the contacts of the switch.

Air flow switches are often used in air conditioning and refrigeration circuits to give a positive indication that the evaporator or condenser fan is operating before the compressor is permitted to start. A circuit of this

Figure 10–1 Air flow switch. (Courtesy Honeywell Inc.)

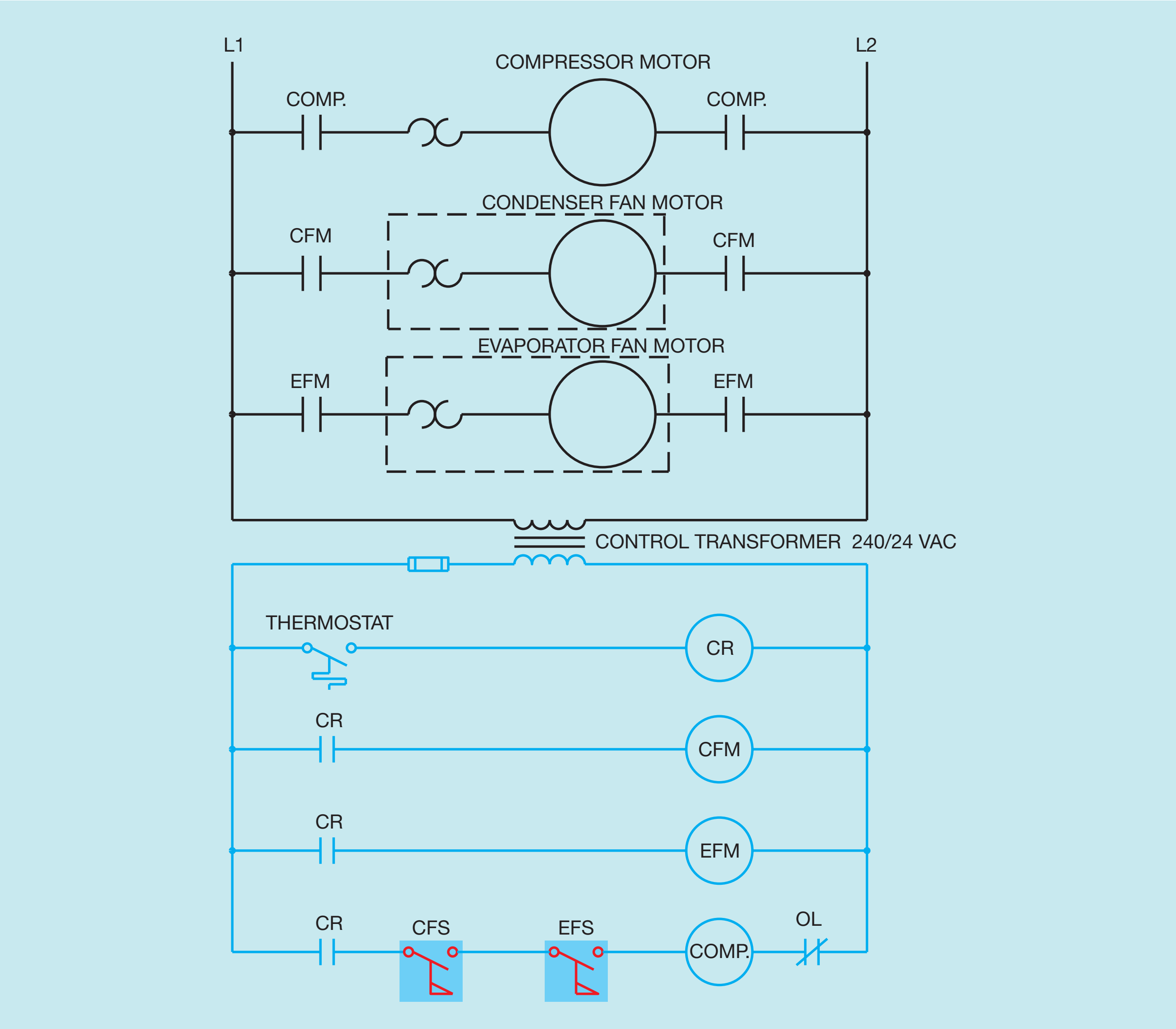


Figure 10–2 Air flow switches indicate a positive movement of air before the compressor can start. (Source: Delmar/Cengage Learning.)

type is shown in Figure 10–2. When the thermostat contact closes, control relay CR energizes and closes all CR contacts. This energizes both the condenser fan motor relay (CFM) and the evaporator fan motor relay (EFM). The compressor relay (Comp.) cannot start because of the two normally open air flow switches. If both the condenser fan and evaporator fan start, air movement will cause both air flow switches to close and complete a circuit to the compressor relay.

Notice in this circuit that a normally closed overload contact is shown in series with the compressor contactor only. Also notice that a dashed line has been drawn around the condenser fan motor and overload symbol, and around the evaporator fan motor and overload symbol. This indicates that the overload for these motors is located on the motor itself and is not part of the control circuit.

Liquid flow switches are equipped with a paddle that inserts into the pipe (Figure 10–3). A flow switch can be installed by placing a tee in the line as shown in Figure 10–4. When liquid moves through the line, force is exerted against the paddle, causing the contacts to change position.

Regardless of the type of flow switch used, they generally contain a single-pole double-throw micro switch (Figure 10–5). Flow switches are used to control

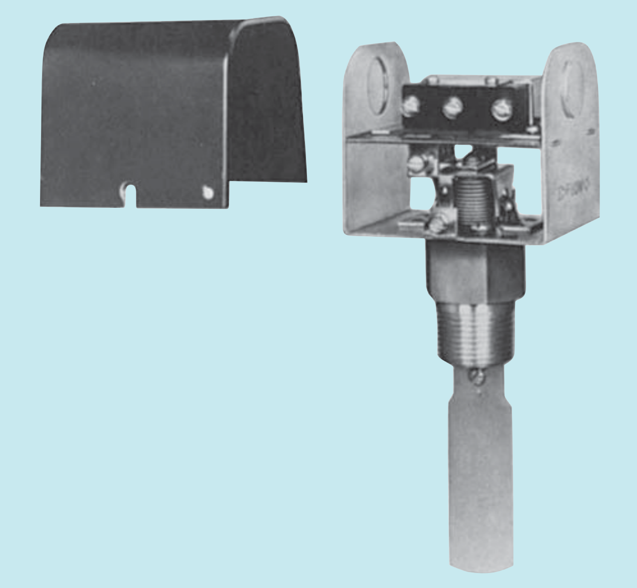


Figure 10–3 Liquid flow switch. (Courtesy McDonnell & Miller ITT Fluid Handling Division.)

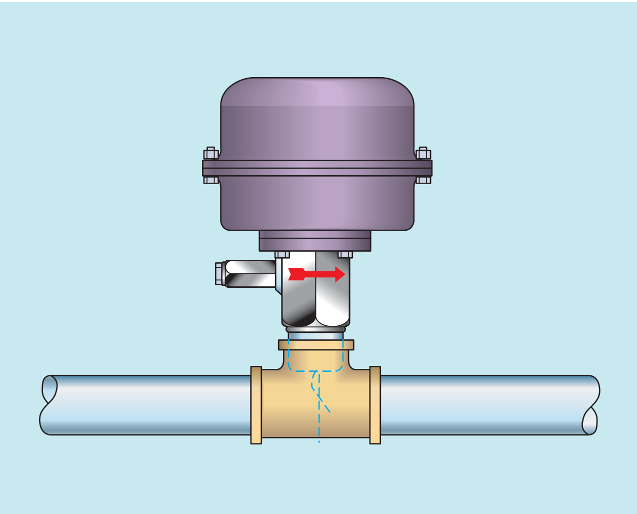


Figure 10–4 Flow switch installed in a tee. (Source: Delmar/Cengage Learning.)

low current loads such as contactor or relay coils or pilot lights. A circuit that employs both the normally open and normally closed contact of a flow switch is shown in Figure 10–6. The circuit is designed to control the operation of an air compressor. A pressure switch controls the operation of the compressor. In this circuit, a normally open push button is used as a reset button. The control relay must be energized before

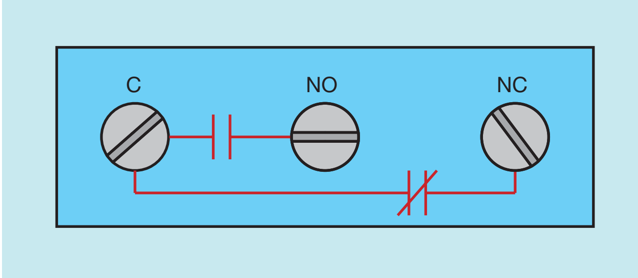


Figure 10–5 Connections of a single-pole double-throw micro switch. (Source: Delmar/Cengage Learning.)

power can be supplied to the rest of the control circuit. When the pressure switch contact closes, power is supplied to the lube oil pump relay. The flow switch detects the flow of lubricating oil before the compressor is permitted to start. Note that a red warning light indicates when there is no flow of oil. To connect the flow switch in this circuit, power from the control relay contact must be connected to the common terminal of the flow switch so that power can be supplied to both the normally open and normally closed contacts (Figure 10–7). The normally open section of the switch connects to the coil of the compressor contactor, and the normally closed section connects to the red pilot light.

Regardless of whether a flow switch is intended to detect the movement of air or liquid, the NEMA symbol is the same. Standard NEMA symbols for flow switches are shown in Figure 10–8.

Flow Sensors

Flow switches are used to detect liquid flowing through a pipe or air flowing through a duct. Flow switches, however, cannot detect the amount of liquid or air flow. To detect the amount of liquid or air flow, a *transducer* must be used. A transducer is a device that converts one form of energy into another. In the case of a flow sensor, the kinetic energy of a moving liquid or gas is converted into electrical energy. Many flow sensors are designed to produce an output current of 4 to 20 milliamperes. This current can be used as the input signal to a programmable controller or to a meter designed to measure the flow rate of the liquid or gas being metered (Figure 10–9).

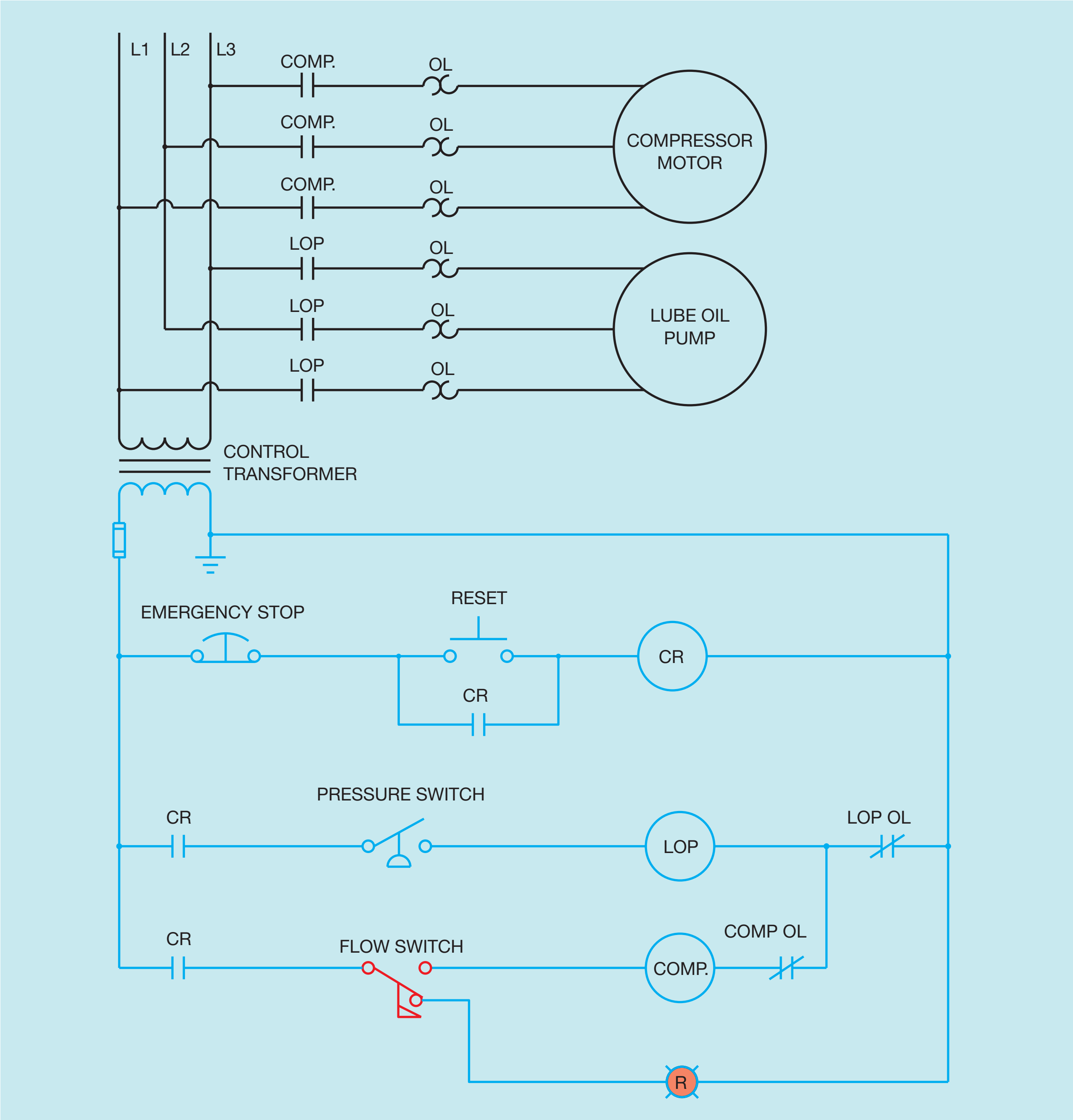


Figure 10–6 A red warning light indicates there is no oil flow. (Source: Delmar/Cengage Learning.)

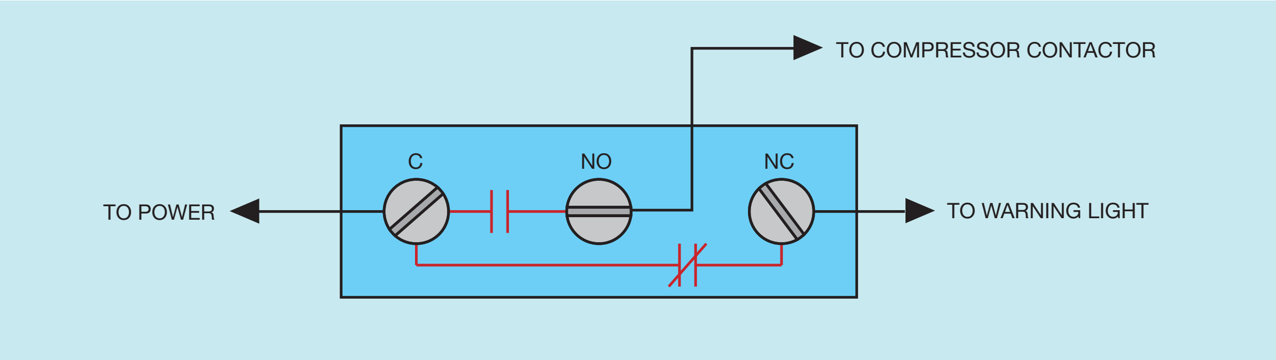


Figure 10–7 Connecting the flow switch. (Source: Delmar/Cengage Learning.)

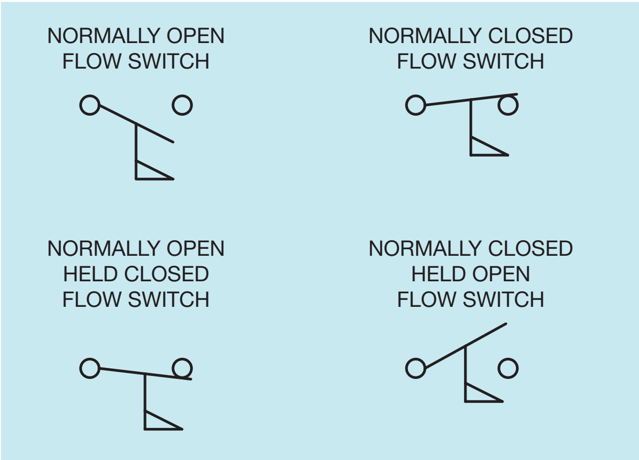


Figure 10–8 NEMA standard flow switch symbols. (Source: Delmar/Cengage Learning.)

Liquid Flow Sensors

There are several methods that can be used to measure the flow rate of a liquid in a pipe. One method uses a *turbine* type sensor (Figure 10–10). The turbine sensor consists of a turbine blade that must be inserted inside the pipe containing the liquid. The moving liquid causes the turbine blade to turn. The speed at which the blade turns is proportional to the amount of flow in the pipe. The sensor's electrical output is determined by the speed of the turbine blade. One disadvantage of the turbine type sensor is that the turbine blade offers some resistance to the flow of the liquid.

Electromagnetic Flow Sensors

Another type of flow sensor is the *electromagnetic* flow sensor. These sensors operate on the principle of Faraday's Law concerning conductors moving through a magnetic field. This law states that when a conductor moves through a magnetic field, a voltage will be induced into the conductor. The amount of induced voltage is proportional to the strength of the magnetic field and the speed of the moving conductor. In the case of the electromagnetic flow sensor, the moving liquid is the conductor. As a general rule, liquids should have a minimum conductivity of about 20 microhms per centimeter.

Flow rate is measured by small electrodes mounted inside the pipe of the sensor. The electrodes measure the amount of voltage induced in the liquid as it flows through the magnetic field produced by the sensor (Figure 10–11A). Since the strength of the magnetic field is known, the induced voltage will be proportional to the flow rate of the liquid. A cut-away view of an electromagnetic flow sensor with a ceramic liner is shown in Figure 10–11B.

Orifice Plate Flow Sensors

Orifice plate flow sensors operate by inserting a plate with an orifice of known size into the flow path (Figure 10–12). The plate is installed between two special flanges (Figure 10–13). The flanges are constructed to permit a differential pressure meter to

Figure 10–9 Several different flow sensors shown with a meter used to measure the flow rate of liquid. (Courtesy ©1998 Rosemount, Inc., used by permission.)

be connected across the plate. When liquid flows through the orifice, a difference of pressure is produced across the plate. Since the orifice is of known size, the pressure difference is proportional to flow rate. It is the same principle as measuring the voltage drop across a known resistance to determine the amount of current flow in a circuit. The disadvantage of the orifice plate sensor is that it does add restriction to the line. A differential pressure sensor is shown in Figure 10–14.

Vortex Flow Sensors

Vortex flow sensors operate on the principle that when a moving liquid strikes an object, a swirling current, called a vortex, is created. Vortex sensors insert a *shedder bar* in the line to produce a swirling current or vortex (Figure 10–15). This swirling current causes the shedder bar to alternately flex from side to side. The shedder bar is connected to a pressure sensor that can sense the amount of movement of the shedder bar (Figure 10–16). The amount of movement

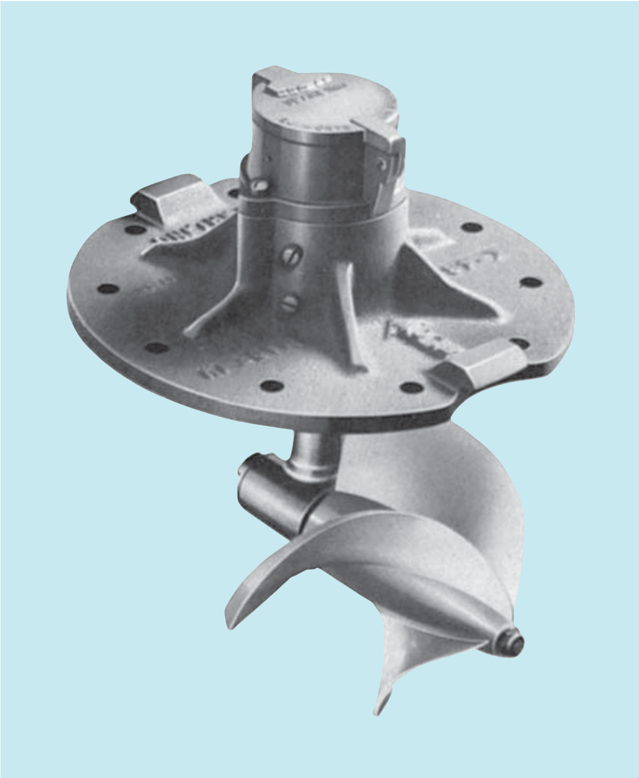


Figure 10–10 Turbine type flow sensor. (Courtesy Sparling Instruments Co., Inc.)

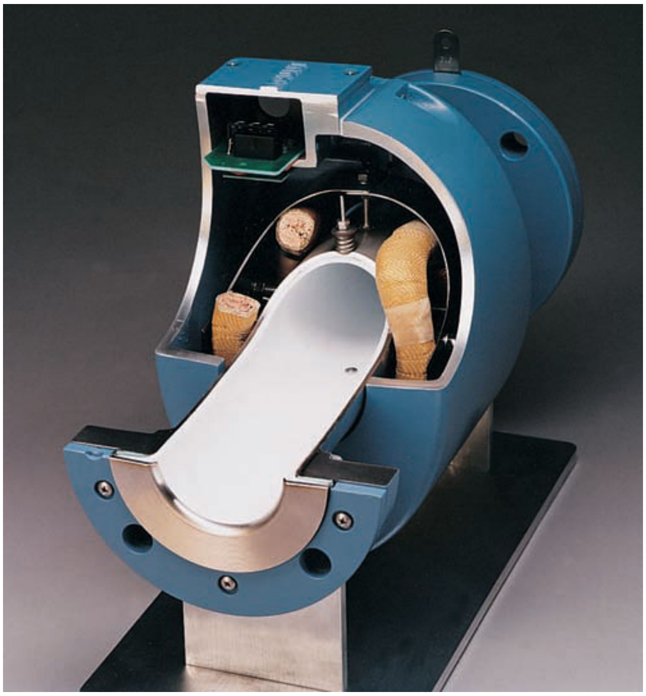


Figure 10–11B Cut-away view of an electromagnetic flow sensor with ceramic liner. (Courtesy ©1998 Rosemount, Inc., used by permission.)

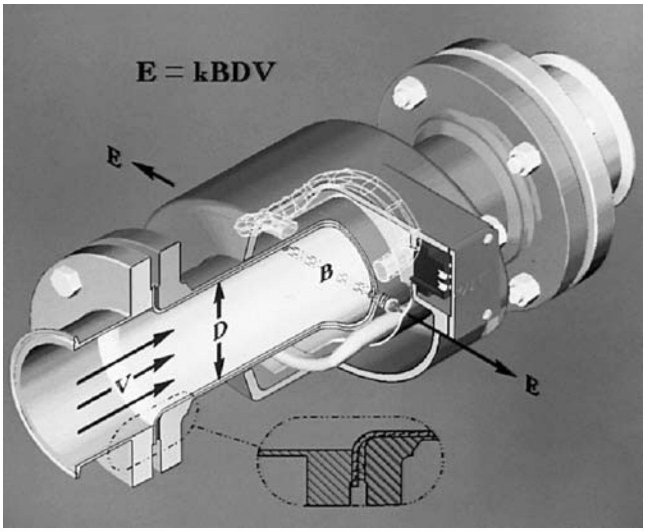


Figure 10–11A Operating principle of an electromagnetic flow sensor. (Courtesy ©1998 Rosemount, Inc., used by permission.)

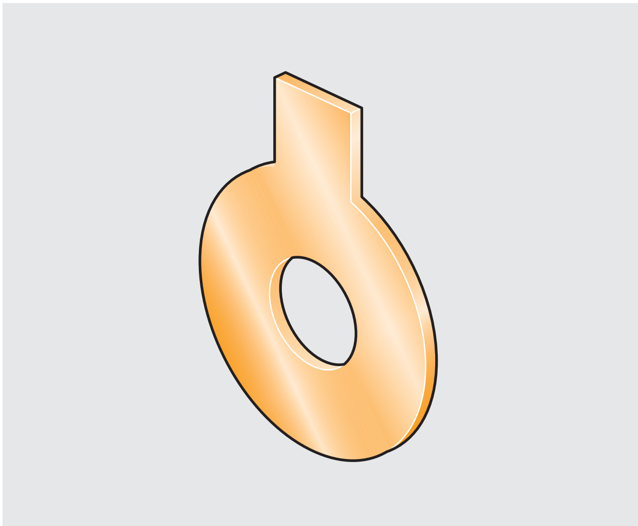


Figure 10–12 Concentric orifice plate. (Source: Delmar/Cengage Learning.)

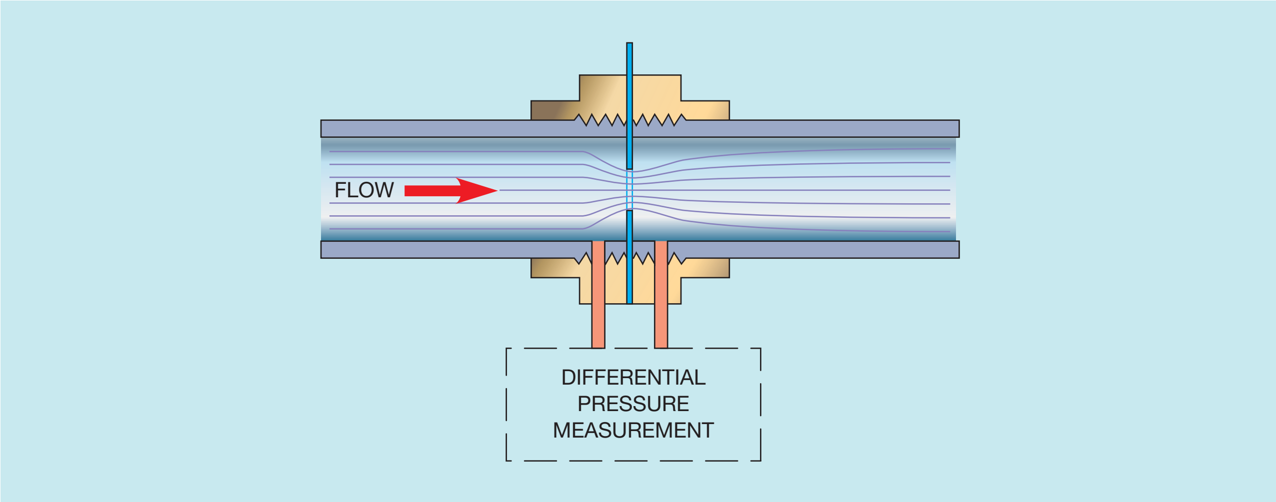


Figure 10–13 A difference in pressure is produced across the orifice plate. (Source: Delmar/Cengage Learning.)

Figure 10–14 Differential pressure sensor. (Courtesy ©1998 Rosemount, Inc., used by permission.)

of the shedder bar is proportional to the flow rate. Several different sizes of vortex flow sensors are shown in Figure 10–17.

Airflow Sensors

Large volumes of air flow can be sensed by prop-driven devices similar to the liquid flow sensor shown in Figure 10–10. Solid-state devices similar to the one shown in Figure 10–18 are commonly used to sense smaller amounts of air or gas flow. This device operates on the principle that air or gas flowing across a surface causes heat transfer. The sensor contains a thin-film thermally isolated bridge with a heater and temperature sensors. The output voltage is dependent on the temperature of the sensor surface. Increased air flow through the inlet and outlet ports will cause a greater amount of heat transfer, reducing the surface temperature of the sensor.

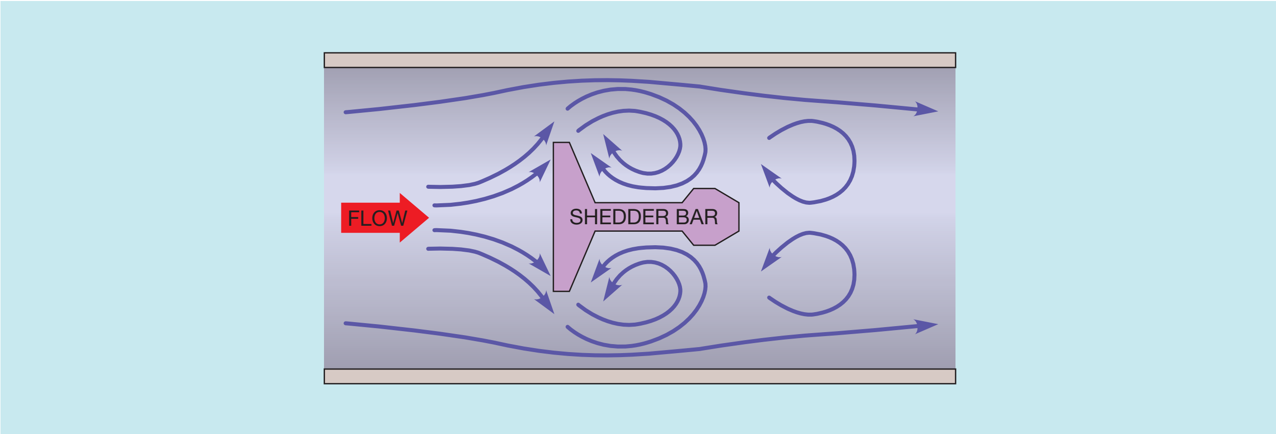


Figure 10–15 The shedder bar causes the liquid to swirl producing vortexes that produce alternating pressures on the bar. (Source: Delmar/Cengage Learning.)

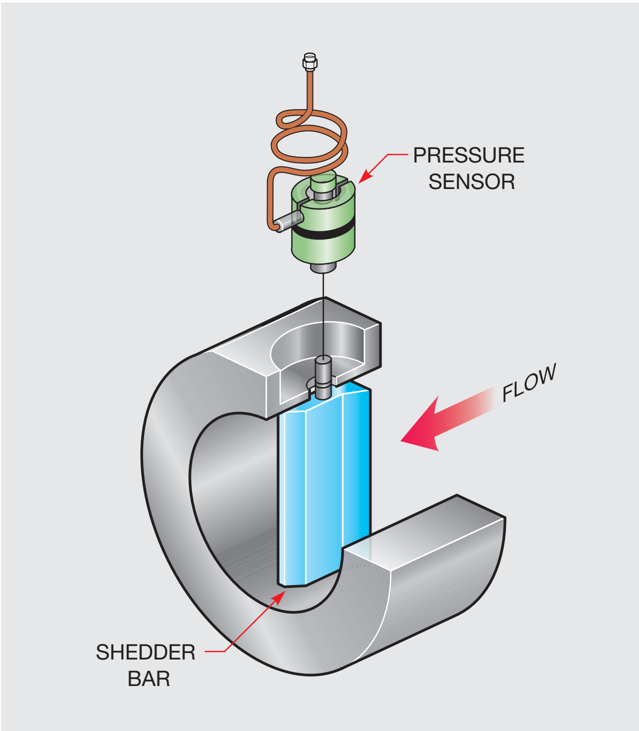


Figure 10–16 Movement against the shedder bar causes pressure against the pressure sensor. (Source: Delmar/Cengage Learning.)

Figure 10–17 Vortex flow sensors. (Courtesy © 1998 Rosemount, Inc., used by permission.)

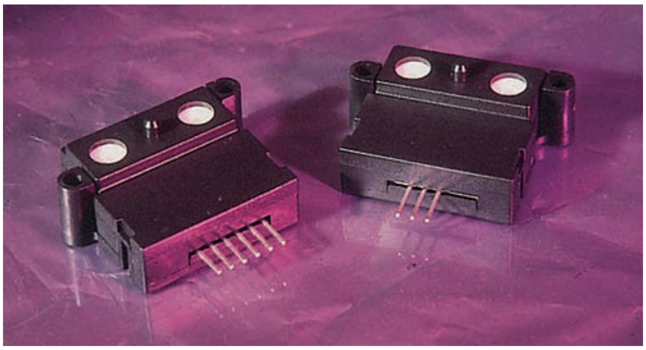


Figure 10–18 Solid-state air flow sensor. (Courtesy Honeywell's Micro Switch Division.)

Review Questions

1. What are typical uses of flow switches?
2. Draw a line diagram to show a green light that will glow when liquid flow occurs.
3. Draw a one-line diagram showing a bell that will ring in the absence of flow. Include a switch to turn off the bell manually.
4. What is a transducer?
5. What is the most common output current for flow sensors?
6. What is Faraday's Law concerning conductors moving through a magnetic field?
7. What type of flow sensors use Faraday's Law as their principle of operation?
8. What is the operating principle of the solid-state air flow sensor described in this text?

CHAPTER 11
LIMIT SWITCHES

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of a limit switch.
- Connect a limit switch in a circuit.
- Recognize limit switch symbols in a ladder diagram.
- Discuss the different types of limit switches.

Limit switches are used to detect when an object is present or absent from a particular location. They can be activated by the motion of a machine or by the presence or absence of a particular object. Limit switches contain some type of bumper arm that is impacted by an object. The type of bumper arm used is determined by the application of the limit switch. When the bumper arm is impacted, it causes the contacts to change position. Figure 11–1 illustrates the use of a limit switch to detect the position of boxes on a conveyer line. This particular limit switch uses a long metal rod that is free to move in any direction when hit by an object. This type of bumper arm is generally called a wobble stick or wiggle stick. Limit switches with different types of bumper arm are shown in Figure 11–2.

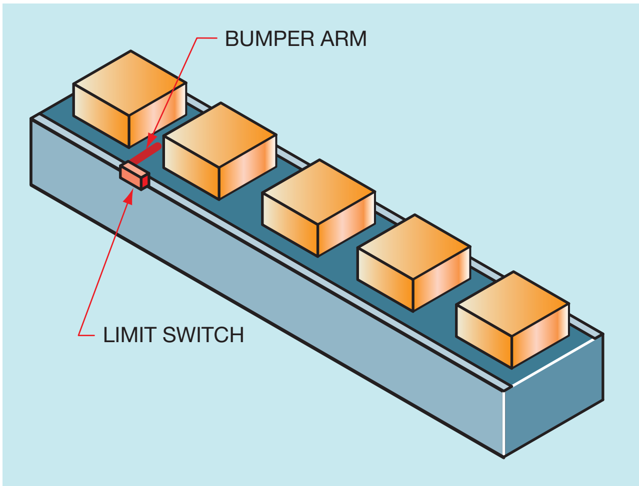


Figure 11–1 A limit switch is used to detect the position of boxes on a conveyer line. (Source: Delmar/Cengage Learning.)

Limit switches vary in size and contact arrangement depending on the application. Some are constructed of heavy gauge metal and are intended to be struck by moving objects thousands of time. Others are small and designed to fit into constricted spaces. Some

Figure 11–2 Limit switches with different types of activating arms. (Courtesy Micro Switch, a Honeywell Division.)

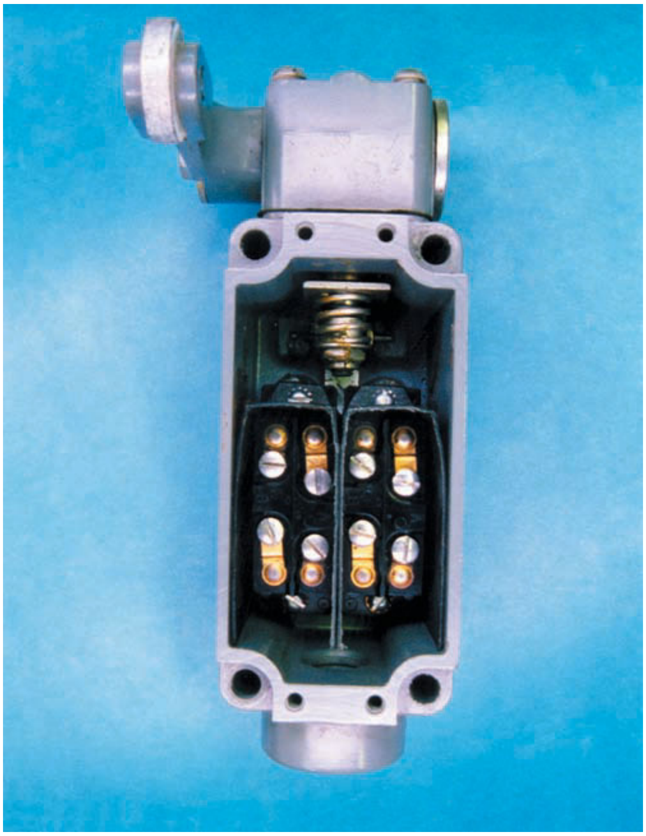


Figure 11–3 Limit switch with cover removed to show multiple contacts. (Source: Delmar/Cengage Learning.)

contain a single set of contacts and others contain multiple contacts, as shown in Figure 11–3. Some limit switches are momentary contact (spring returned) and others are maintained contact.

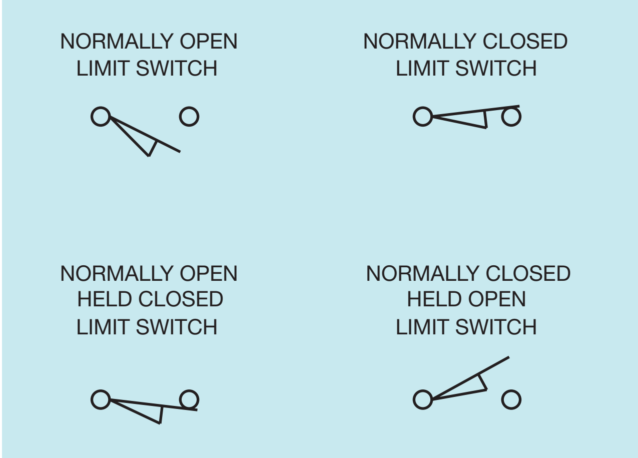


Figure 11–4 NEMA standard symbols for limit switches. (Source: Delmar/Cengage Learning.)

Generally, limit switches are used as pilot devices to control the coil of relays and motor starters in control circuits. The standard NEMA symbols used to indicate limit switches are shown in Figure 11–4. The wedge drawn under the switch symbol represents the bumper arm of the switch.

Micro Limit Switches

Another type of limit switch often used in different types of control circuits is the micro limit switch or *micro switch*. Micro switches are much smaller in size than the limit switch shown in Figure 11–3, which permits them to be used in small spaces that would never be accessible to the larger device. Another characteristic of the micro switch is that the actuating plunger requires only a small amount of travel to cause the contacts to change position. The micro switch shown in Figure 11–5 has an activating plunger located at the top of the switch. This switch requires that the plunger be depressed approximately 0.015 inch or 0.38 millimeters. Switching the contact position with this small amount of movement is accomplished by spring loading the contacts, as shown in Figure 11–6. A small amount of movement against the spring will cause the movable contact to snap from one position to another.

Electrical ratings for the contacts of the basic micro switch are generally in the range of 250 volts AC and 10 to 15 amperes, depending on the type of switch. The basic micro switch can be obtained with a variety of different activating arms, as shown in Figure 11–7.

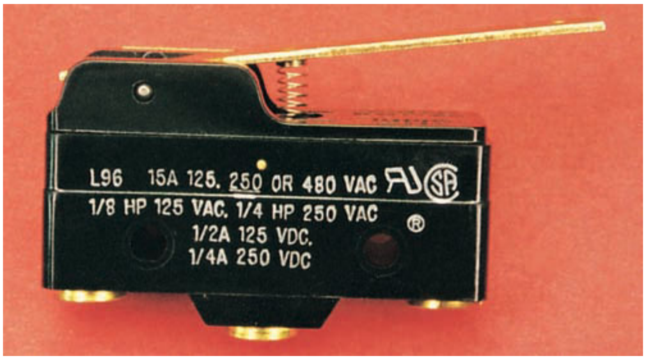


Figure 11–5 Micro limit switch. (Source: Delmar/Cengage Learning.)

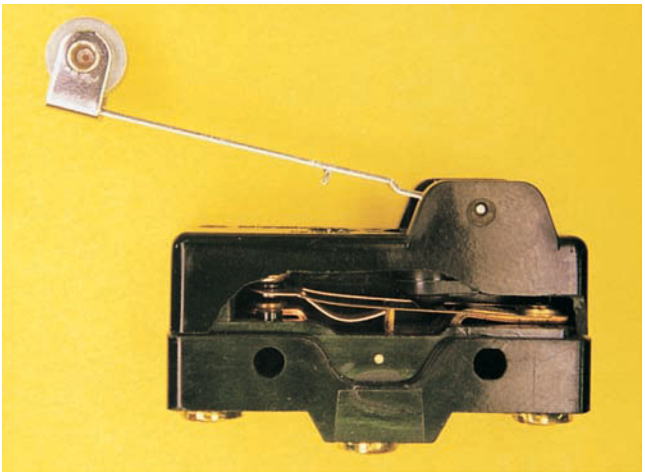


Figure 11–6 Spring loaded contacts of a basic micro switch. (Source: Delmar/Cengage Learning.)

Figure 11–7 Micro switches can be obtained with different types of activating arms. (Courtesy Micro Switch, a Honeywell Division.)

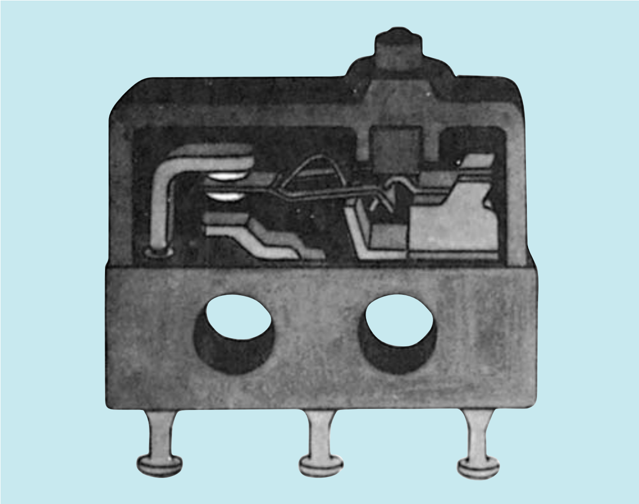


Figure 11–8 Cutaway view of a subminiature micro switch. (Courtesy Honeywell's Micro Switch Division.)

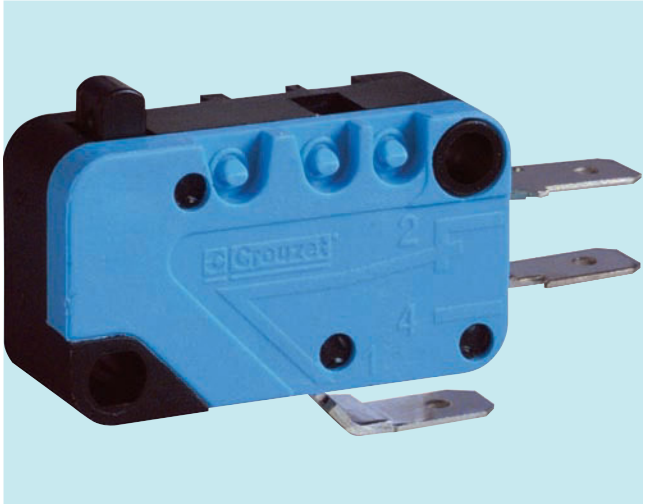


Figure 11–9 Subminiature micro switch. (Courtesy Square D Company.)

Subminiature Micro Switches

The *subminiature micro switch* employs a similar spring contact arrangement as the basic micro switch (Figure 11–8). The subminiature switches are approximately one-half to one-quarter the size of the basic switch, depending on the model. Due to their reduced size, the contact ratings of subminiature switches range from about 1 ampere to about 7 amperes depending on the switch type. A different type of subminiature micro switch is shown in Figure 11–9.

Limit Switch Application

Figure 11–10 illustrates a common use for limit switches. A platform is used to raise material from a bottom floor to an upper floor. A hydraulic cylinder is used to raise the platform. A limit switch located on the

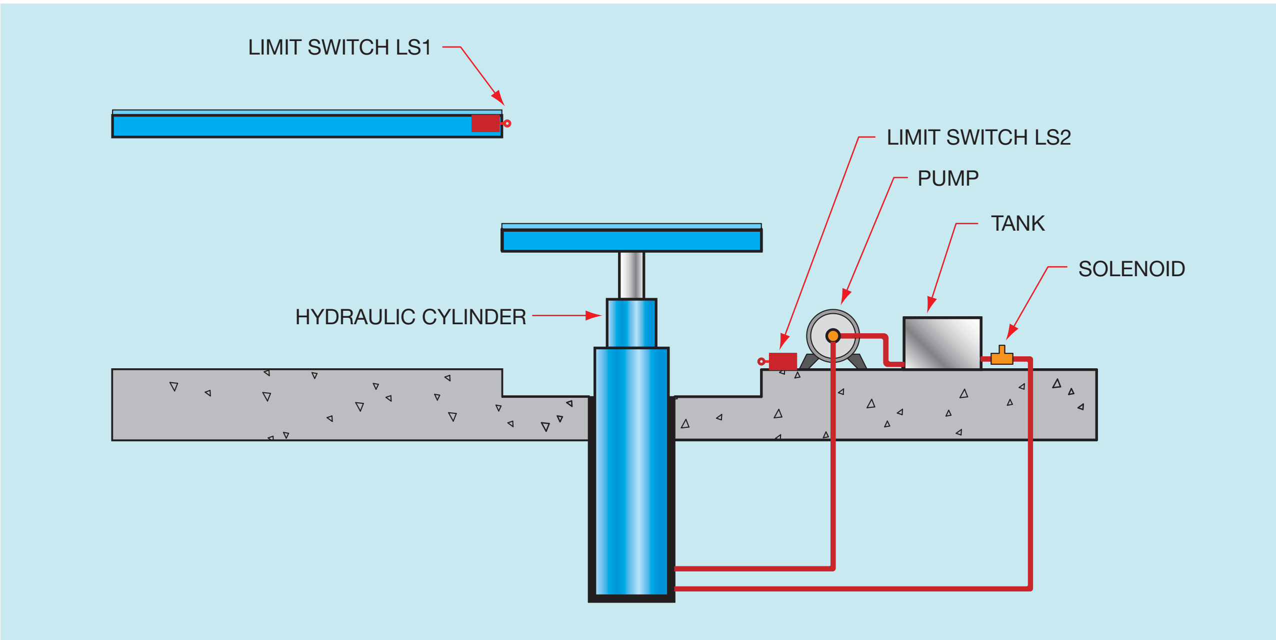


Figure 11–10 Platform rises between floors. (Source: Delmar/Cengage Learning.)

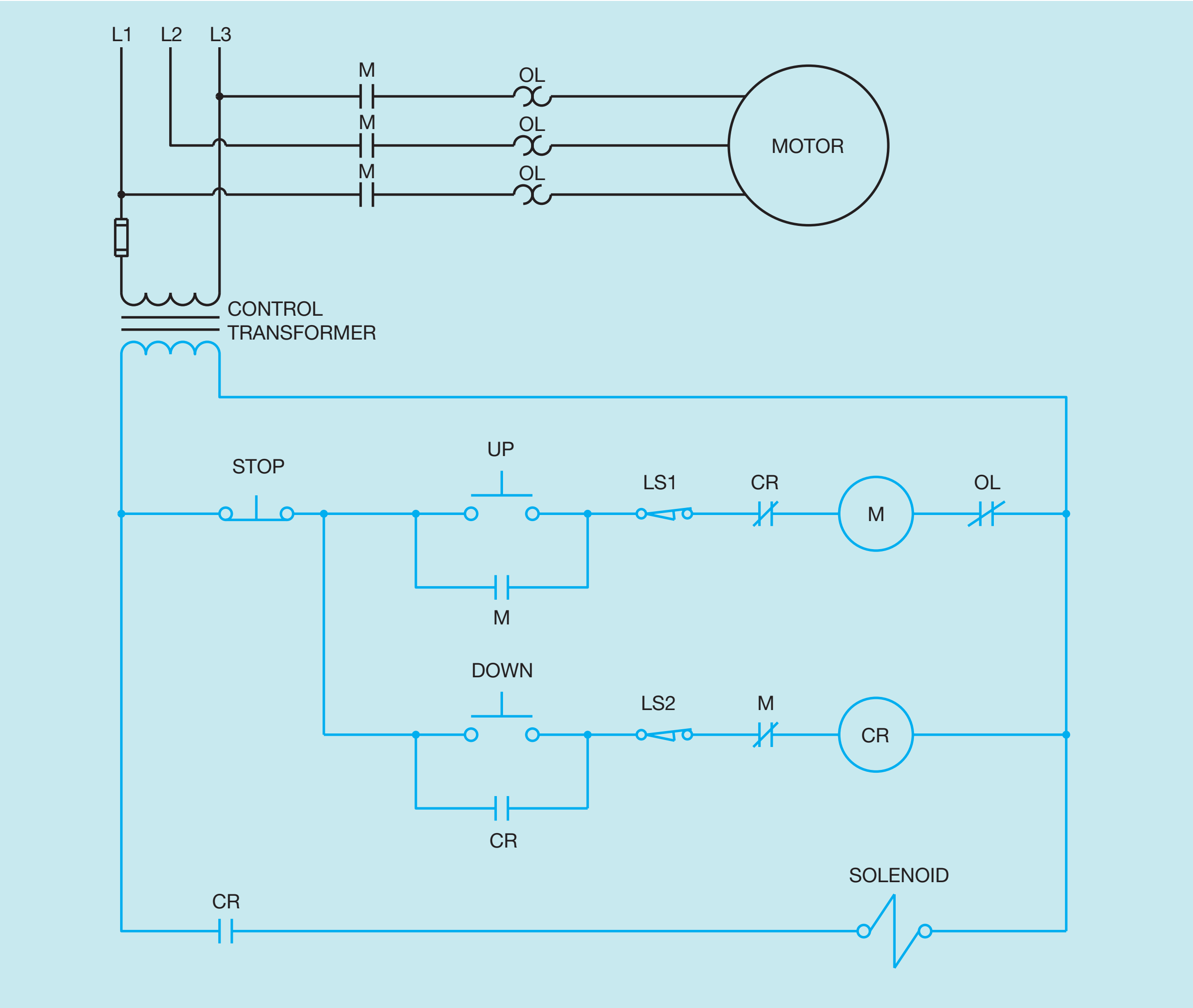


Figure 11–11 Control circuit to raise and lower platform. (Source: Delmar/Cengage Learning.)

bottom floor detects when the platform is in that position, and a second limit switch on the upper floor detects when the platform has reached the upper floor. A hydraulic pump is used to raise the platform. When the platform is to travel from the upper floor to the lower floor, a solenoid valve opens and permits oil to return to a holding tank. It is not necessary to use the pump to lower the platform because the weight of the platform will return it to the lower floor.

The schematic diagram for this control circuit is shown in Figure 11–11. The schematic shows both limit switches to be normally closed. When the platform is at the extent of travel in either direction, however, one of the limit switches will be open. If the platform is at the bottom floor, limit switch LS2 will be open. If the UP push button is pressed, a circuit will be completed to M starter, causing the motor to start raising the platform. The M normally closed contact will open to prevent CR from being energized at the same time. When the platform begins to rise, limit switch LS2 will close. The platform will continue upward until it reaches the top, causing limit switch LS1 to open. This will de-energize M contactor, causing the motor to stop and the normally closed auxiliary contact in series with CR coil to re-close.

When the DOWN push button is pressed, control relay CR will energize. The normally closed CR contacts connected in series with M contactor will open to interlock the circuit, and the normally open CR contact connected in series with the solenoid coil will close. When the solenoid coil energizes, the platform will start downward, causing limit switch LS1 to re-close. When the platform reaches the bottom floor, limit switch LS2 will open and de-energize coil CR.

Review Questions

1. What is the primary use of a limit switch?
2. Why are the contacts of a micro switch spring loaded?
3. Refer to the circuit shown in Figure 11–11. Assume that the platform is located on the bottom floor. When the UP push button is pressed, the pump motor does not start. Which of the following could **not** cause this problem?
   a. The contacts of limit switch LS1 are closed.
   b. The contacts of limit switch LS2 are open.
   c. Motor starter coil M is open.
   d. The overload contact is open.
4. Refer to the circuit shown in Figure 11–11. Assume that the platform is located on the lower floor. When the UP pushbutton is pressed, the platform raises. When the platform reaches the upper floor, however, the pump does not turn off but continues to run until the overload relay opens the overload contacts. Which of the following could cause this problem?
   a. The solenoid valve opened when limit switch LS1 opened.
   b. The UP pushbutton is shorted.
   c. Limit switch LS1 did not open its contacts.
   d. Limit switch LS2 contacts did not re-close when the platform began to rise.
5. Refer to the circuit shown in Figure 11–11. Assume that the platform is located at the upper floor. When the DOWN push button is pressed, the platform does not begin to lower. Which of the following could **not** cause the problem?
   a. Control relay coil CR is open.
   b. Limit switch LS1 contacts are open.
   c. Limit switch LS2 contacts are open.
   d. The solenoid coil is open.

CHAPTER 12
PHASE FAILURE RELAYS

OBJECTIVES

After studying this chapter, the student will be able to:

- Explain the purpose of phase failure relays.
- List hazards of phase failure and phase reversal.

If two of the lines supplying power to a three-phase motor are reversed, it will cause the motor to reverse the direction of rotation. This can be a serious problem with some types of equipment. Unintended reversal of direction can cause gear teeth to shear, chains to break, and the impeller of submersible pumps to unscrew off the end of the motor shaft. It can not only cause damage to equipment but also injury to operators or personnel in the vicinity of the machine.

Phase failure occurs when power is lost to one of the lines supplying power to a three-phase motor. The motor will continue to operate but will draw an excessive amount of current. In this condition, the overload relay should cause the motor starter to disconnect the motor from the power line if the overload heaters have been sized correctly. Single phasing will cause the two phases that remain energized in a three-phase motor to increase current by an average of 173%.

Effects of Voltage Variation on Motors

Motors are affected when operated at other than their rated nameplate voltage. NEMA rated motors are designed to operate at plus or minus 10% of their rated voltage. Figure 12–1 shows the approximate change in full load current and starting current for typical electric motors when operated over their rated voltage (110%) and under their rated voltage (90%). Motors are intended to operate on systems with balanced voltage (the voltage is the same between all phases). Unbalanced voltage is one of the leading causes of motor failure. Unbalanced voltage is generally caused when single-phase loads are supplied by three-phase systems.

Determining the Amount of Voltage Unbalance

Figure 12–1 refers to the voltage across the phase conductors of a balanced three-phase system as measured between phases AB, BC, and AC. In other words,

Voltage Variation	Full Load Current	Starting Current
110%	7%	10–12% Increase
90%	11%	10–12% Decrease

Figure 12–1 Change in current for electric motors when operated over or under rated voltage. (Source: Delmar/Cengage Learning.)

the table indicates the effect on motor current when voltage is greater or less than the motor nameplate rating in a balanced system. Greater harm is caused when the voltages are unbalanced. NEMA recommends that the unbalanced voltage not exceed plus or minus 1%. The following steps illustrate how to determine the percentage of voltage unbalance in a three-phase system:

1. Take voltage measurements between all phases. In this example, assume the voltage between AB = 496 volts, BC = 460 volts, and AC = 472 volts.
2. Find the average voltage.

$$\begin{array}{r} 496 \\ 460 \\ \underline{472} \\ 1428 \end{array} \qquad 1428/3 = 476 \text{ V}$$

3. Subtract the average voltage from the voltage reading that results in the greatest difference.

$$496 - 476 = 20 \text{ V}$$

4. Determine the percentage difference.

$$\frac{100 \times \text{Greatest Voltage Difference}}{\text{Average Voltage}}$$

$$= \frac{100 \times 20}{476} = 4.2\% \text{ voltage unbalance}$$

Heat Rise

The percentage of heat rise in the motor caused by the voltage unbalance is equal to twice the percent squared.

$$2 \times (\text{percent voltage unbalance})^2$$

$$2 \times 4.2 \times 4.2 = 35.28\% \text{ temperature increase in the winding with the highest current.}$$

A solid-state phase monitoring relay is shown in Figure 12–2. This relay provides protection in the event of a voltage unbalance or a phase reversal. The unit automatically resets after the correct voltage conditions return. An indicating light shows when the relay is activated.

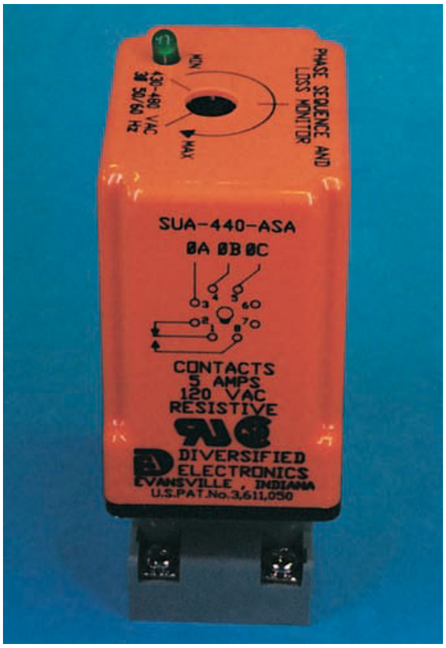


Figure 12–2 Solid-state phase monitoring relay. (Source: Delmar/Cengage Learning.)

Review Questions

1. A three-phase motor has a nameplate current of 56 amperes. If one phase is lost and the motor begins single-phasing, what would be the average amount of current flowing in the two remaining phases?
2. NEMA rated motors are designed to operate at what percentage of their rated voltage?
3. A three-phase motor is rated to operate on 208 volts. The following voltage readings are taken: A-B 177, A-C 187, B-C 156. What is the percentage of temperature increase in the phase with the highest current draw?

CHAPTER 13

SOLENOID AND MOTOR OPERATED VALVES

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the purpose and operation of two-way solenoid valves.
- Describe the operation of four-way solenoid valves.
- Connect and troubleshoot solenoid valves.
- Read and draw symbols for solenoid valves.
- Discuss the operation of motor operated valves.

Valves are employed throughout industry to control the flow of both liquids and gasses. Many valves are manually operated by turning a handle, but in industrial applications, electrically operated valves are generally used. Electrically operated valves can be placed near the equipment they operate, which helps to minimize the amount of piping required. Also, electrically operated valves can be controlled from remote locations by running a pair of wires from the control station to the valve.

Solenoid Valves

Solenoid valves contain two distinct parts, the electrical part and the valve part. The electrical part consists of a coil of wire that supplies an electromagnetic field that operates the plunger or core. When the solenoid coil is energized, the plunger is drawn into the coil, opening or closing the valve. Solenoid valves can be opened or closed when de-energized. If the valve is normally closed, it will open when the solenoid is energized. The plunger will return to its normal position when the solenoid is de-energized. Most valves contain a spring that re-seats the valve when de-energized. Some valves are normally open and will close when energized. They will return to their normal open state when the solenoid is de-energized.

Although solenoid valves are very similar to the solenoid used to operate relays and contacts, the symbol used to represent a solenoid valve is often drawn differently. Relay and contactor coils are generally represented by a circle. Solenoid valves are often represented by the symbol shown in Figure 13–1.

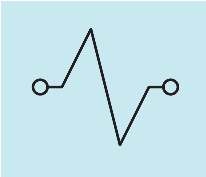


Figure 13–1 Symbol often used to represent a solenoid. (Source: Delmar/Cengage Learning.)

Two-Way Solenoid Valves

Two-way valves are used to control the flow of liquids or gasses. They are digital devices in that they are completely on or completely off. They do not have the ability to control the rate of flow. Two-way valves have an inlet and an outlet and are connected directly into the pipe line. The inlet and outlet should not be reversed, because the valve is designed is such a manner that the pressure of the inlet liquid or gas is used to help maintain a seal (Figure 13–2). The valve contains a wedge-shaped disc that seats against a wedge-shaped seat. The inlet pressure forces the disc against the seat to help provide a more secure seal. If the valve is reversed, the inlet pressure tries to force the disc up against the spring. If the pressure is great enough, it can cause the valve to leak.

Four-Way Solenoid Valves

Four-way valves are generally used to control the air supplied to double acting cylinders (Figure 13–3). When the valve is de-energized, one side of the cylinder is open to atmospheric pressure, and the other side is supplied by line pressure. When the solenoid coil is energized, the valve permits the high pressure side to exhaust to the atmosphere and the side that was previously open to the atmosphere to be supplied by line pressure. The piston inside the cylinder will move back and forth in accord with the solenoid being energized or de-energized. The speed of the piston's movement is determined by the amount of air pressure, the surface area of the piston, and the amount of force the load places against the piston.

Motor Operated Valves

Motor operated valves (MOVs) are used extensively in industries where the control of liquids or gasses is required. Pipe line companies and the petrol-chemical industry are just two examples of these types of industries. Motor operated valves are valves that employ an electric motor to open or close the valve (Figure 13–4).

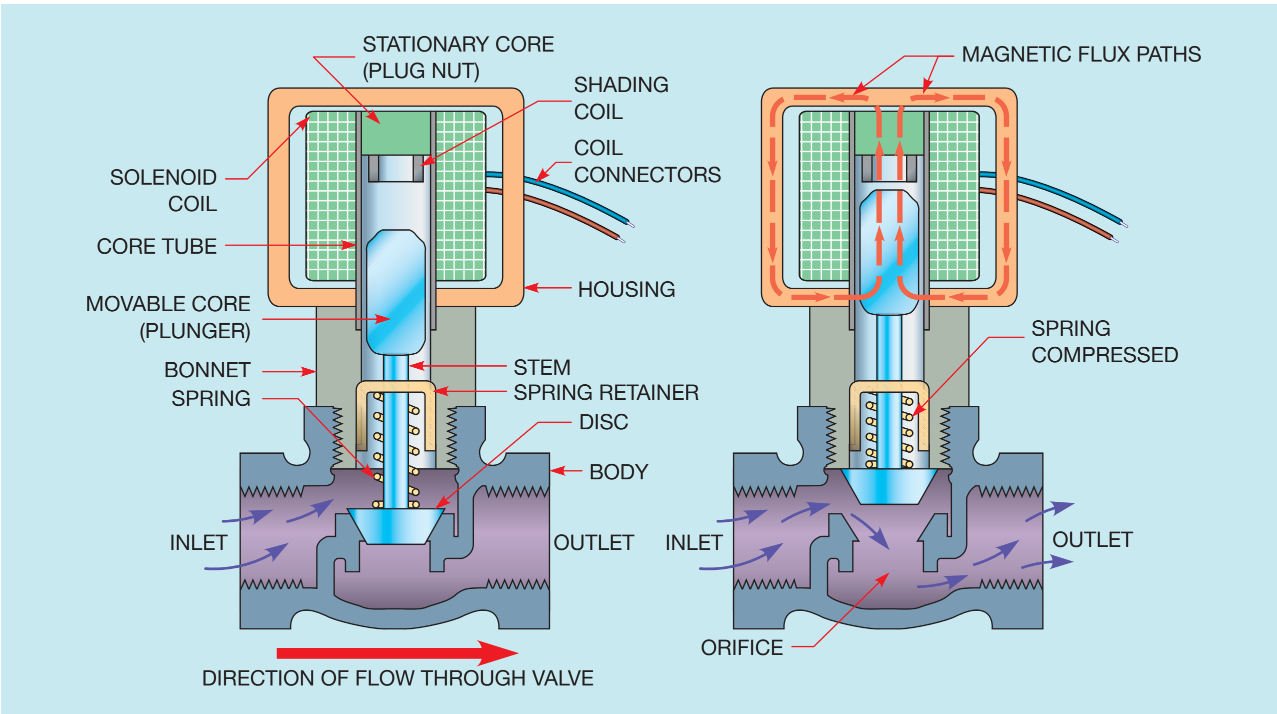


Figure 13–2 Pressure of the liquid or gas helps to maintain the seal by applying pressure to the disc. (Source: Delmar/Cengage Learning.)

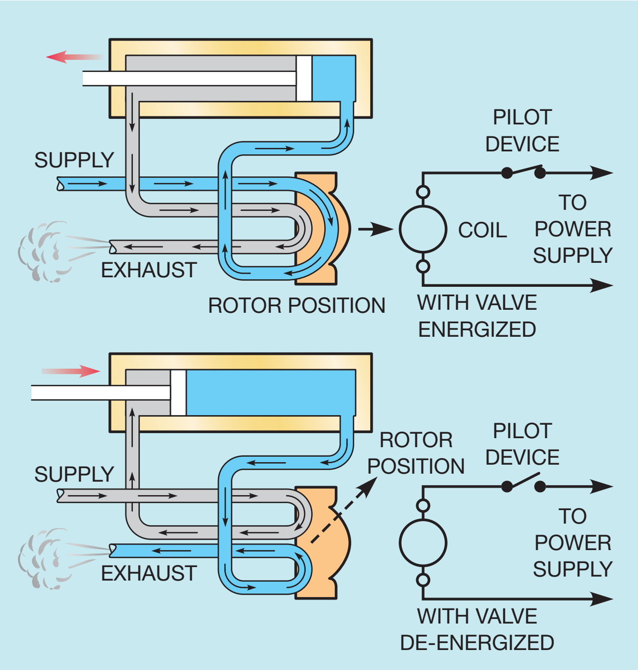


Figure 13–3 Four-way valve used to control a double acting cylinder. (Source: Delmar/Cengage Learning.)

There are generally two sections to the control system for MOVs, local and remote. The local controls are housed with the valve at the field location and the remote controls are housed in a control room some distance away.

The control system is basically a forward/reverse control with the addition of a special limit switch that detects when the valve is open or closed and a torque switch that can be used to ensure that the valve is tightly seated (Figure 13–5). It is common practice to use the limit switch (Figure 13–6) to determine when the valve is completely open, and the torque switch (Figure 13–7) to determine when the valve is closed. The schematic for an MOV is shown in Figure 13–8. The schematic is drawn to assume that the valve is in the open position, and all limit switches are drawn to reflect this condition.

This control circuit for an MOV is of particular interest because a two-wire circuit is used to control the opening and closing of the valve from a remote location. This two-wire circuit consists mainly of an 80 volt transformer, relay coils K1A, K1B, K2A, and K2B, and push buttons. Two-wire control is accomplished by

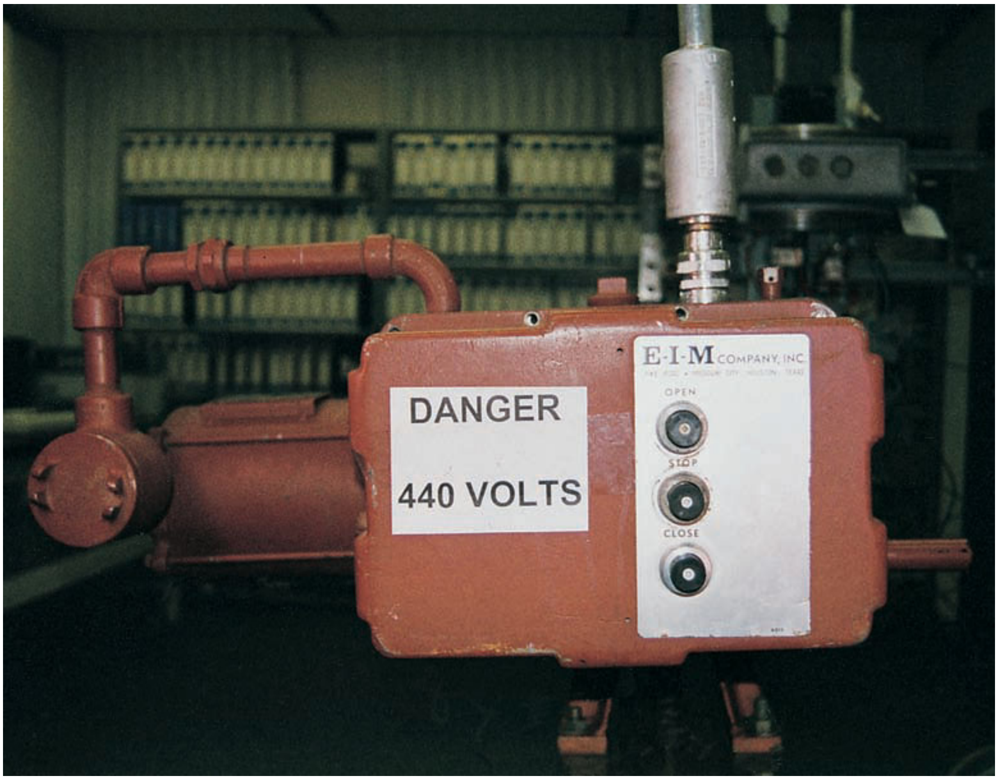


Figure 13–4 Motor operated valve. (Source: Delmar/Cengage Learning.)

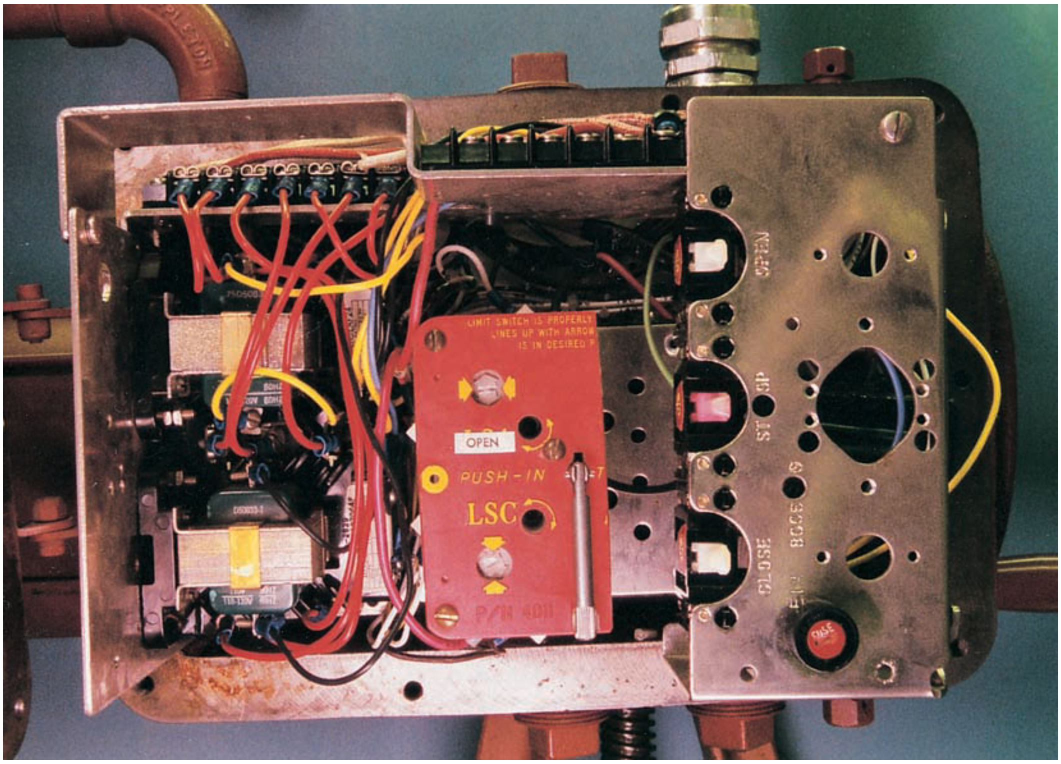


Figure 13–5 The MOV control circuit is basically a forward-reverse circuit. (Source: Delmar/Cengage Learning.)

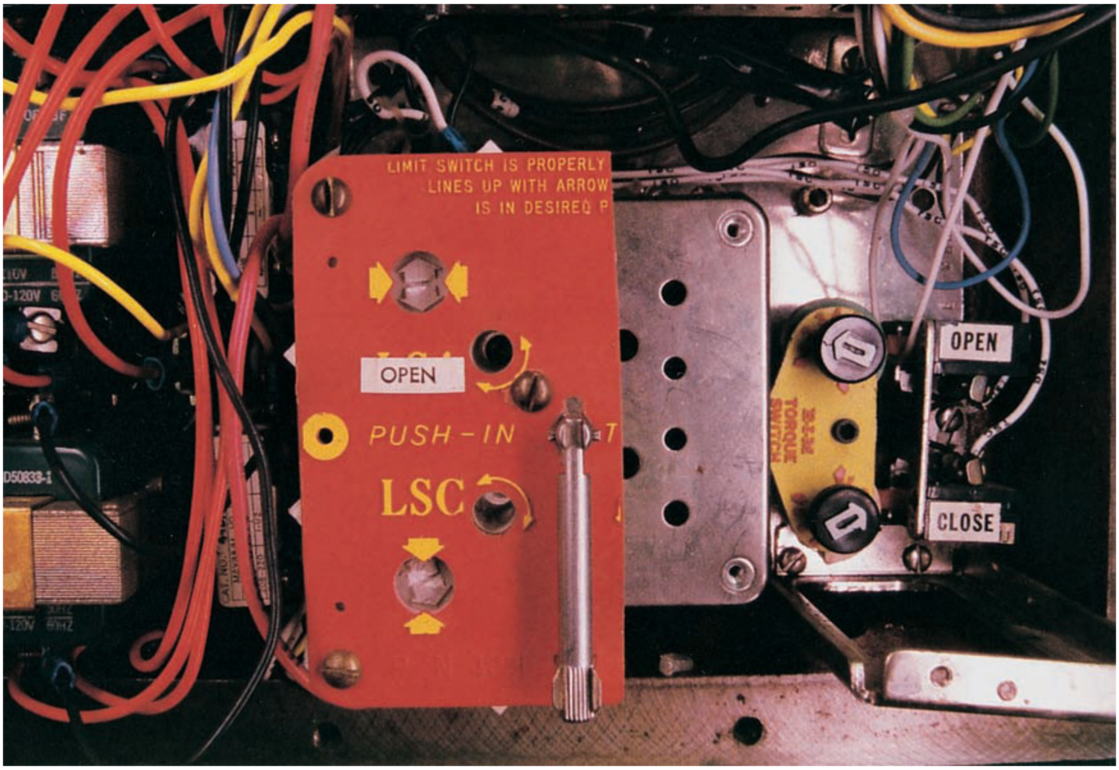


Figure 13–6 MOV limit switch. (Source: Delmar/Cengage Learning.)

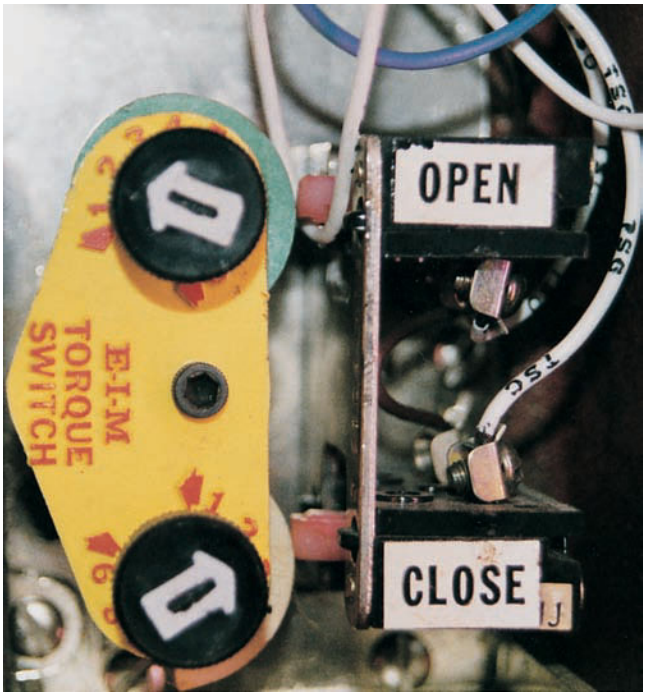


Figure 13–7 MOV torque switch. (Source: Delmar/Cengage Learning.)

converting the 80 volts AC into half-wave rectified DC with a voltage of 36 volts.

$$80\text{ VAC} \times 0.9\text{ (RMS to Average)} = 72\text{ VDC (Full-Wave)}$$

$$\frac{72\text{ VDC (Full-Wave)}}{2} = 36\text{ VDC (Half-Wave)}$$

With the valve in the open position, normally closed limit switch LSC connected in series with coil K2B is closed and normally closed limit switch LSO connected in series with coil K2A is held open. This permits a current path through coil K2B and diode D4 to the coils of K1A and K1B. At this point, current cannot flow through coil K1A because diode Dl is reverse biased. Current can flow through coil K1B and diode D2, however. Coils K2A and K2B have a voltage rating of 36 VDC, and coils K1A and K1B have a voltage rating of 24 VDC. Since coils K1B and K2B are connected in series, the voltage drops across both these coils must equal the applied voltage of 36 VDC. The coil resistances are such that 24 VDC is dropped across coil K1B and 12 VDC is dropped across coil K2B. Since coil K1B has a voltage rating of 24 VDC, it energizes and closes a contact to turn on the OPEN indicator light. Coil K2B has a voltage rating of 36 VDC. The 12 VDC applied to it is not enough to energize it, so its contacts remain in their normal position.

Now assume that the CLOSE push button is pressed at the remote location. This short-circuits coil K1B, which causes the entire 36 VDC to be applied across coil K2B. When coil K2B energizes, C contactor energizes and the motor begins closing the valve. As the valve closes, limit switch LSC connected in series with coil K2B opens, breaking the current path through coils K1B and K2B.

When the valve reaches the closed position, limit switch LSO connected in series with coil K2A closes. A current path now exists through coils K2A, diode D3, coil K1A, and diode D1. Relay K1A energizes and turns on the CLOSED indicator light. Although the torque switch is generally used to stop the motor when the valve is closed, the limit switch is adjusted to indicate that the valve is in the closed position.

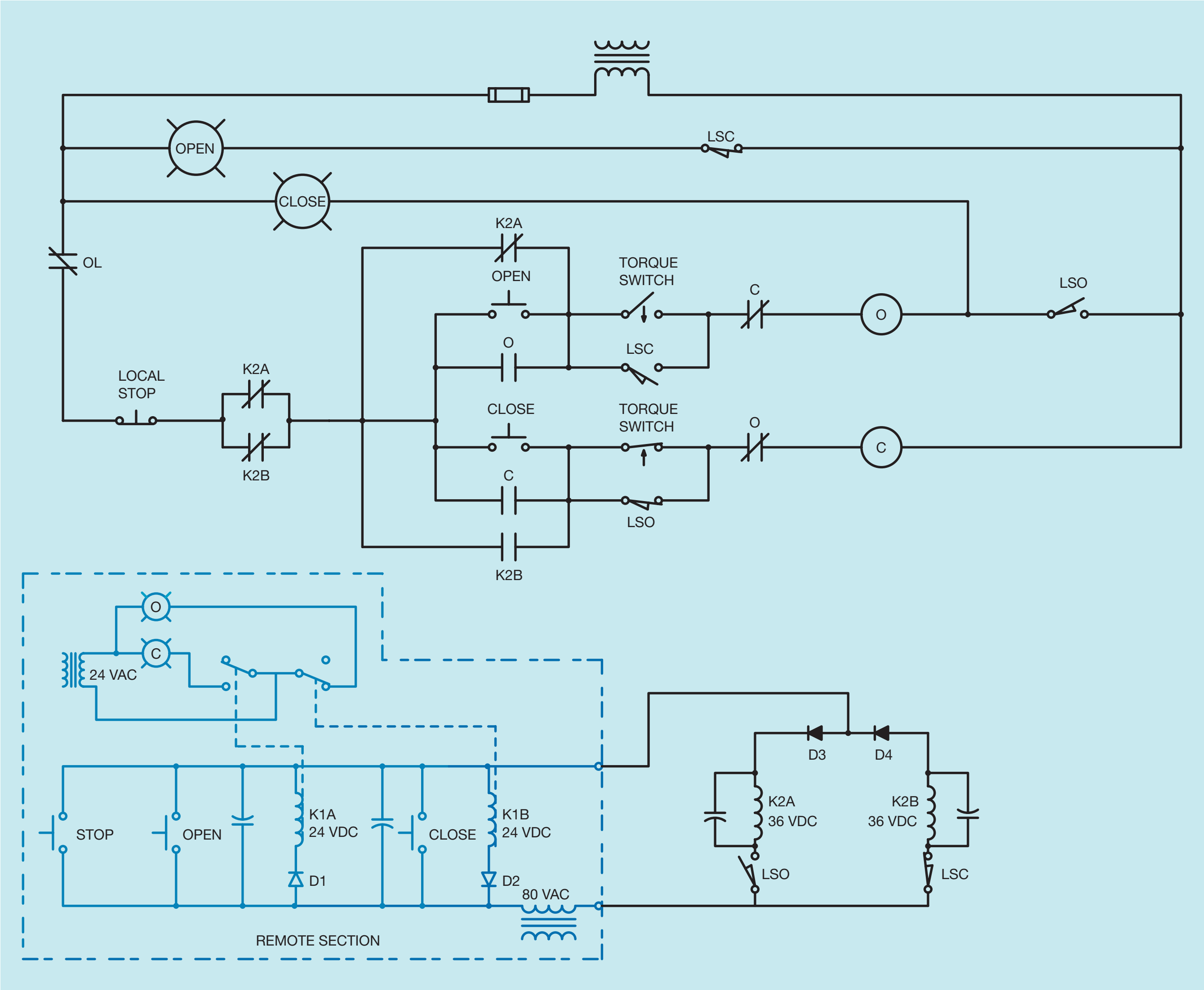


Figure 13–8 Control circuit for a motor operated valve. (Source: Delmar/Cengage Learning.)

Review Questions

1. What is meant by the statement that solenoid valves are digital devices?
2. Why is it important that the inlet and outlet ports on a two-way valve not be reversed?
3. What type of valve is generally used to supply air pressure to a double acting cylinder?
4. What two sections are generally used to operate motor operated valves?
5. What type of switch is generally used to ensure that a motor operated valve is tightly seated?

CHAPTER 14

TEMPERATURE SENSING DEVICES

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe different methods for sensing temperature.
- Discuss different devices intended to be operated by a change of temperature.
- List several applications for temperature sensing devices.
- Read and draw the NEMA symbols for temperature switches.

There are many times when the ability to sense temperature is of great importance. The industrial electrician will encounter some devices designed to change a set of contacts with a change of temperature and other devices used to sense the amount of temperature. The method used depends a great deal on the applications of the circuit and the amount of temperature that must be sensed.

Expansion of Metal

A very common and reliable method for sensing temperature is by the expansion of metal. It has long been known that metal expands when heated. The amount of expansion is proportional to two factors:

1. The type of metal used.
2. The amount of temperature.

Consider the metal bar shown in Figure 14–1. When the bar is heated, its length expands. When the metal is permitted to cool, it will contract. Although the

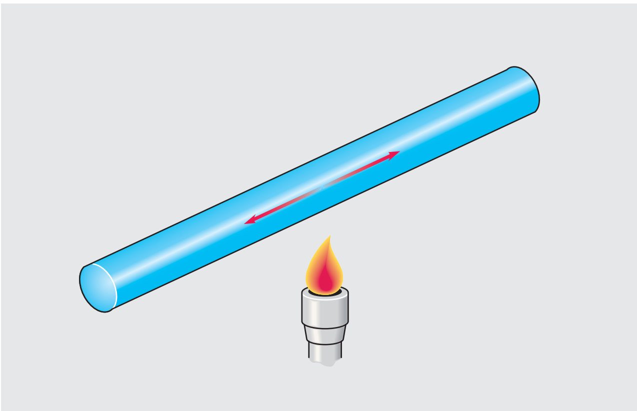


Figure 14–1 Metal expands when heated. (Source: Delmar/Cengage Learning.)

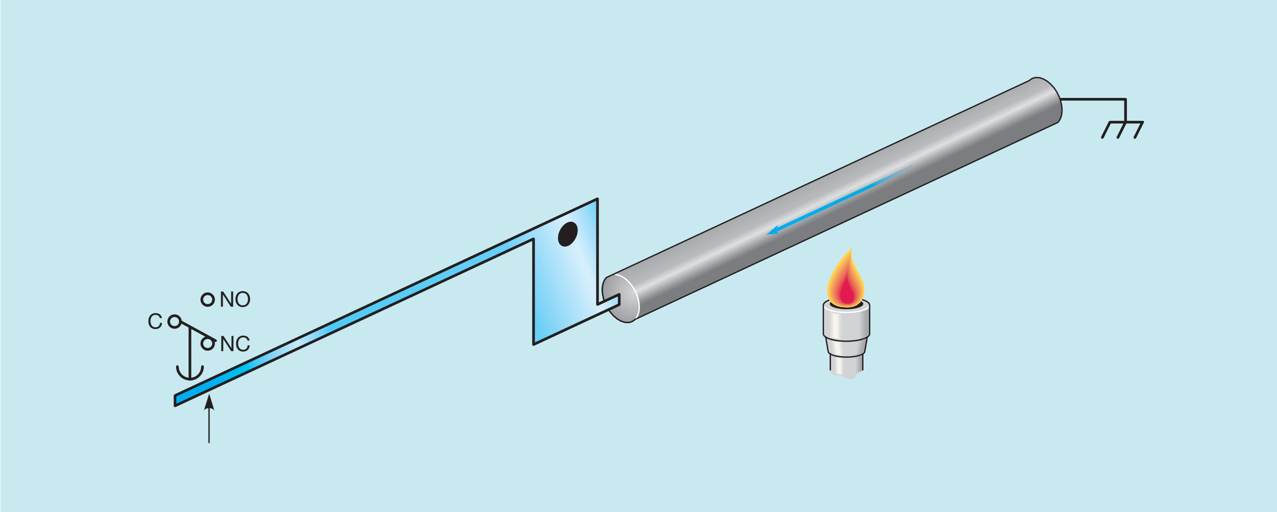


Figure 14–2 Expanding metal operates a set of contacts. (Source: Delmar/Cengage Learning.)

amount of movement due to contractions and expansion is small, a simple mechanical principle can be used to increase the amount of movement (Figure 14–2).

The metal bar is mechanically held at one end. This permits the amount of expansion to be in one direction only. When the metal is heated and the bar expands, it pushes against the mechanical arm. A small movement of the bar causes a great amount of movement in the mechanical arm. This increased movement in the arm can be used to indicate the temperature of the bar by attaching a pointer and scale, or to operate a switch as shown. It should be understood that illustrations are used to convey a principle. In actual practice, the switch shown in Figure 14–2 would be spring loaded to provide a "snap" action for the contacts. Electrical contacts must never be permitted to open or close slowly. This produces poor contact pressure and will cause the contacts to burn or will cause erratic operation of the equipment they are intended to control.

Hot-wire Starting Relay

A very common device that uses the principle of expanding metal to operate a set of contacts is the *hot-wire starting relay* found in the refrigeration industry. The hot-wire relay is so named because it uses a length of resistive wire connected in series with the motor to sense motor current. A diagram of this type of relay is shown in Figure 14–3.

When the thermostat contact closes, current can flow from line L1 to terminal L of the relay. Current then flows through the resistive wire, the movable arm, and the normally closed contacts to the run and start windings. When current flows through the resistive wire, its temperature increases. This increase of temperature causes the wire to expand in length. When the length increases, the movable arm is forced downward. This downward pressure produces tension on the springs of both contacts. The relay is so designed that the start contact will snap open first, disconnecting the motor start winding from the circuit. If the motor current is not excessive, the wire will never become hot enough to cause the overload contact to open. If the motor current should become too great, however, the temperature of the resistive wire will become high enough to cause the wire to expand to the point that it will cause the overload contact to snap open and disconnect the motor run winding from the circuit.

The Mercury Thermometer

Another very useful device that works on the principle of contraction and expansion of metal is the *mercury thermometer*. Mercury is a metal that remains in a liquid state at room temperature. If the mercury is confined in a glass tube as shown in Figure 14–4, it will rise up the tube as it expands due to an increase in temperature. If the tube is calibrated correctly, it provides an accurate measurement for temperature.

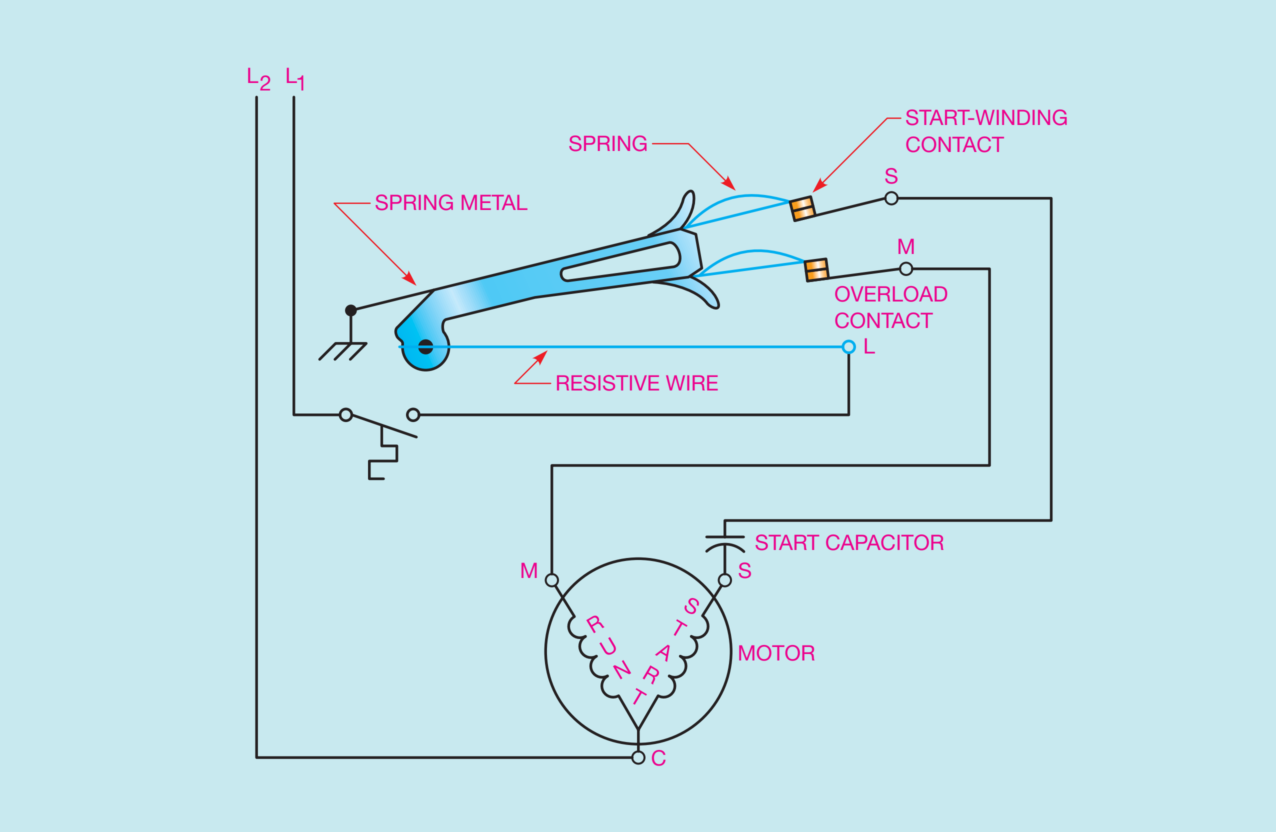


Figure 14–3 Hot-wire relay connection. (Source: Delmar/Cengage Learning.)

The Bimetal Strip

The *bimetal strip* is another device that operates by the expansion of metal. It is probably the most common heat sensing device used in the production of room thermostats and thermometers. The bimetal strip is made by bonding two dissimilar types of metal together (Figure 14–5). Since these two metals are not alike, they have different expansion rates. This causes the strip to bend or warp when heated (Figure 14–6). A bimetal strip is often formed into a spiral shape, as shown in Figure 14–7. The spiral permits a longer bimetal strip to be used in a small space. A long bimetal strip is desirable because it exhibits a greater amount of movement with a change of temperature.

If one end of the strip is mechanically held and a pointer is attached to the center of the spiral, a change in temperature will cause the pointer to rotate. If a calibrated scale is placed behind the pointer, it becomes a thermometer. If the center of the spiral is held in position and a contact is attached to the end of the

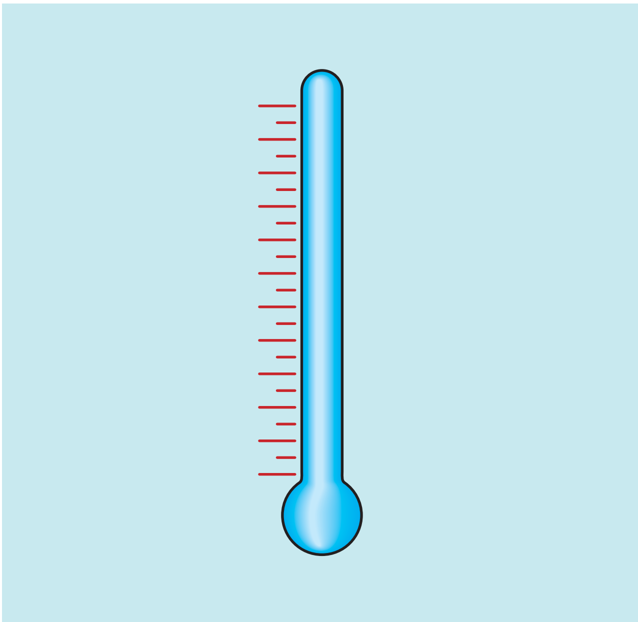


Figure 14–4 A mercury thermometer operates by the expansion of metal. (Source: Delmar/Cengage Learning.)

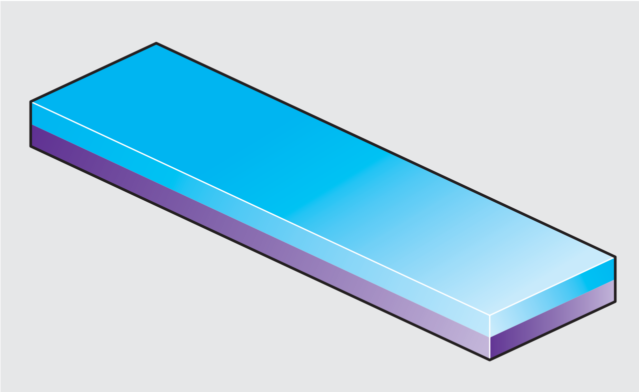


Figure 14–5 A bimetal strip. (Source: Delmar/Cengage Learning.)

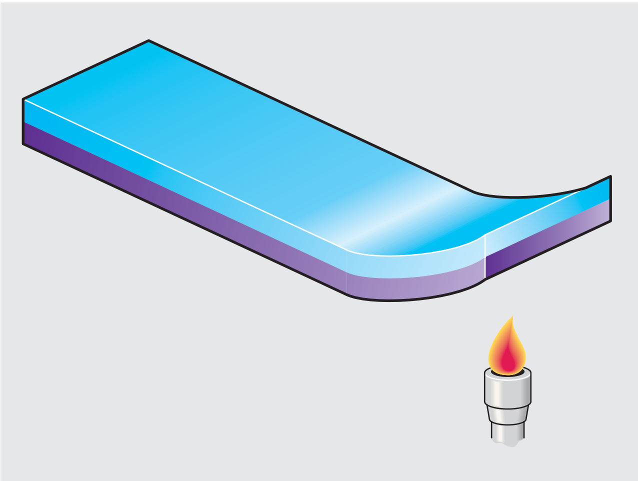


Figure 14–6 A bimetal strip warps with a change of temperature. (Source: Delmar/Cengage Learning.)

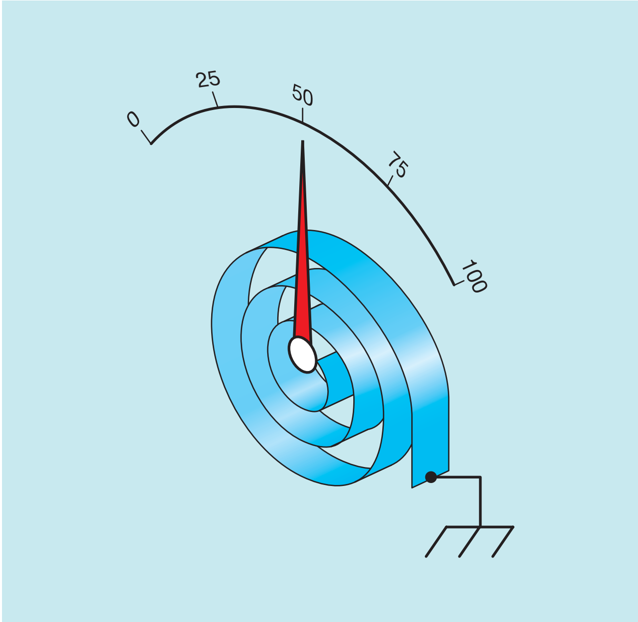


Figure 14–7 A bimetal strip used as a thermometer. (Source: Delmar/Cengage Learning.)

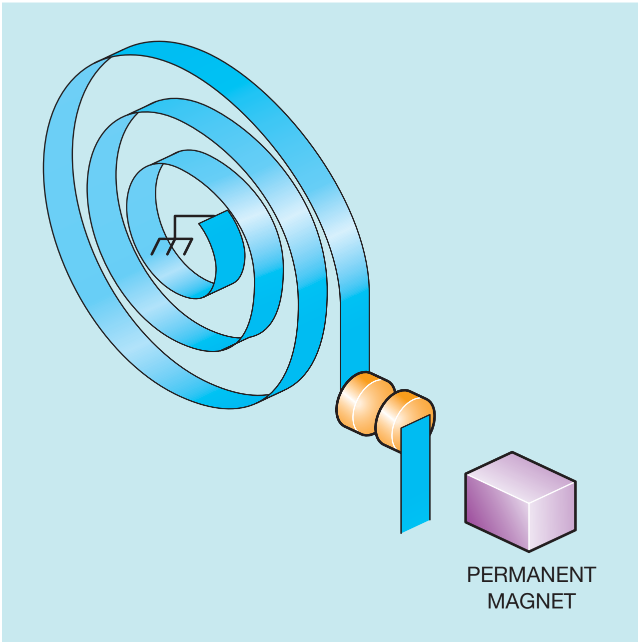


Figure 14–8 A bimetal strip used to operate a set of contacts. (Source: Delmar/Cengage Learning.)

bimetal strip, it becomes a thermostat. A small permanent magnet is used to provide a snap action for the contacts (Figure 14–8). When the moving contact reaches a point that is close to the stationary contact, the magnet attracts the metal strip and causes a sudden closing of the contacts. When the bimetal strip cools, it pulls away from the magnet. When the force of the bimetal strip becomes strong enough, it overcomes the force of the magnet and the contacts snap open.

Thermocouples

In 1822, a German scientist named Seebeck discovered that when two dissimilar metals are joined at one end, and that junction is heated, a voltage is produced (Figure 14–9). This is known as the *Seebeck effect.* The device produced by the joining of two dissimilar metals for the purpose of producing electricity with heat is called a *thermocouple.* The amount of voltage produced by a thermocouple is determined by:

1. The type of materials used to produce the thermocouple.
2. The temperature difference of the two junctions.

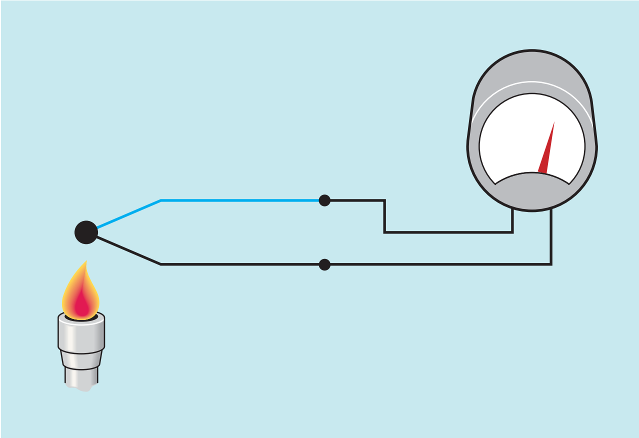


Figure 14–9 Thermocouple. (Source: Delmar/Cengage Learning.)

The chart in Figure 14–10 shows common types of thermocouples. The different metals used in the construction of thermocouples is shown as well as their normal temperature ranges.

The amount of voltage produced by a thermocouple is small, generally in the order of millivolts (1 millivolt = 0.001 volt). The polarity of the voltage of some thermocouples is determined by the temperature. For example, a type "J" thermocouple produces zero volts at about 32°F. At temperatures above 32°F, the iron wire is positive and the constantan wire is negative. At temperatures below 32°F, the iron wire becomes negative and the constantan wire becomes positive. At a temperature of +300°F, a type "J" thermocouple will produce a voltage of about +7.9 millivolts. At a temperature of −300°F, it will produce a voltage of about −7.9 millivolts.

Since thermocouples produce such low voltages, they are often connected in series, as shown in Figure 14–11. This connection is referred to as a *thermopile.* Thermocouples and thermopiles are generally used for making temperature measurements and are sometimes used to detect the presence of a pilot light in appliances that operate with natural gas. The thermocouple is heated by the pilot light. The current produced by the thermocouple is used to produce a magnetic field

TYPE	MATERIAL		DEGREES F	DEGREES C
J	IRON	CONSTANTAN	−328 to +32 +32 to +1432	−200 to 0 0 to 778
K	CHROMEL	ALUMEL	−328 to +32 +32 to 2472	−200 to 0 0 to 1356
T	COPPER	CONSTANTAN	−328 to +32 +32 to 752	−200 to 0 0 to 400
E	CHROMEL	CONSTANTAN	−328 to +32 +32 to 1832	−200 to 0 0 to 1000
R	PLATINUM 13% RHODIUM	PLATINUM	+32 to + 3232	0 to 1778
S	PLATINUM 10% RHODIUM	PLATINUM	+32 to +3232	0 to 1778
B	PLATINUM 30% RHODIUM	PLATINUM 6% RHODIUM	+992 to +3352	533 to 1800

Figure 14–10 Thermocouple chart. (Source: Delmar/Cengage Learning.)

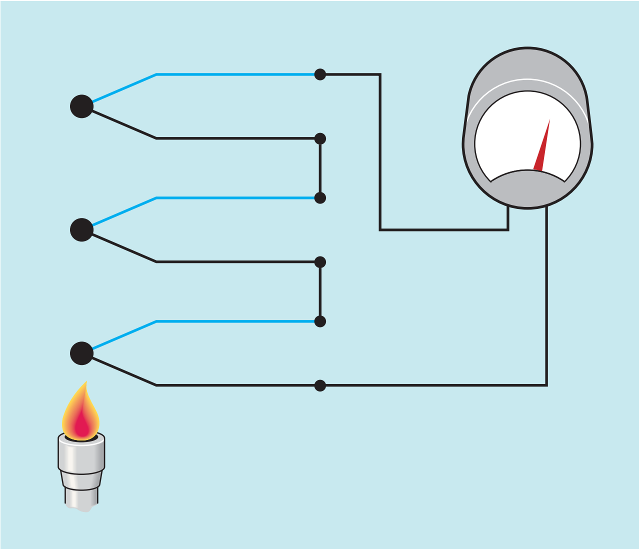


Figure 14–11 Thermopile. (Source: Delmar/Cengage Learning.)

that holds a gas valve open and permits gas to flow to the main burner. If the pilot light should go out, the thermocouple ceases to produce current and the valve closes (Figure 14–12).

Resistance Temperature Detectors

The *resistance temperature detector* (RTD) is made of platinum wire. The resistance of platinum changes greatly with temperature. When platinum is heated, its resistance increases at a very predictable rate; this makes the RTD an ideal device for measuring temperature very accurately. RTDs are used to measure temperatures that range from −328 to +1166 degrees Fahrenheit (−200° to +630°C). RTDs are made in different styles to perform different functions. Figure 14–13 illustrates a typical RTD used as a probe. A very small coil of platinum wire is encased inside a copper tip. Copper is used to provide good thermal contact. This permits the probe to be very fast-acting. The chart in Figure 14–14 shows resistance versus temperature for a typical RTD probe. The temperature is given in degrees Celsius and the resistance is given in ohms. RTDs in two different case styles are shown in Figure 14–15.

Thermistors

The term *thermistor* is derived from the words "thermal resistor." Thermistors are actually thermally sensitive semiconductor devices. There are two basic

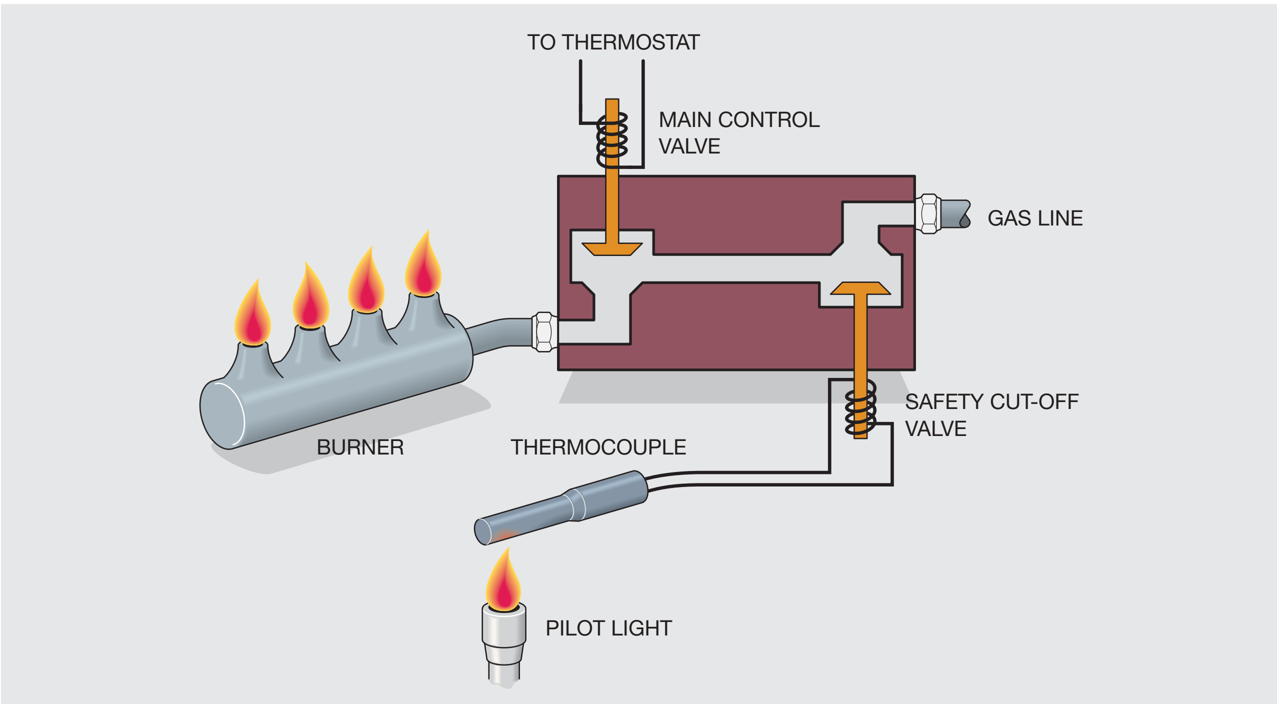


Figure 14–12 A thermocouple provides power to the safety cut-off valve. (Source: Delmar/Cengage Learning.)

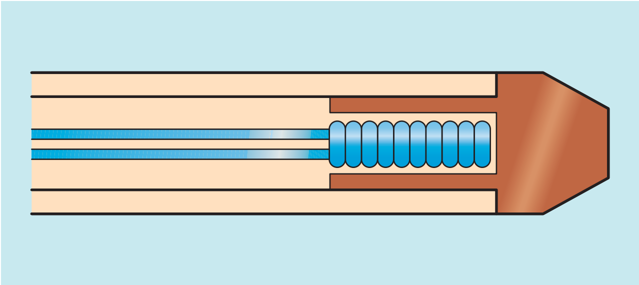


Figure 14–13 Resistance temperature detector. (Source: Delmar/Cengage Learning.)

Degrees C	Resistance (Ω)
0	100
50	119.39
100	138.5
150	157.32
200	175.84
250	194.08
300	212.03
350	229.69
400	247.06
450	264.16
500	280.93
550	297.44
600	313.65

Figure 14–14 Temperature and resistance for a typical RTD. (Source: Delmar/Cengage Learning.)

types of thermistors: one type has a negative temperature coefficient (NTC) and the other has a positive temperature coefficient (PTC). A thermistor that has a negative temperature coefficient will decrease its resistance as the temperature increases. A thermistor that has a positive temperature coefficient will increase its resistance as the temperature increases. The NTC thermistor is the most widely used.

Thermistors are highly nonlinear devices. For this reason they are difficult to use for measuring temperature. Devices that measure temperature with a thermistor must be calibrated for the particular type of thermistor being used. If the thermistor is ever replaced, it has to be an exact replacement or the circuit will no longer operate correctly. Because of their nonlinear characteristics, thermistors are often used as *set point detectors* as opposed to actual temperature measurement. A set point detector is a device that activates some process or circuit when the temperature reaches a certain level. For example, assume a thermistor has been placed inside the stator winding of a motor. If the motor should become overheated, the windings could become severely damaged or destroyed. The thermistor can be used to detect the temperature of the windings. When the temperature reaches a certain point, the resistance value of the thermistor changes enough to cause the starter coil to drop out and disconnect the motor from the line. Thermistors can be operated in temperatures that range from about −100° to +300°F.

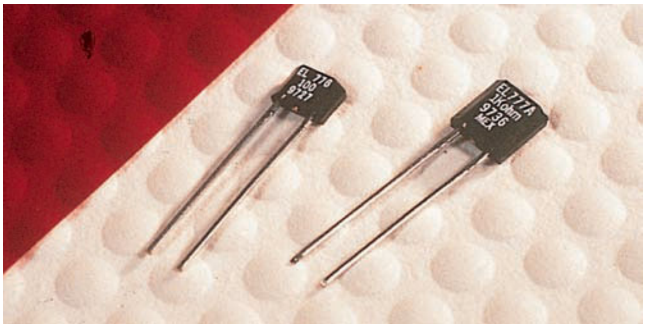


Figure 14–15 RTDs in different case styles. (Courtesy Honeywell's Micro Switch Division.)

One common use for thermistors is in the solid-state starting relays used with small refrigeration compressors (Figure 14–16). Starting relays are used with hermetically sealed motors to disconnect the start windings from the circuit when the motor reaches about 75% of its full speed. Thermistors can be used for this application because they exhibit an extremely rapid change of resistance with a change of temperature. A schematic diagram showing the connection for a solid-state relay is shown in Figure 14–17.

When power is first applied to the circuit, the thermistor is cool and has a relatively low resistance.

Figure 14–16 Solid-state starting relay. (Source: Delmar/Cengage Learning.)

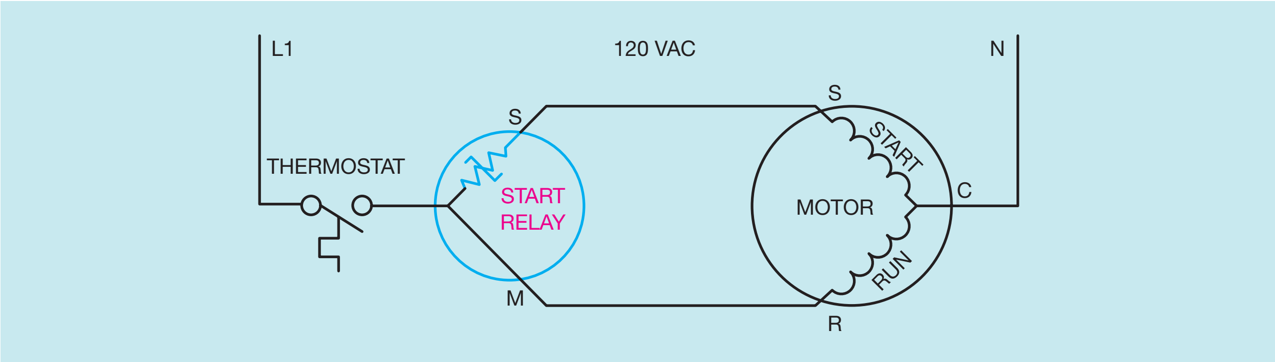


Figure 14–17 Connection of solid-state starting relay. (Source: Delmar/Cengage Learning.)

This permits current to flow through both the start and run windings of the motor. The temperature of the thermistor increases because of the current flowing through it. The increase of temperature causes the resistance to change from a very low value of 3 or 4 ohms to several thousand ohms. This increase of resistance is very sudden and has the effect of opening a set of contacts connected in series with the start winding. Although the start winding is never completely disconnected from the power line, the amount of current flow through it is very small, typically 0.03 to 0.05 amperes, and does not affect the operation of the motor. This small amount of *leakage current* maintains the temperature of the thermistor and prevents it from returning to a low resistance. After power has been disconnected from the motor, a cool-down period of about 2 minutes should be allowed before restarting the motor. This cool-down period is needed for the thermistor to return to a low value of resistance.

The PN Junction

Another device that has the ability to measure temperature is the PN junction, or diode. The diode is becoming a very popular device for measuring temperature because it is accurate and linear.

When a silicon diode is used as a temperature sensor, a constant current is passed through the diode. Figure 14–18 illustrates this type of circuit. In this circuit, resistor R1 limits the current flow through the transistor and sensor diode. The value of R1 also determines the amount of current that flows through the diode. Diode D1 is a 5.1 volt zener used to produce a constant voltage drop between the base and emitter of the PNP transistor. Resistor R2 limits the amount of current flow through the zener diode and the base of the transistor. D1 is a common silicon diode. It is being used as the temperature sensor for the circuit. If a digital voltmeter is connected across the diode, a voltage drop between 0.8 and 0 volts can be seen. The amount of voltage drop is determined by the temperature of the diode.

Another circuit that can be used as a constant current generator is shown in Figure 14–19. In this circuit, a field effect transistor (FET) is used to produce a current generator. Resistor R1 determines the amount of current that will flow through the diode. Diode D1 is the temperature sensor.

If the diode is subjected to a lower temperature, say by touching it with a piece of ice, the voltage drop across the diode will increase. If the diode temperature is increased, the voltage drop will decrease because the

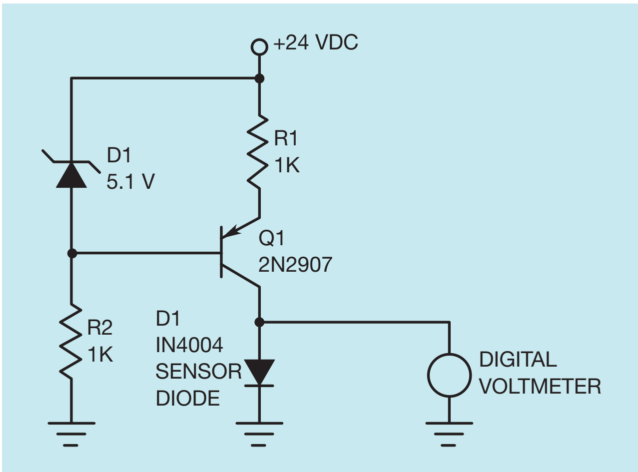


Figure 14–18 Constant current generator. (Source: Delmar/Cengage Learning.)

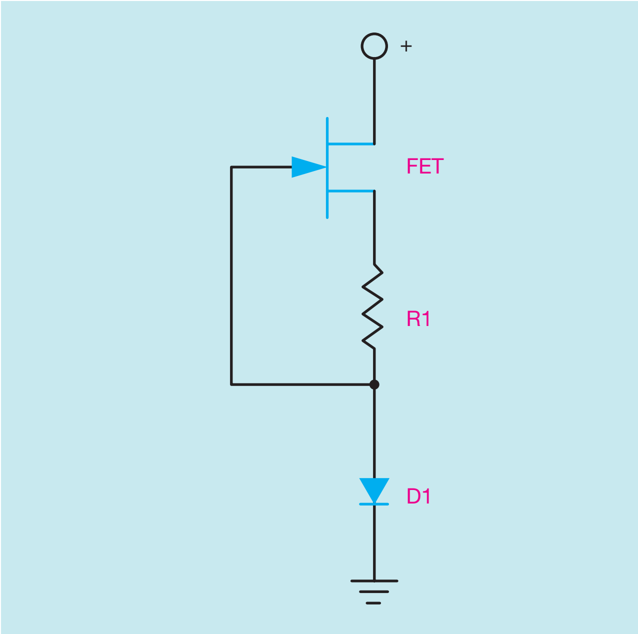


Figure 14–19 Field effect transistor used to produce a constant current generator. (Source: Delmar/Cengage Learning.)

diode has a negative temperature coefficient. As its temperature increases, its voltage drop becomes less.

In Figure 14–20, two diodes connected in a series are used to construct an electronic thermostat. Two diodes are used to increase the amount of voltage drop as the temperature changes. A field effect transistor and resistor are used to provide a constant current to the two diodes used as the heat sensor. An operational amplifier is used to turn a solid-state relay on or off as the temperature changes. In the example shown, the circuit will operate as a heating thermostat. The output of the amplifier will turn on when the temperature decreases sufficiently. The circuit can be converted to a cooling thermostat by reversing the connections of the inverting and noninverting inputs of the amplifier.

Expansion Due to Pressure

Another common method of sensing a change of temperature is by the increase of pressure of some chemicals. Refrigerants confined in a sealed container, for

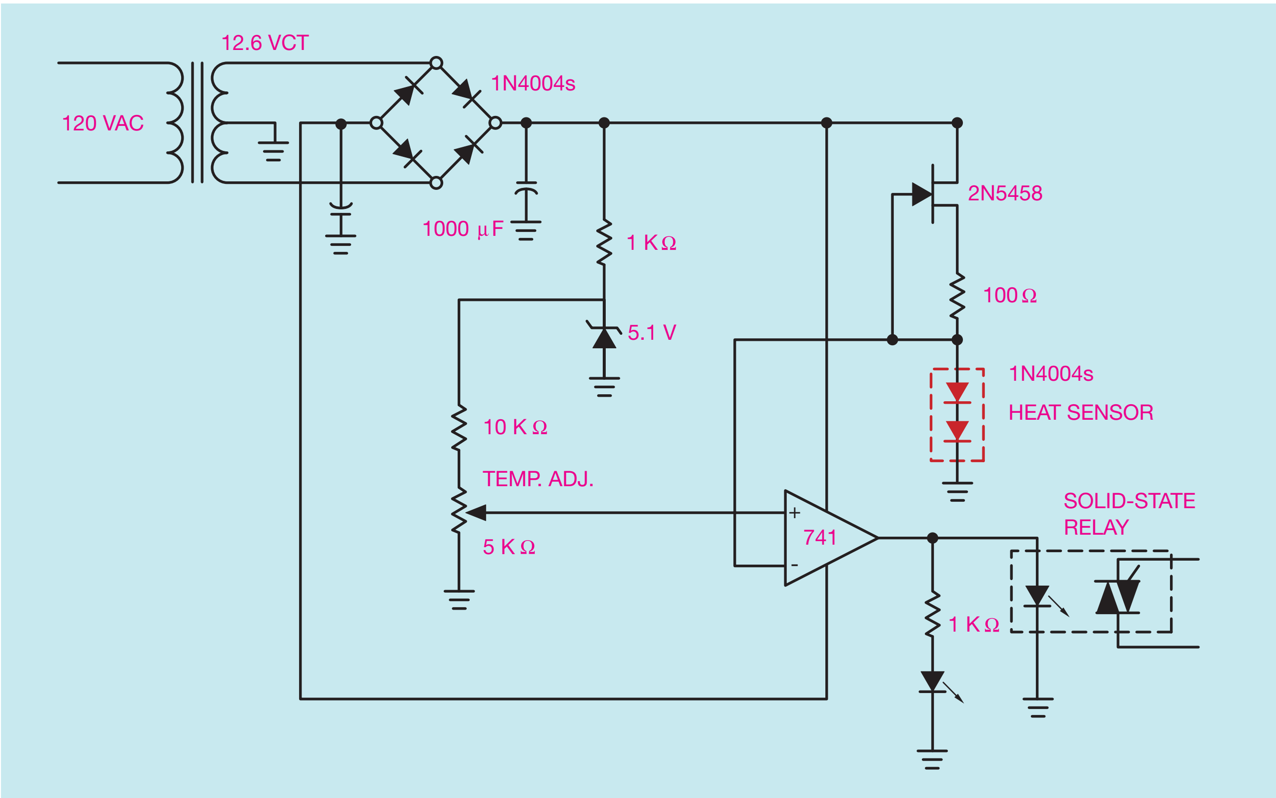


Figure 14–20 Solid-state thermostat using diodes as heat sensors. (Source: Delmar/Cengage Learning.)

example, will increase the pressure in the container with an increase of temperature. If a simple bellows is connected to a line containing refrigerant (Figure 14–21) the bellows will expand as the pressure inside the sealed system increases. When the surrounding air temperature decreases, the pressure inside the system decreases and the bellows contracts. When the air temperature increases, the pressure increases and the bellows expands. If the bellows controls a set of contacts, it becomes a bellows type thermostat. A bellows thermostat and the standard NEMA symbols used to represent a temperature operated switch are shown in Figure 14–22.

Smart Temperature Transmitters

Standard temperature transmitters generally send a 4 to 20 milliampere signal to indicate the temperature. They are calibrated for a specific range of temperature such as 0 to 100 degrees. Standard transmitters are designed to operate with one type of sensor such as RTD, thermocouple, and so on. Any changes to the setting require a recalibration of the unit.

Smart transmitters contain an internal microprocessor and can be calibrated from the control room by sending a signal to the transmitter. It is also possible to check the transmitter for problems from a remote location. A cutaway view of a smart temperature transmitter is shown in Figure 14–23. The transmitter illustrated in Figure 14–23 uses HART (Highway Addressable

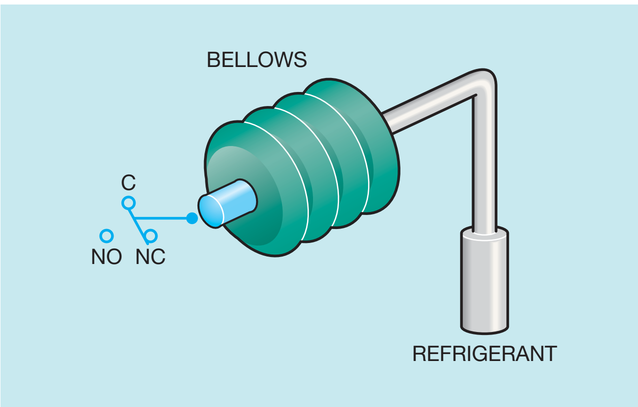


Figure 14–21 Bellows contracts and expands with a change of refrigerant pressure. (Source: Delmar/Cengage Learning.)

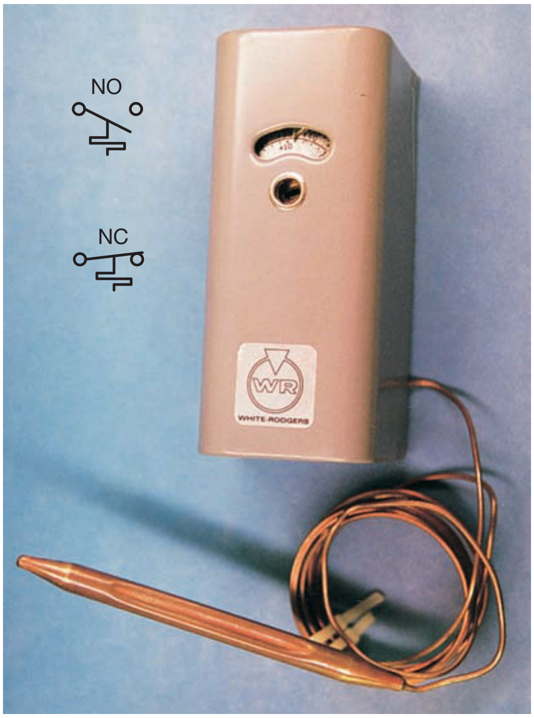


Figure 14–22 Industrial temperature switch. (Source: Delmar/Cengage Learning.)

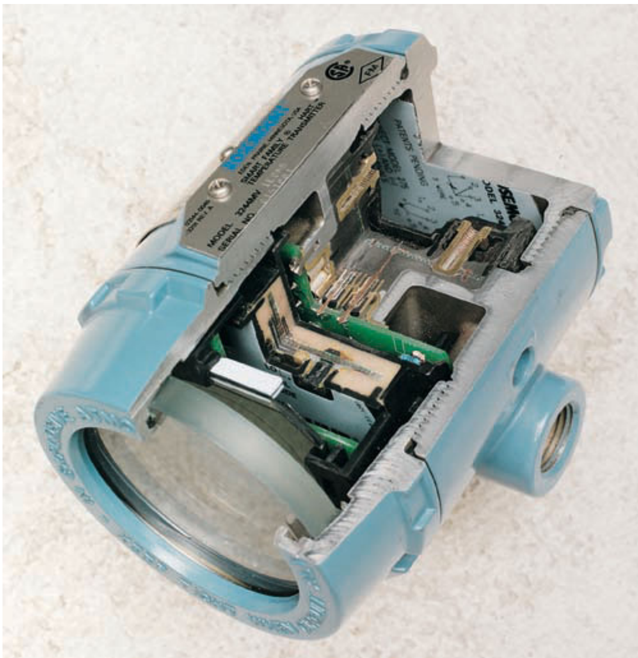


Figure 14–23 Cut-away view of a smart temperature transmitter. (Courtesy © 1998 Rosemount, Inc. used by permission.)

Remote Transducer) protocol. This transmitter can accept RTD, differential RTD, thermocouple, ohm, and millivolt inputs. A smart temperature transmitter with meter is shown in Figure 14–24.

Figure 14–24 Smart temperature transmitter with meter. (Courtesy © 1998 Rosemount, Inc. used by permission.)

Review Questions

1. Should a metal bar be heated or cooled to make it expand?
2. What type of metal remains in a liquid state at room temperature?
3. How is a bimetal strip made?
4. Why are bimetal strips often formed into a spiral shape?
5. Why should electrical contacts never be permitted to open or close slowly?
6. What two factors determine the amount of voltage produced by a thermocouple?
7. What is a thermopile?
8. What do the letters RTD stand for?
9. What type of wire is used to make an RTD?
10. What material is a thermistor made of?
11. Why is it difficult to measure temperature with a thermistor?
12. If the temperature of an NTC thermistor increases, will its resistance increase or decrease?
13. How can a silicon diode be made to measure temperature?
14. Assume that a silicon diode is being used as a temperature detector. If its temperature increases, will its voltage drop increase or decrease?
15. What type of chemical is used to cause a pressure change in a bellows type thermostat?

CHAPTER 15
HALL EFFECT SENSORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the Hall effect.
- Discuss the principles of operation of a Hall generator.
- Discuss applications in which Hall generators can be used.

Principles of Operation

The Hall effect is a simple principle that is widely used in industry today. The Hall effect was discovered by Edwin H. Hall at Johns Hopkins University in 1879. Mr. Hall originally used a piece of pure gold to produce the Hall effect, but today a piece of semiconductor material is used because semiconductor material works better and is less expensive to use. The device is often referred to as the Hall generator.

Figure 15–1 illustrates how the Hall effect is produced. A constant current power supply is connected to opposite sides of a piece of semiconductor material. A sensitive voltmeter is connected to the other two sides. If the current flows straight through the semiconductor material, no voltage is produced across the voltmeter connection.

Figure 15–2 shows the effect of bringing a magnetic field near the semiconductor material. The magnetic field causes the current flow path to be deflected to one side of the material. This causes a potential or voltage to be produced across the opposite sides of the semiconductor material.

If the polarity of the magnetic field is reversed, the current path is deflected in the opposite direction, as shown in Figure 15–3. This causes the polarity of the

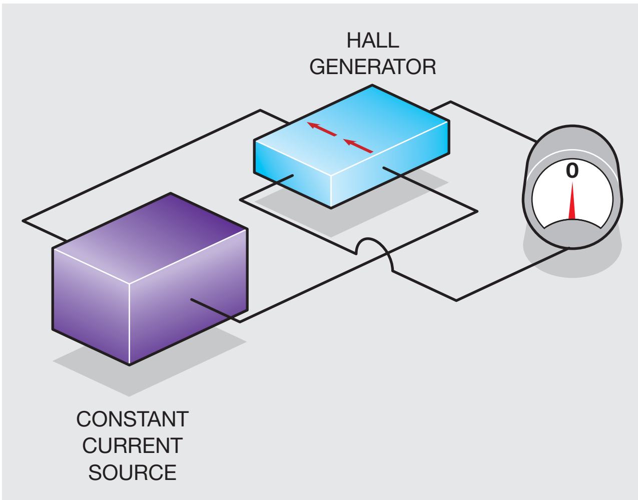


Figure 15–1 Constant current flows through a piece of semiconductor material. (Source: Delmar/Cengage Learning.)

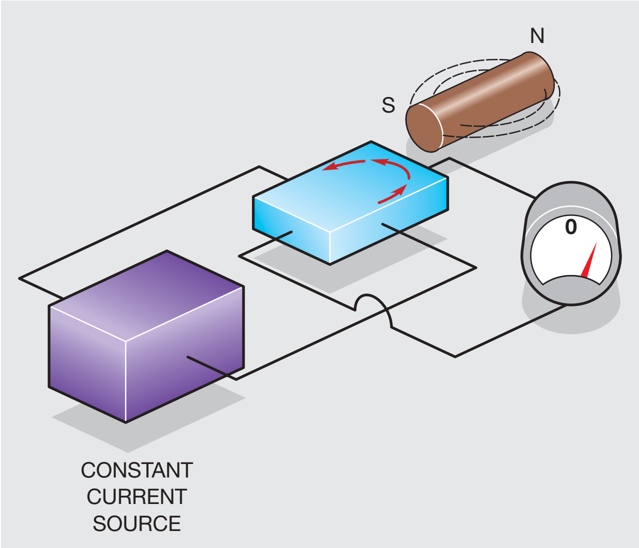


Figure 15–2 A magnetic field deflects the path of current flow through the semiconductor. (Source: Delmar/Cengage Learning.)

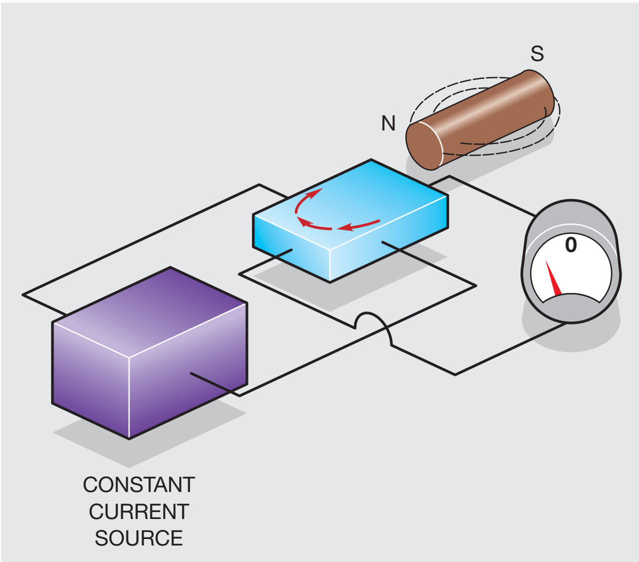


Figure 15–3 The current path is deflected in the opposite direction. (Source: Delmar/Cengage Learning.)

voltage produced by the Hall generator to change. Two factors determine the polarity of the voltage produced by the Hall generator:

1. the direction of current flow through the semiconductor material; and
2. the polarity of the magnetic field used to deflect the current.

The amount of voltage produced by the Hall generator is determined by:

1. the amount of current flowing through the semiconductor material; and
2. the strength of the magnetic field used to deflect the current path.

The Hall generator has many advantages over other types of sensors. Since it is a solid-state device, it has no moving parts or contacts to wear out. It is not affected by dirt, oil, or vibration. The Hall generator is an integrated circuit that is mounted in many different types and styles of cases.

Hall Generator Applications

Motor Speed Sensor

The Hall generator can be used to measure the speed of a rotating device. If a disk with magnetic poles around its circumference is attached to a rotating shaft, and a Hall sensor is mounted near the disk, a voltage will be produced when the shaft turns. Since the disk has alternate magnetic polarities around its circumference, the sensor will produce an AC voltage. Figure 15–4 shows a Hall generator used in this manner. Figure 15–5 shows the AC waveform produced by the rotating disk. The frequency of the AC voltage is proportional to the number of magnetic poles on the disk and the speed of rotation.

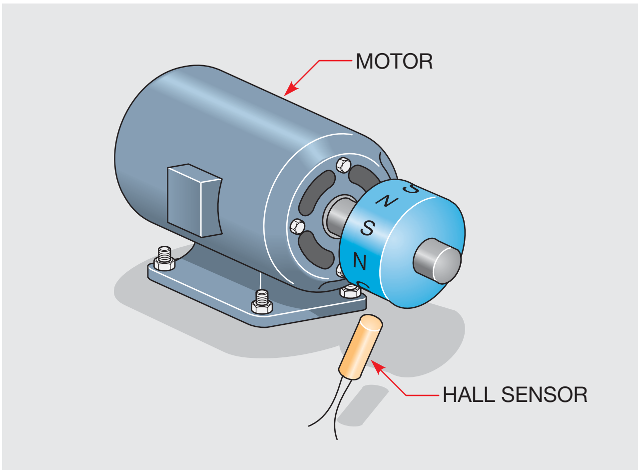


Figure 15–4 An AC voltage is produced by the rotating magnetic disk. (Source: Delmar/Cengage Learning.)

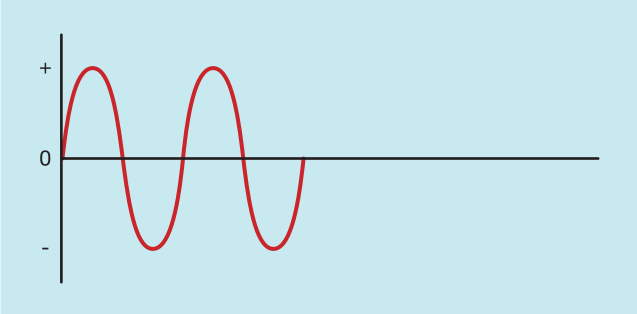


Figure 15–5 Sine Wave. (Source: Delmar/Cengage Learning.)

Another method for sensing speed is to use a *reluctor.* A reluctor is a ferrous metal disk used to shunt a magnetic field away from some other object. This type of sensor uses a notched metal disk attached to a rotating shaft. The disk separates a Hall sensor and a permanent magnet (Figure 15–6). When the notch is between the sensor and the magnet, a voltage is produced by the Hall generator. When the solid metal part of the disk is between the sensor and magnet, the magnetic field is shunted away from the sensor. This causes a significant drop in the voltage produced by the Hall generator.

Since the polarity of the magnetic field does not change, the voltage produced by the Hall generator is pulsating direct current instead of alternating current. Figure 15–7 shows the DC pulses produced by the

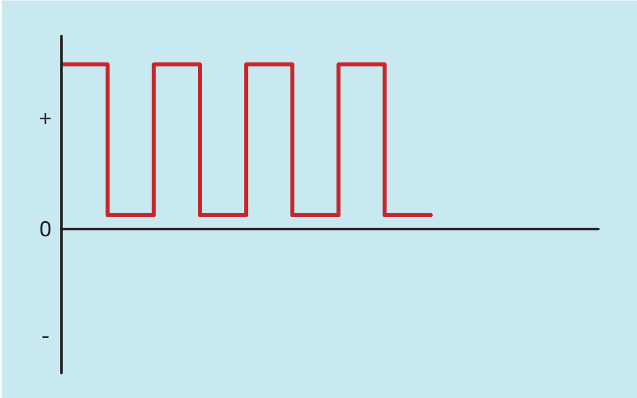


Figure 15–7 Square wave pulses produced by the Hall generator. (Source: Delmar/Cengage Learning.)

generator. The number of pulses produced per second is proportional to the number of notches on the reluctor and the speed of the rotating shaft.

Position Sensor

The Hall generator can be used in a manner similar to a limit switch. If the sensor is mounted beside a piece of moving equipment, and a permanent magnet is attached to the moving equipment, a voltage will be produced when the magnet moves near the sensor (Figure 15–8). The advantages of the Hall sensor are that it has no lever arm or contacts to wear like a common limit switch, so it can operate through millions of operations of the machine.

A Hall effect position sensor is shown in Figure 15–9. Notice that this type of sensor varies in size

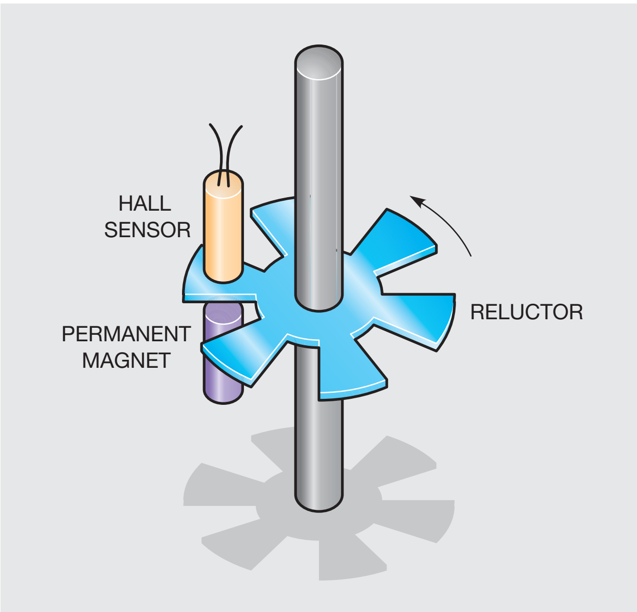


Figure 15–6 Reluctor shunts magnetic field away from sensor. (Source: Delmar/Cengage Learning.)

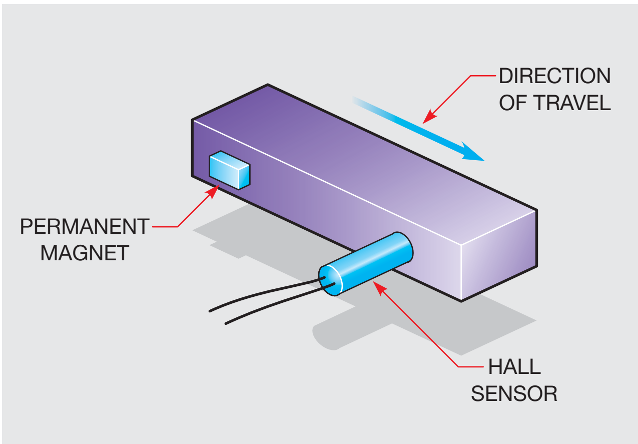


Figure 15–8 Hall generator used to sense position of moving device. (Source: Delmar/Cengage Learning.)

Figure 15–9 Hall effect position sensor. (Courtesy Turck, Inc.)

and style to fit almost any application. Position sensors operate as digital devices in that they sense the presence or absence of a magnetic field. They do not have the ability to sense the intensity of the field.

Hall Effect Limit Switches

Another Hall effect device used in a very similar application is the Hall effect limit switch (Figure 15–10). This limit switch uses a Hall generator instead of a set of contacts. A magnetic plunger is mechanically activated by the small button. Different types of levers can be fitted to the switch, which permits it to be used for many applications.

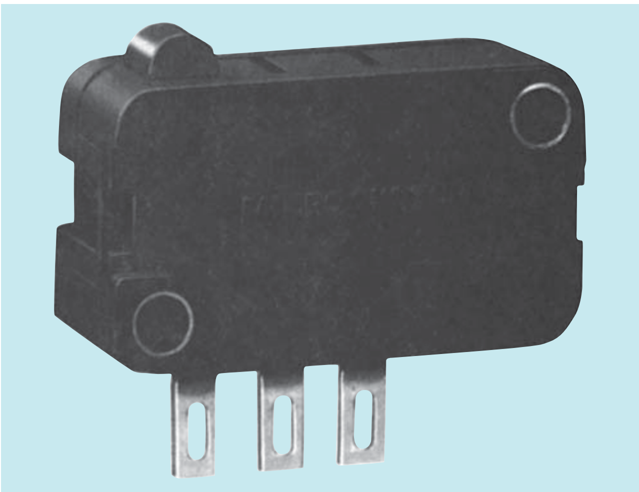


Figure 15–10 Hall effect limit switch. (Courtesy Honeywell's Micro Switch Division.)

These switches are generally intended to be operated by a 5 volt DC supply for TTL (Transistor-Transistor Logic) applications, or by a 6 to 24 volt DC supply for interface with other types of electronic controls or to provide input for programmable controllers.

Current Sensor

Since the current source for the Hall generator is provided by a separate power supply, the magnetic field does not have to be moving or changing to produce an output voltage. If a Hall sensor is mounted near a coil of wire, a voltage will be produced by the generator when current flows through the wire. Figure 15–11 shows a Hall sensor used to detect when a DC current flows through a circuit. A Hall effect sensor is shown in Figure 15–12.

The Hall generator is being used more and more in industrial applications. Since the signal rise and fall time of the Hall generator is generally less than 10 microseconds, it can operate at pulse rates as high

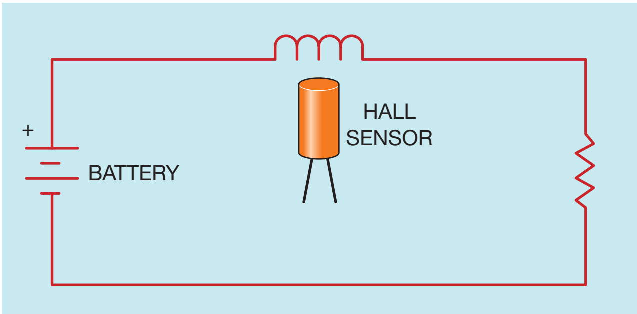


Figure 15–11 Hall sensor detects when DC current flows through the circuit. (Source: Delmar/Cengage Learning.)

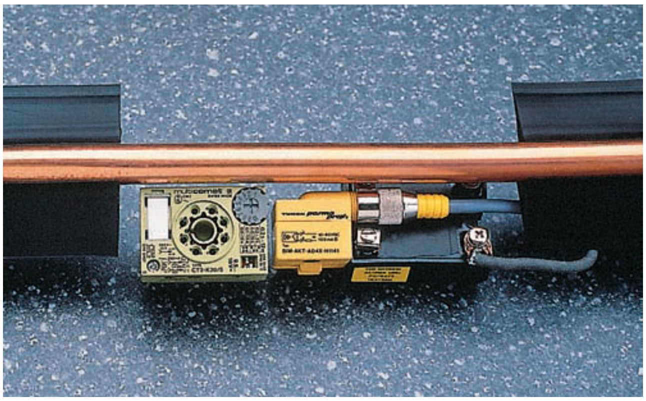


Figure 15–12 Hall effect sensor. (Courtesy Turck, Inc.)

as 100,000 pulses per second. This makes it especially useful in industry.

Linear Transducers

Linear transducers are designed to produce an output voltage that is proportional to the strength of a magnetic field. Input voltage is typically 8 to 16 volts, but the amount of output voltage is determined by the type of transducer used. Hall effect linear transducers can be obtained that have two types of outputs. One type has a *regulated* output and produces voltages of 1.5 to 4.5 volts. The other type has a *ratiometric* output and produces an output voltage that is 25% to 75% of the input voltage. A Hall effect linear transducer is shown in Figure 15–13.

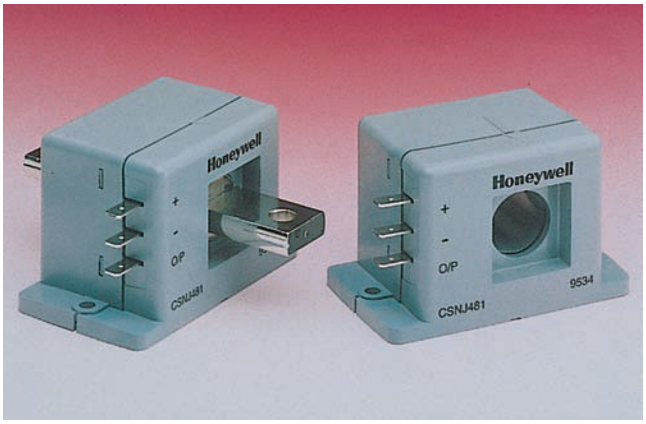


Figure 15–13 Hall effect linear transducer. (Courtesy Honeywell's Micro Switch Division.)

Review Questions

1. What material was used to make the first Hall generator?
2. What two factors determine the polarity of the output voltage produced by the Hall generator?
3. What two factors determine the amount of voltage produced by the Hall generator?
4. What is a reluctor?
5. Why does a magnetic field not have to be moving or changing to produce an output voltage in the Hall generator?

CHAPTER 16
PROXIMITY DETECTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of proximity detectors.
- Describe different types of proximity detectors.

Applications

Proximity detectors are basically metal detectors. They are used to detect the presence or absence of metal without physically touching it. This prevents wear on the unit and gives the detector the ability to sense red hot metals. Most proximity detectors are designed to detect ferrous metals only, but there are some units that detect all metals.

Circuit Operation

There are several methods used to make proximity detectors. One method is shown in Figure 16–1. This is a very simple circuit intended to illustrate the principle of operation of a proximity detector. The sensor coil is connected through a series resistor to an oscillator. A voltage detector, in this illustration a voltmeter, is connected across the resistor. Since AC voltage is applied to this circuit, the amount of current flow is determined by the resistance of the resistor and the inductive reactance of the coil. The voltage drop across the resistor is proportional to its resistance and the amount of current flow.

If ferrous metal is placed near the sensor coil, its inductance increases in value. This causes an increase in inductive reactance and a decrease in the amount of current flow through the circuit. When the current flow through the resistor is decreased, the voltage drop across the resistor decreases also (Figure 16–2). The drop in voltage can be used to turn relays or other devices on or off.

This method of detecting metal does not work well for all conditions. Another method, which is more sensitive to small amounts of metal, is shown in Figure 16–3. This detector uses a tank circuit tuned to the frequency of the oscillator. The sensor head contains two coils instead of one. This type of sensor is a small transformer. When the tank circuit is tuned to the frequency of the oscillator, current flow around the tank loop is high. This causes a high voltage to be induced into the secondary coil of the sensor head.

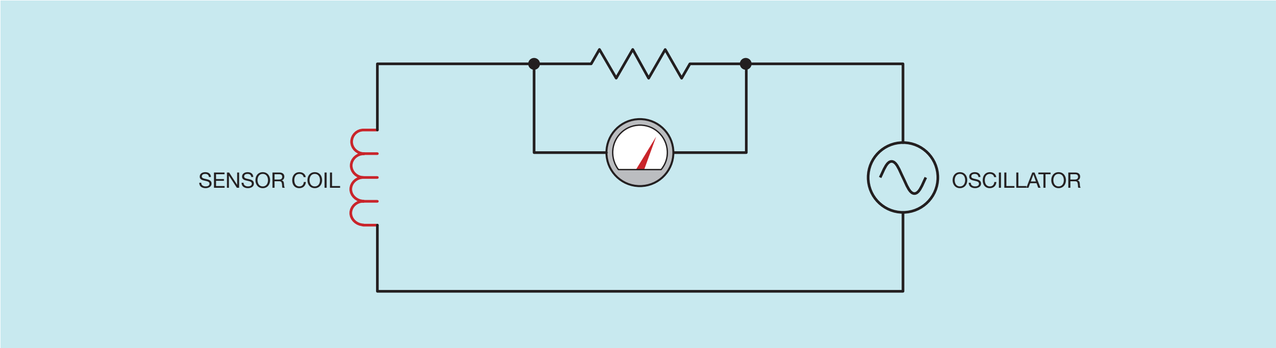


Figure 16–1 Simple proximity detector. (Source: Delmar/Cengage Learning.)

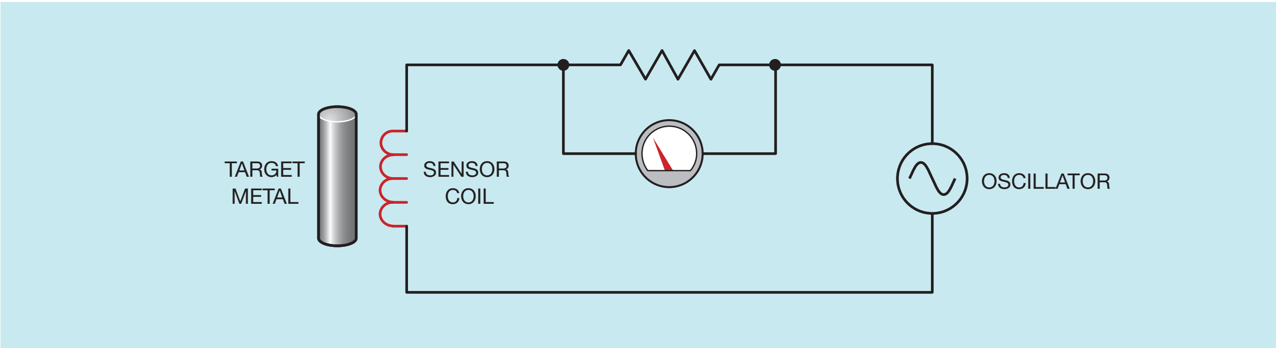


Figure 16–2 The presence of metal causes a decrease of voltage drop across the resistor. (Source: Delmar/Cengage Learning.)

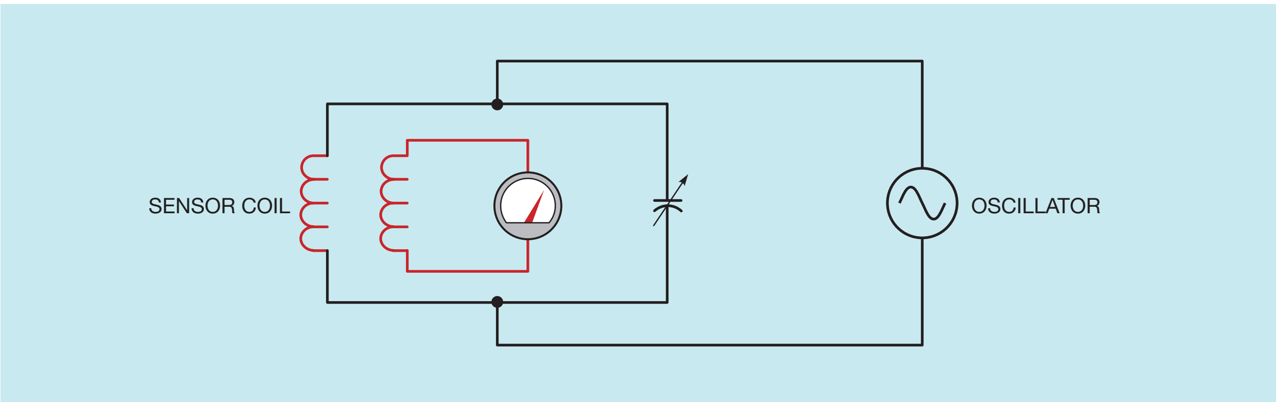


Figure 16–3 Tuned tank circuit used to detect metal. (Source: Delmar/Cengage Learning.)

When ferrous metal is placed near the sensor, as shown in Figure 16–4, the inductance of the coil increases. When the inductance of the coil changes, the tank circuit no longer resonates to the frequency of the oscillator. This causes the current flow around the loop to decrease significantly. The decrease of current flow through the sensor coil causes the secondary voltage to drop, also.

Notice that both types of circuits depend on a ferrous metal to change the inductance of a coil. If a detector is to be used to detect nonferrous metals, some means other than changing the inductance of the coil must be used. An all-metal detector uses a tank circuit as shown in Figure 16–5. All-metal detectors operate at radio frequencies, and the balance of the tank circuit is used to keep the oscillator running. If the tank circuit becomes unbalanced, the oscillator stops operating. When a nonferrous metal, such as aluminum, copper, or brass, is placed near the sensor coil, eddy currents are induced into the surface of the metal. The induction of eddy currents into the metal causes the tank circuit to become unbalanced and the oscillator to stop operating. When the oscillator stops operating, some other part of the circuit signals an output to turn on or off.

All-metal proximity detectors will sense ferrous metals better than nonferrous. A ferrous metal can be sensed at about three times the distance of a nonferrous metal.

Mounting

Some proximity detectors are made as a single unit. Other detectors use a control unit that can be installed in a relay cabinet and a sensor that is mounted at a remote location. Figure 16–6 shows different types of proximity detectors. Regardless of the type of detector

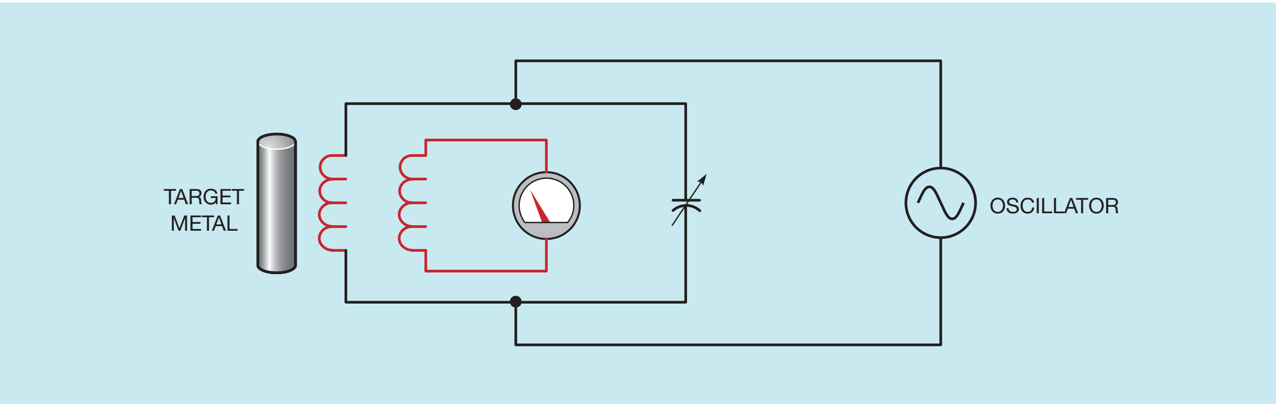


Figure 16–4 The presence of metal detunes the tank circuit. (Source: Delmar/Cengage Learning.)

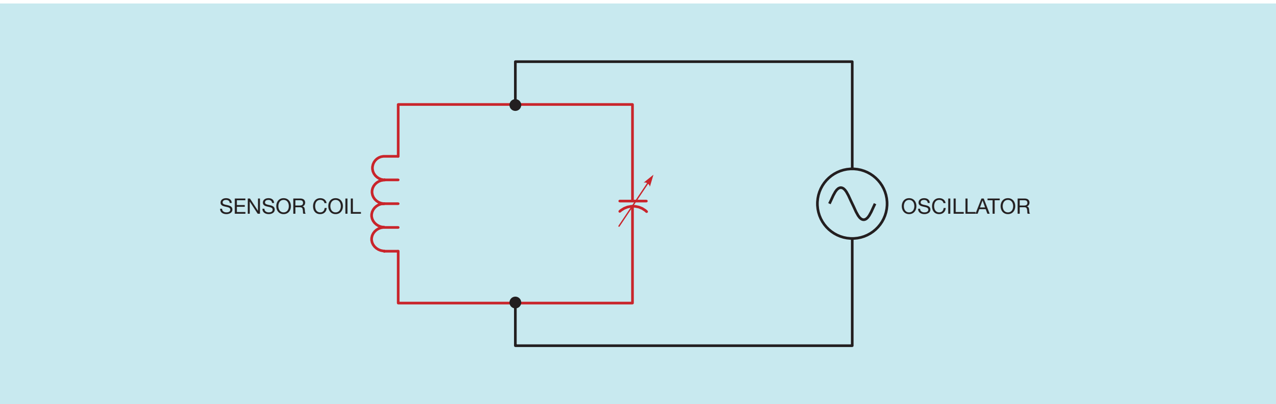


Figure 16–5 Balance of the tank circuit permits the oscillator to operate. (Source: Delmar/Cengage Learning.)

Figure 16–6 Proximity detectors. (Courtesy Turck, Inc.)

Figure 16–7 Capacitive proximity detectors. (Courtesy Turck, Inc.)

used, care and forethought should be used when mounting the sensor. The sensor must be near enough to the target metal to provide a strong positive signal, but it should not be so near that there is a possibility of the sensor being hit by the metal object. One advantage of the proximity detector is that no physical contact is necessary between the detector and the metal object for the detector to sense the object.

Sensors should be mounted as far away from other metals as possible. This is especially true for sensors used with units designed to detect all types of metals. In some cases, it may be necessary to mount the sensor unit on a nonmetal surface such as wood or plastic. If proximity detectors are to be used in areas that contain metal shavings or metal dust, an effort should be made to place the sensor in a position that will prevent the shavings or dust from collecting around it. In some installations, it may be necessary to periodically clean the metal shavings or dust away from the sensor.

Capacitive Proximity Detectors

Although proximity detectors are generally equated with metal detectors, there are other types that sense the presence of objects that do not contain metal of any kind. One type of these detectors operates on a change of capacitance. When an object is brought into the proximity of one of these detectors, a change of capacitance causes the detector to activate. Several different types of capacitive proximity detectors are shown in Figure 16–7.

Since capacitive proximity detectors do not depend on metal to operate, they will sense virtually any material such as wood, glass, concrete, plastic, and sheet rock. They can even be used to sense liquid levels through a sight glass. One disadvantage of capacitive proximity detectors is that they have a very limited range. Most cannot sense objects over approximately one inch or 25 millimeters away. Many capacitive proximity detectors are being used to replace mechanical limit switches since they do not have to make contact with an object to sense its position. Most can be operated with a wide range of voltages such as 2 to 250 volts AC, or 20 to 320 volts DC.

Ultrasonic Proximity Detectors

Another type of proximity detector that does not depend on the presence of metal for operation is the *ultrasonic detector*. Ultrasonic detectors operate by emitting a pulse of high frequency sound and then detecting the echo when it bounces off an object (Figure 16–8). These detectors can be used to determine the distance to the object by measuring the time interval between the emission of the pulse and the return of the echo. Many ultrasonic sensors have an analog output of voltage or current, the value of which is determined by the distance to the object. This feature permits them to be used in applications where it is necessary to sense the position of an object (Figure 16–9). An ultrasonic proximity detector is shown in Figure 16–10.

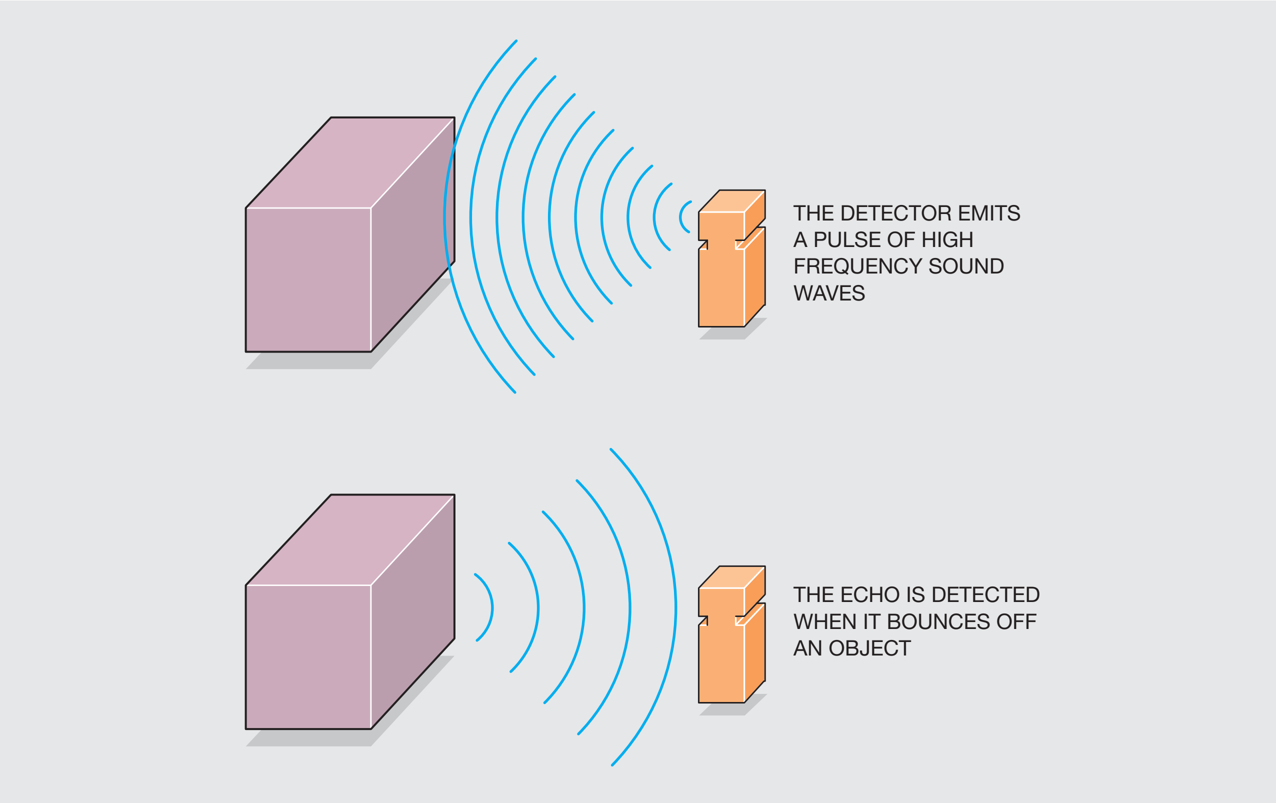


Figure 16–8 Ultrasonic proximity detectors operate by emitting high frequency sound waves. (Source: Delmar/Cengage Learning.)

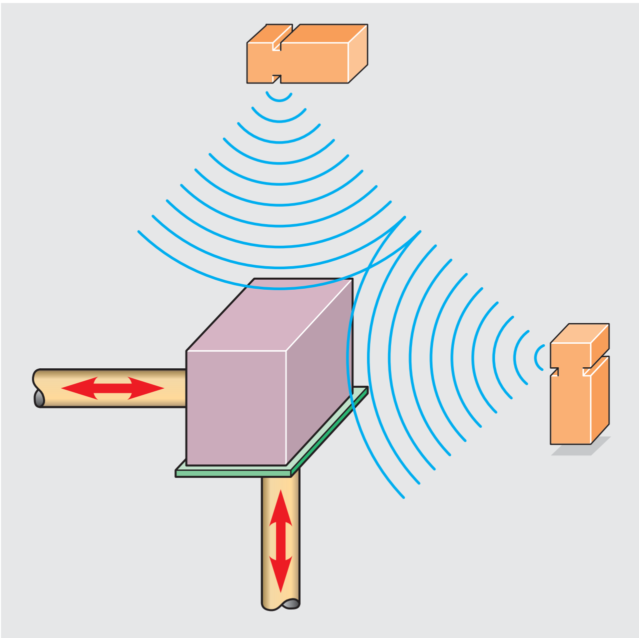


Figure 16–9 Ultrasonic proximity detectors used as position sensors. (Source: Delmar/Cengage Learning.)

Figure 16–10 Ultrasonic proximity detector. (Courtesy Turck, Inc.)

Review Questions

1. Proximity detectors are basically ________________ ____.
2. What is the basic principle of operation used with detectors designed to detect only ferrous metals?
3. What is the basic principle of operation used with detectors designed to detect all types of metals?
4. What type of electric circuit is used to increase the sensitivity of the proximity detector?
5. What type of proximity detector uses an oscillator that operates at radio frequencies?
6. Name two types of proximity detectors that can be used to detect objects not made of metal.
7. What is the maximum range at which most capacitive proximity detectors can be used to sense an object?
8. How is it possible for an ultrasonic proximity detector to measure the distance to an object?

CHAPTER 17
PHOTODETECTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- List different devices used as light sensors.
- Discuss the advantages of photo-operated controls.
- Describe different methods of installing photodetectors.

Applications

Photodetectors are widely used in today's industry. They can be used to sense the presence or absence of almost any object. Photodetectors do not have to make physical contact with the object they are sensing, so there is no mechanical arm to wear out. Many photodetectors can operate at speeds that cannot be tolerated by mechanical contact switches. They are used in almost every type of industry, and their uses are increasing steadily.

Types of Detectors

Photo-operated devices fall into one of three categories: photovoltaic, photoemissive, and photoconductive.

Photovoltaic

Photovoltaic devices are more often called solar cells. They are usually made of silicon and have the ability to produce a voltage in the presence of light. The amount of voltage produced by a cell is determined by the material it is made of. When silicon is used, the solar cell produces 0.5 volts in the presence of direct sunlight. If there is a complete circuit connected to the cell, current will flow through the circuit. The amount of current produced by a solar cell is determined by the surface area of the cell. For instance, assume a solar cell has a surface area of 1 square inch, and another cell has a surface area of 4 square inches. If both cells are made of silicon, both will produce 0.5 volts when in direct sunlight. The larger cell, however, will produce four times as much current as the small one.

Figure 17–1 shows the schematic symbol for a photovoltaic cell. Notice that the symbol is the same as

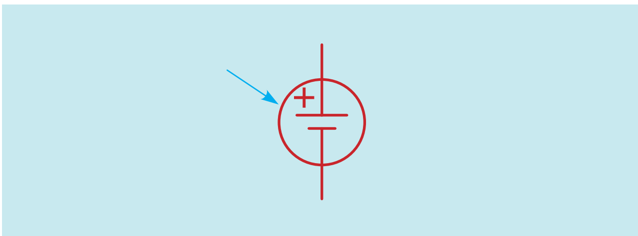


Figure 17–1 Schematic symbol for a photovoltaic cell. (Source: Delmar/Cengage Learning.)

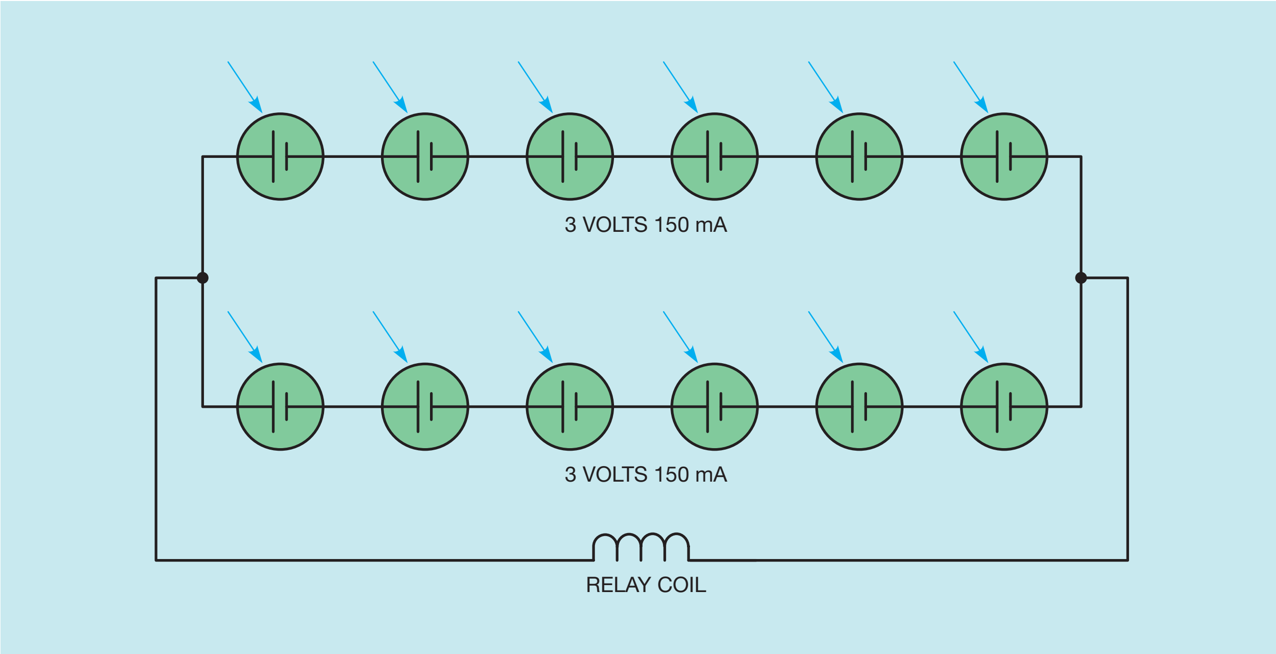


Figure 17–2 Series-parallel connection of solar cells produces 3 volts at 300 milliamperes. (Source: Delmar/Cengage Learning.)

the symbol used to represent a single cell battery except for the arrow pointing toward it. The battery symbol means the device has the ability to produce a voltage, and the arrow means that it must receive light to do so.

Photovoltaic cells have the advantage of being able to operate electrical equipment without external power. Since silicon solar cells produce only 0.5 volt, it is often necessary to connect several of them together to obtain enough voltage and current to operate the desired device. For example, assume that solar cells are to be used to operate a DC relay coil that requires 3 volts at 250 milliamperes. Now assume that the solar cells to be used have the ability to produce 0.5 volt at 150 milliamperes. If six solar cells are connected in series, they will produce 3 volts at 150 milliamperes (Figure 17–2). The voltage produced by the connection is sufficient to operate the relay, but the current capacity is not. Therefore, six more solar cells must be connected in series. This connection is then connected parallel to the first connection, producing a circuit that has a voltage rating of 3 volts and a current rating of 300 milliamperes, which is sufficient to operate the relay coil.

Photoemissive Devices

Photoemissive devices emit electrons when in the presence of light. They include such devices as the phototransistor, the photodiode, and the photo-SCR. The schematic symbols for these devices are shown in Figure 17–3. The emission of electrons is used to turn these solid-state components on. The circuit in Figure 17–4 shows a phototransistor used to turn on a

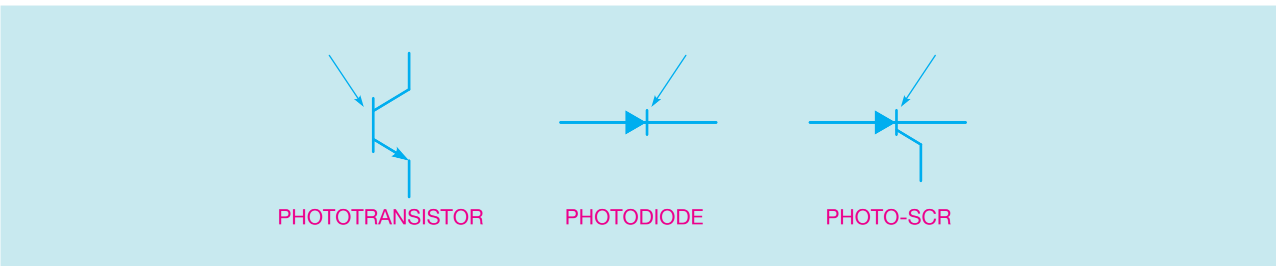


Figure 17–3 Schematic symbols for the phototransistor, the photodiode, and the photo-SCR. (Source: Delmar/Cengage Learning.)

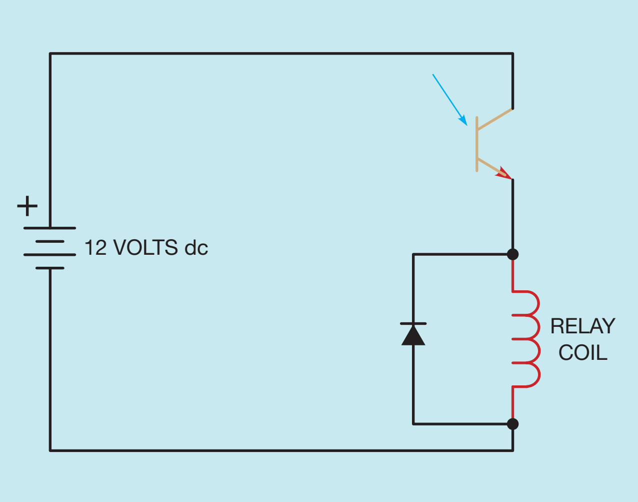


Figure 17–4 Phototransistor controls relay coil. (Source: Delmar/Cengage Learning.)

relay coil. When the phototransistor is in darkness, no electrons are emitted by the base junction, and the transistor is turned off. When the phototransistor is in the presence of light, it turns on and permits current to flow through the relay coil. The diode connected parallel to the relay coil is known as a kickback, or freewheeling, diode. Its function is to prevent induced voltage spikes from occurring if the current suddenly stops flowing through the coil and the magnetic field collapses.

In the circuit shown in Figure 17–4, the relay coil will turn on when the phototransistor is in the presence of light, and turn off when the phototransistor is in darkness. Some circuits may require the reverse operation. This can be accomplished by adding a resistor and a junction transistor to the circuit (Figure 17–5). In this circuit, a common junction transistor is used to control the current flow through the relay coil. Resistor R1 limits the current flow through the base of the junction transistor. When the phototransistor is in darkness, it has a very high resistance. This permits current to flow to the base of the junction transistor and turn it on. When the phototransistor is in the presence of light, it turns on and connects the base of the junction transistor to the negative side of the battery. This causes the junction transistor to turn off. The phototransistor in the circuit is used as a *stealer* transistor. A stealer transistor steals the base current away from some other transistor to keep it turned off.

Some circuits may require the phototransistor to have a higher gain than it has under normal conditions. This can be accomplished by using the phototransistor as the driver for a Darlington amplifier circuit, Figure 17–6. A Darlington amplifier circuit generally has a gain of over 10,000.

Photodiodes and photo-SCRs are used in circuits similar to those shown for the phototransistor. The photodiode will permit current to flow through it in the presence of light. The photo-SCR has the same operating characteristics as a common junction SCR. The only difference is that light is used to trigger the gate when using a photo-SCR.

Regardless of the type of photoemissive device used or the type of circuit it is used in, the greatest advantage of the photoemissive device is speed. A photoemissive device can turn on or off in a few

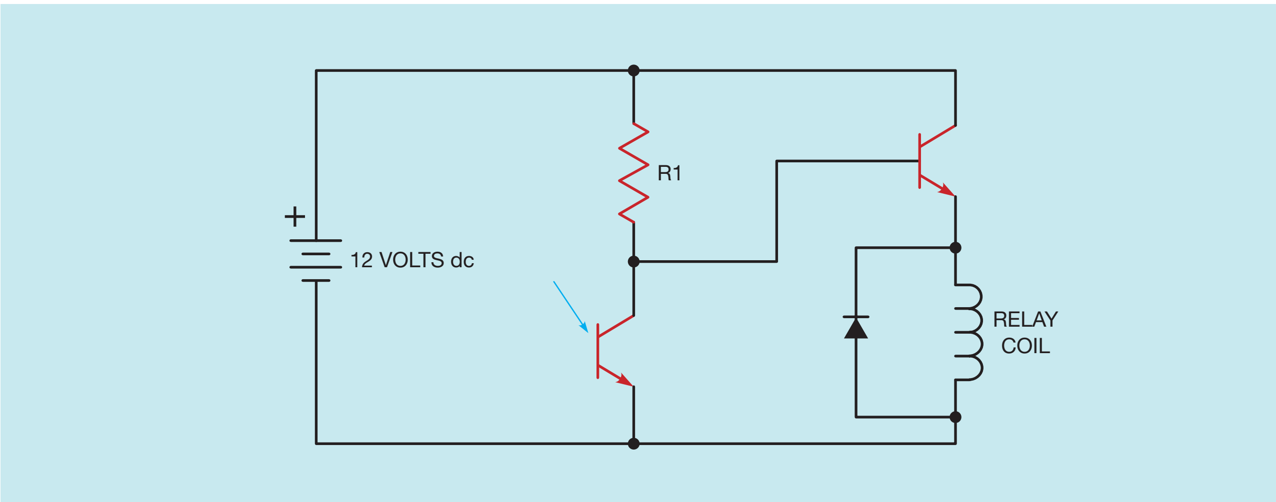


Figure 17–5 The relay turns on when the phototransistor is in darkness. (Source: Delmar/Cengage Learning.)

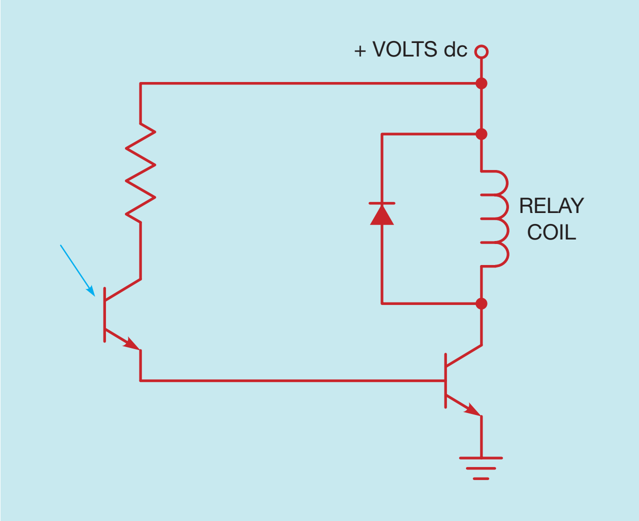


Figure 17–6 The phototransistor is used as the driver for a Darlington Amplifier. (Source: Delmar/Cengage Learning.)

Figure 17–8 Cad cell. (Source: Delmar/Cengage Learning.)

microseconds. Photovoltaic or photoconductive devices generally require several milliseconds to turn on or off. This makes the use of photoemissive devices imperative in high speed switching circuits.

Photoconductive Devices

Photoconductive devices exhibit a change of resistance due to the presence or absence of light. The most common photoconductive device is the cadmium sulfide cell, or cad cell. A cad cell has a resistance of about 50 ohms in direct sunlight and several hundred thousand ohms in darkness. It is generally used as a light sensitive switch. The schematic symbol for a cad cell is shown in Figure 17–7. Figure 17–8 shows a typical cad cell.

Figure 17–9 shows a basic circuit of a cad cell being used to control a relay. When the cad cell is in darkness, its resistance is high. This prevents the amount of current needed to turn the relay on from flowing through

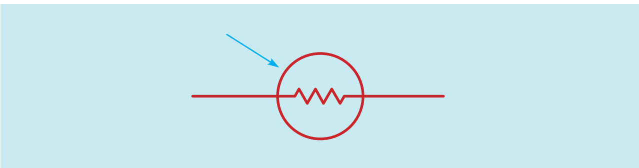


Figure 17–7 Schematic symbol for a cad cell. (Source: Delmar/Cengage Learning.)

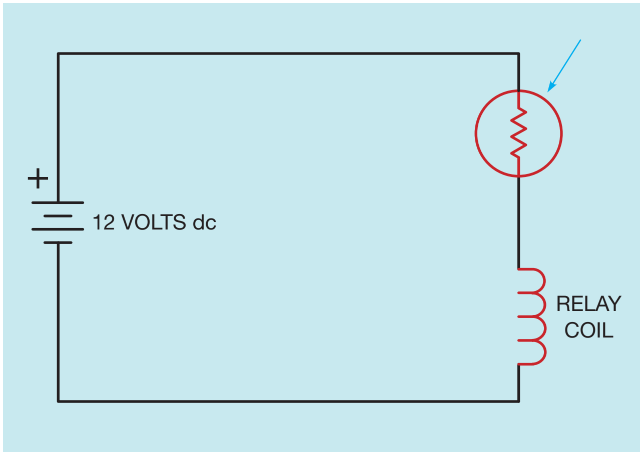


Figure 17–9 Cad cell controls relay coil. (Source: Delmar/Cengage Learning.)

the circuit. When the cad cell is in the presence of light, its resistance is low. The amount of current needed to operate the relay can now flow through the circuit.

Although this circuit will work if the cad cell is large enough to handle the current, it has a couple of problems:

1. There is no way to adjust the sensitivity of the circuit. Photo-operated switches are generally located in many different areas of a plant. The surrounding light intensity can vary from one area to another. It is, therefore, necessary to be able to adjust the sensor for the amount of light needed to operate it.

2. The sense of operation of the circuit cannot be changed. The circuit shown in Figure 17–9 permits the relay to turn on when the cad cell is in the presence of light. There may be conditions that would make it desirable to turn the relay on when the cad cell is in darkness.

Figure 17–10 shows a photodetector circuit that uses a cad cell as the sensor and an operational amplifier (op amp) as the control circuit. The circuit operates as follows: Resistor R1 and the cad cell form a voltage divider circuit, which is connected to the inverting input of the amplifier. Resistor R2 is used as a potentiometer to preset a positive voltage at the noninverting input. This control adjusts the sensitivity of the circuit. Resistor R3 limits the current to a light-emitting diode (LED). The LED is mounted on the outside of the case of the photodetector and is used to indicate when the relay coil is energized. Resistor R4 limits the base current to the junction transistor. The junction transistor is used to control the current needed to operate the relay coil. Many op amps do not have enough current rating to control this amount of current. Diode D1 is used as a kickback diode.

Assume that Resistor R2 has been adjusted to provide a potential of 6 volts at the noninverting input. When the cad cell is in the presence of light, it has a low resistance, and a potential less than 6 volts is applied to the inverting input. Since the noninverting input has a higher positive voltage connected to it, the output is high also. When the output of the op amp is high, the LED and the transistor are turned on.

When the cad cell is in the presence of darkness, its resistance increases. When its resistance becomes greater than 4.7 kilohms, a voltage greater than 6 volts is applied to the inverting input. This causes the output of the op amp to change from a high state to a low state, and to turn the LED and transistor off. Notice in this circuit that the relay is turned on when the cad cell is in the presence of light, and turned off when it is in darkness.

Figure 17–11 shows a connection that will reverse the operation of the circuit. The potentiometer has been reconnected to the inverting input, and the voltage divider circuit has been connected to the noninverting input. To understand the operation of this circuit, assume that a potential of 6 volts has been preset at the inverting input.

When the cad cell is in the presence of light, it has a low resistance, and a voltage less than 6 volts is applied to the noninverting input. Since the inverting input has a greater positive voltage connected to it, the output is low and the LED and the transistor are turned off.

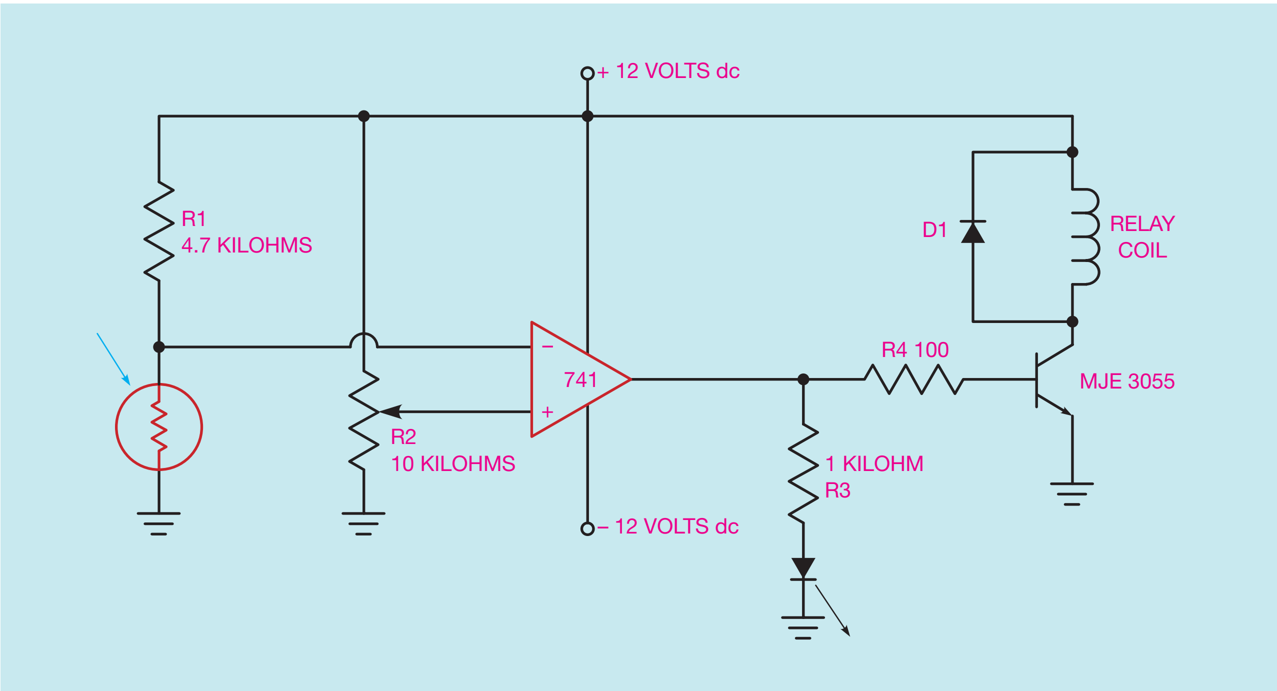


Figure 17–10 The relay coil is energized when the cad cell is in the presence of light. (Source: Delmar/Cengage Learning.)

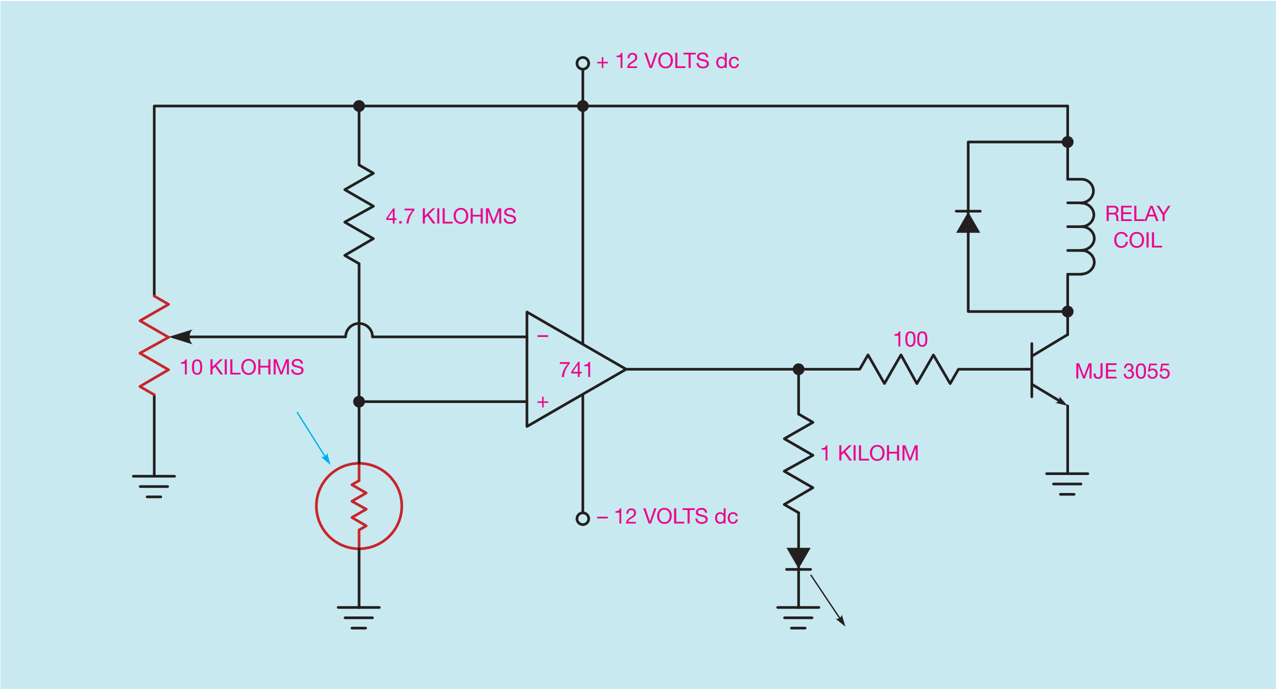


Figure 17–11 The relay is energized when the cad cell is in darkness. (Source: Delmar/Cengage Learning.)

When the cad cell is in darkness, its resistance becomes greater than 4.7 kilohms, and a voltage greater than 6 volts is applied to the noninverting input. This causes the output of the op amp to change to a high state that turns on the LED and transistor. Notice that this circuit turns the relay on when the cad cell is in darkness and off when it is in the presence of light.

Mounting

Photodetectors designed for industrial use are made to be mounted and used in different ways. There are two basic types of photodetectors: one type has separate transmitter and receiver units; the other type has both units mounted in the same housing. The type used is generally determined by the job requirements. The transmitter section is the light source, which is generally a long life incandescent bulb. There are photodetectors, however, that use an infrared transmitter. These cannot be seen by the human eye and are often used in burglar alarm systems. The receiver unit houses the photodetector and, generally, the circuitry required to operate the system.

Figure 17–12 shows a photodetector used to detect the presence of an object on the conveyor line. When the object passes between the transmitter and receiver units, the light beam is broken and the detector activates. Notice that no physical contact is necessary

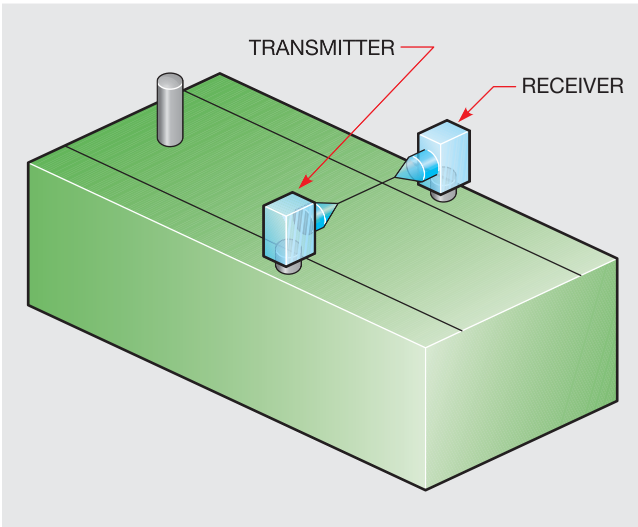


Figure 17–12 Photodetector senses presence of object on conveyor line. (Source: Delmar/Cengage Learning.)

for the photodetector to sense the presence of the object.

Figure 17–13 illustrates another method of mounting the transmitter and receiver. In this example, an object is sensed by reflecting light off of a shiny surface. Notice that the transmitter and receiver must be mounted at the same angle with respect to the object to be sensed. This type of mounting will only work with objects that have the same height, such as cans on a conveyor line.

Photodetectors that have both the transmitter and the receiver units mounted in the same housing depend on a reflector for operation. Figure 17–14 shows this type of unit mounted on a conveyor line. The transmitter is aimed at the reflector. The light beam is reflected back to the receiver. When an object passes between the photodetector unit and the reflector, the light to the receiver is interrupted. This type of unit has the advantage of needing electrical connection at only one piece of equipment. This permits easy mounting of the photodetector unit and mounting of the reflector in hard to reach positions that would make running control wiring difficult. Many of these units have a range of 20 feet and more.

Another type of unit that operates on the principle of reflected light uses an optical fiber cable. The fibers in the cable are divided in half. One half of the fibers are connected to the transmitter, and the other half are connected to the receiver (Figure 17–15). This unit has the advantage of permitting the transmitter and the receiver to be mounted in a very small area. Figure 17–16 illustrates a common use for this type of unit. The unit is used to control a label-cutting machine. The labels are printed on a large roll and must be cut for individual packages. The label roll contains a narrow strip on one side that is dark colored except for shiny sections spaced at regular intervals. The optical fiber cable is located above this narrow strip. When the dark

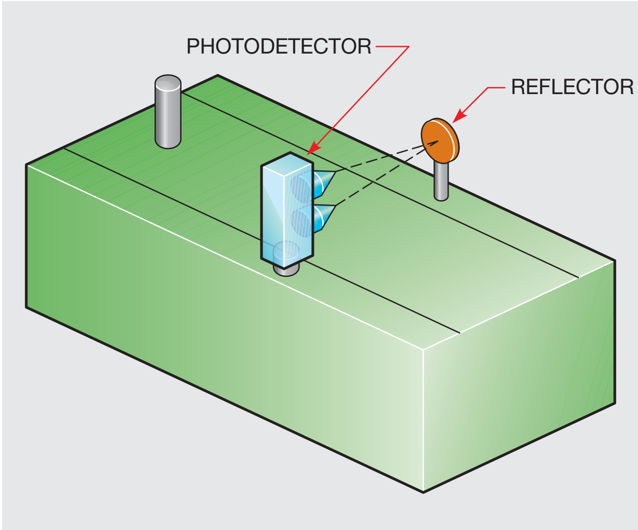


Figure 17–14 The object is sensed when it passes between the photodetector and the reflector. (Source: Delmar/Cengage Learning.)

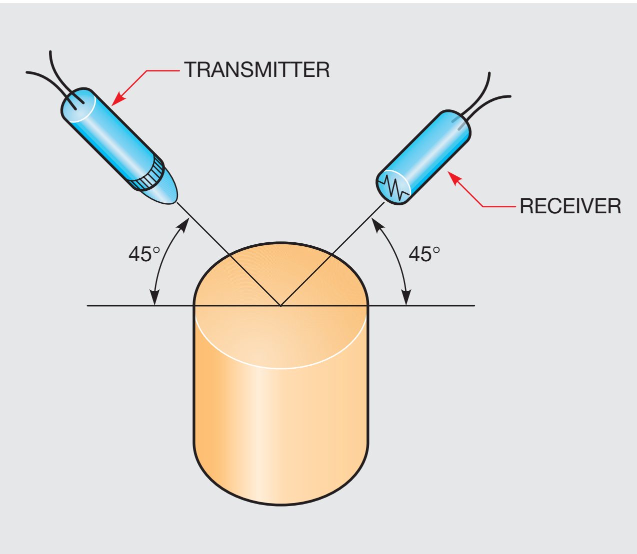


Figure 17–13 Object is sensed by reflecting light off a shiny surface. (Source: Delmar/Cengage Learning.)

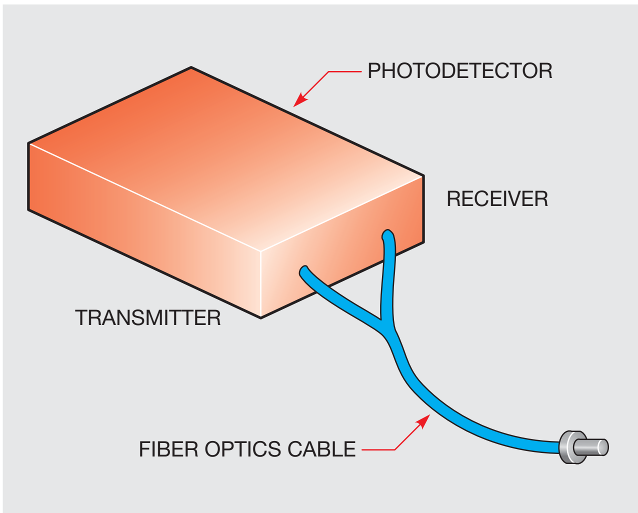


Figure 17–15 Optical cable is used to transmit and receive light. (Source: Delmar/Cengage Learning.)

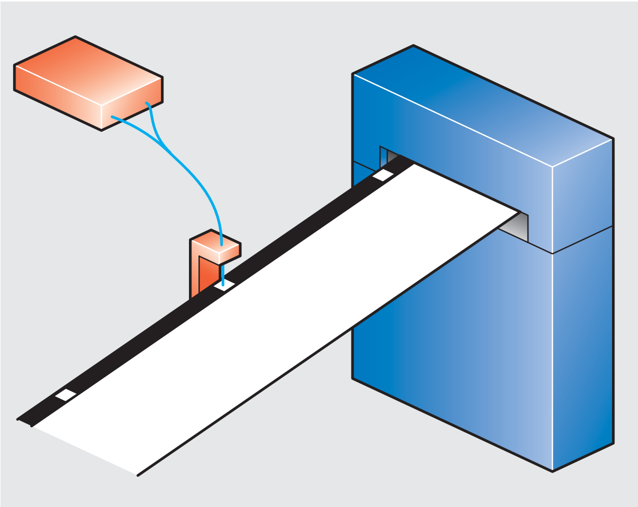


Figure 17–16 Optical cable detects shiny area on one side of label. (Source: Delmar/Cengage Learning.)

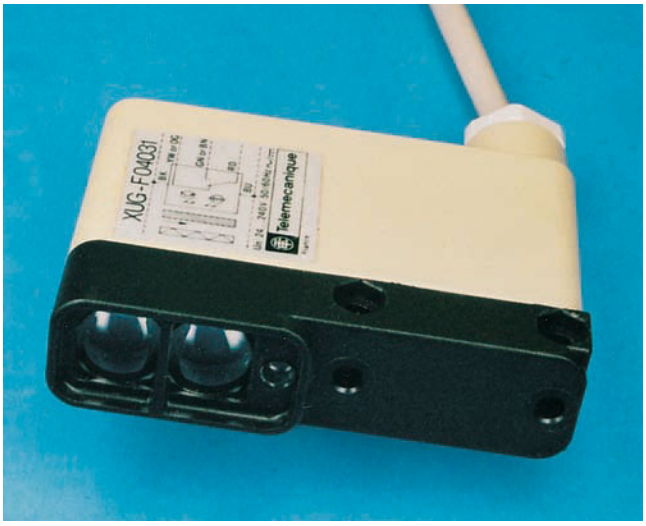


Figure 17–17 Photodetector unit with both transmitter and receiver units. (Source: Delmar/Cengage Learning.)

surface of the strip is passing beneath the optical cable, no reflected light returns to the receiver unit. When the shiny section passes beneath the cable, light is reflected back to the receiver unit. The photodetector sends a signal to the control circuit and tells it to cut the label.

Photodetectors are very dependable and have an excellent maintenance and service record. They can be used to sense almost any object without making physical contact with it, and can operate millions of times without damage or wear. A photodetector is shown in Figure 17–17.

Review Questions

1. List the three major categories of photodetectors.
2. In which category does the solar cell belong?
3. In which category do phototransistors and photodiodes belong?
4. In which category does the cad cell belong?
5. The term cad cell is a common name for what device?
6. What is the function of the transmitter in a photodetector unit?
7. What is the advantage of a photodetector that uses a reflector to operate?
8. An object is to be detected by reflecting light off a shiny surface. If the transmitter is mounted at a 60 degree angle, at what angle must the receiver be mounted?
9. How much voltage is produced by a silicon solar cell?
10. What determines the amount of current a solar cell can produce?

CHAPTER 18
BASIC CONTROL CIRCUITS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of a two-wire control circuit.
- Describe the operation of a three-wire control circuit.

Control circuits can be divided into two major types: two-wire control circuits and three-wire control circuits. A two-wire control circuit can be a simple switch that makes or breaks connection to a motor (Figure 18–1). A good example of this type of control is the single-phase manual starter shown in Figure 3–1. Two-wire control circuits also control the operation of three-phase motors by controlling the power applied to the motor starter coil. A good example of this type of control is an air compressor (Figure 18–2). The

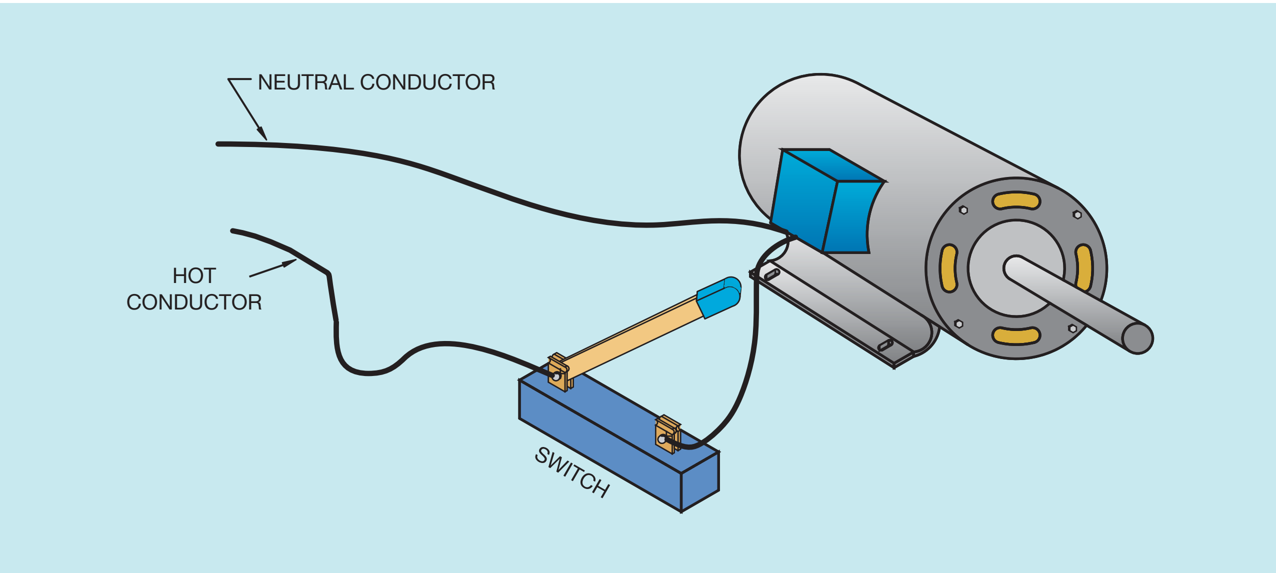


Figure 18–1 A two-wire control can be a simple switch that controls a motor. (Source: Delmar/Cengage Learning.)

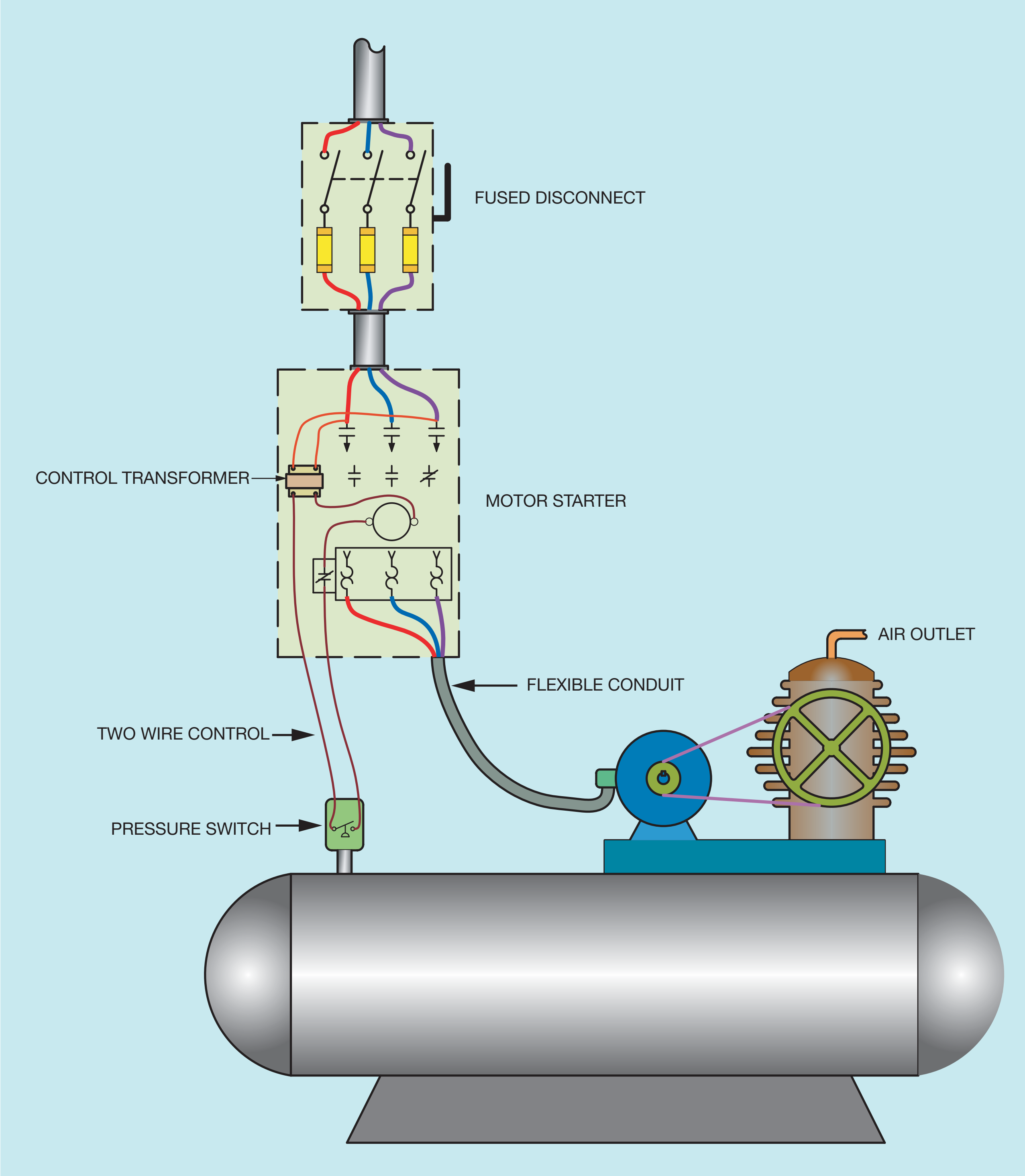


Figure 18–2 The motor starter is controlled by running two wires to a pressure switch. (Source: Delmar/Cengage Learning.)

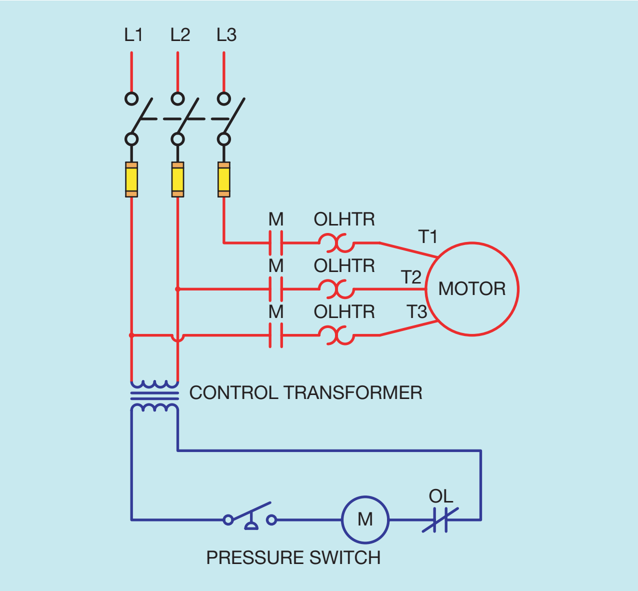


Figure 18–3 Schematic diagram of the circuit shown in Figure 18–2. (Source: Delmar/Cengage Learning.)

pressure switch is used to control the motor starter. A schematic diagram of the circuit in Figure 18–2 is shown in Figure 18–3. Two-wire control circuits are so named because only two wires are required to control the operation of the circuit. Two-wire circuits may incorporate several different external sensing devices, as shown in Figure 18–4. This circuit is a basic control for a hot water boiler. The thermostat controls the action of the burner. Two float switches are used to sense low and high water conditions in the boiler. A high limit temperature switch will stop the burner if the water temperature should become excessive.

It is not unusual for two-wire control circuits to use line voltage controls. Line voltage controls are simply controls that do not employ the use of a control transformer to change the voltage to a lower value. The coils of motor starters and contactors are available that operate at different voltages. Common voltage values for motor starter coils (in volts AC) are: 24, 120, 208, 240, 277, 480, and 560. A two-wire line voltage control circuit is shown in Figure 18–5.

Three-Wire Control Circuits

Three-wire control circuits are characterized by the use of momentary contact devices such as push buttons. When push buttons control the operation of a motor, three wires are run from the push-button control station to the starter (Figure 18–6). A simple three-wire push-button control circuit is shown in Figure 18–7. Three-wire control is used to a much greater extent throughout industry than two-wire control because of its flexibility. Pilot control devices such as push buttons, float switches, and limit switches can be mounted in remote locations, whereas while the motor starter can be located close to the motor it controls or in a control cabinet with other control components. Another advantage of three-wire control circuits is that in the event of a power failure they will not restart automatically when power is restored. This can be a major safety issue in many instances. Three-wire controls depend on a set of normally open contacts, generally called *holding, maintaining,* or *sealing* contacts, connected in parallel with the start push button to maintain the circuit once the normally open start button is released. These contacts are labeled M in Figure 18–7.

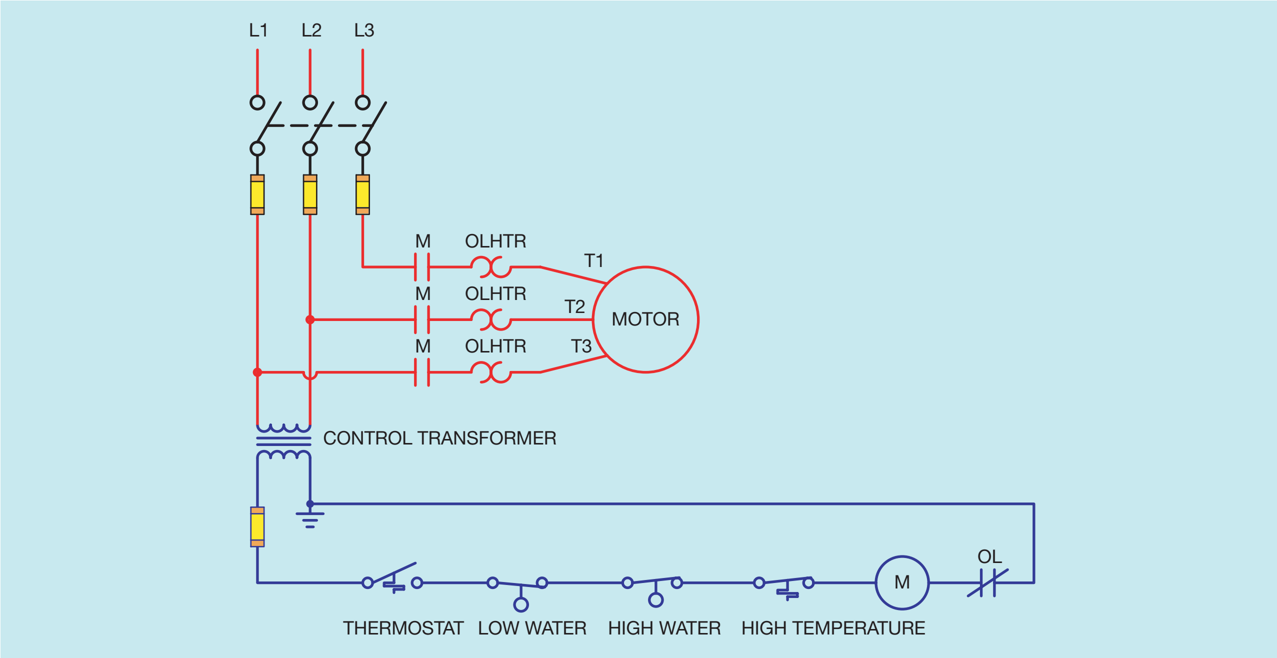


Figure 18–4 Two-wire control circuits may contain any number of external sensing devices. (Source: Delmar/Cengage Learning.)

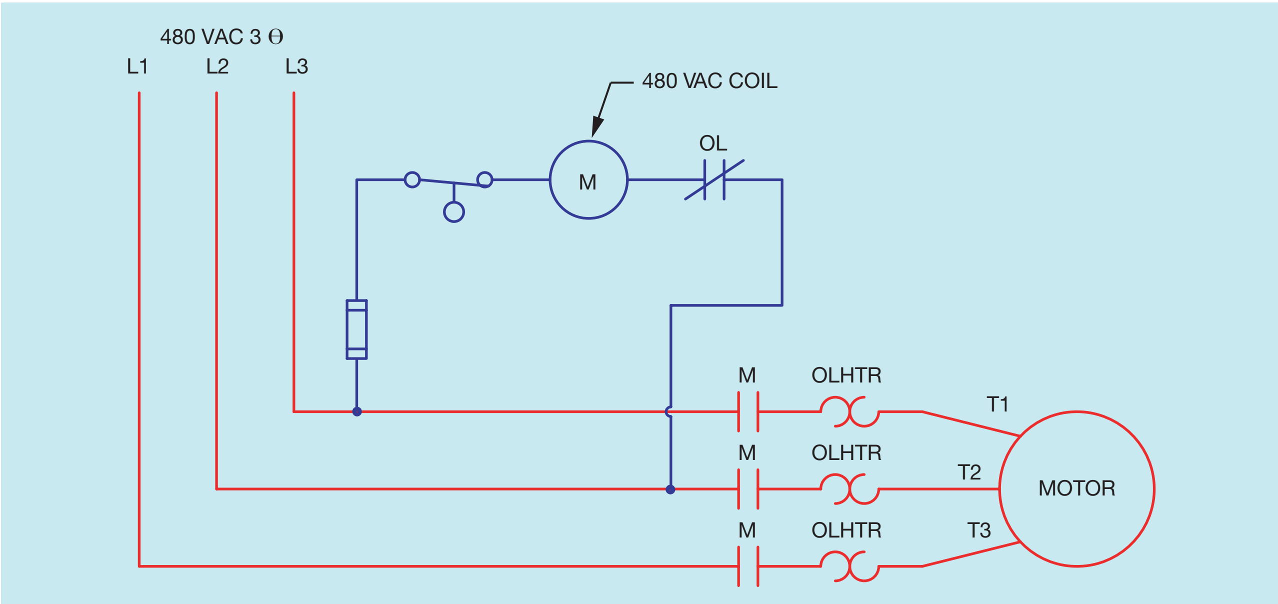


Figure 18–5 A two-wire line voltage control circuit. (Source: Delmar/Cengage Learning.)

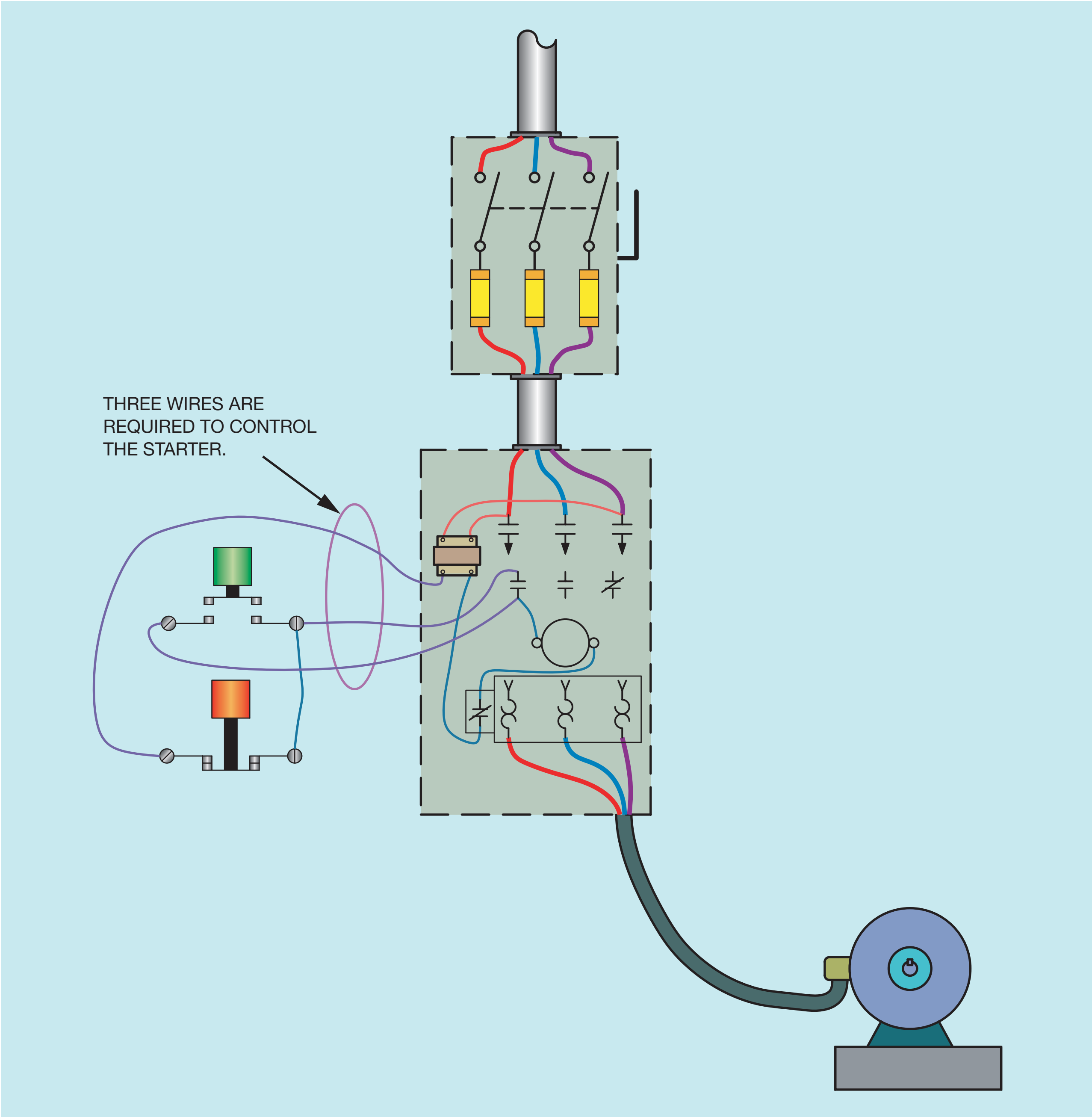


Figure 18–6 Three wires are required to control a starter with momentary contact devices such as push buttons. (Source: Delmar/Cengage Learning.)

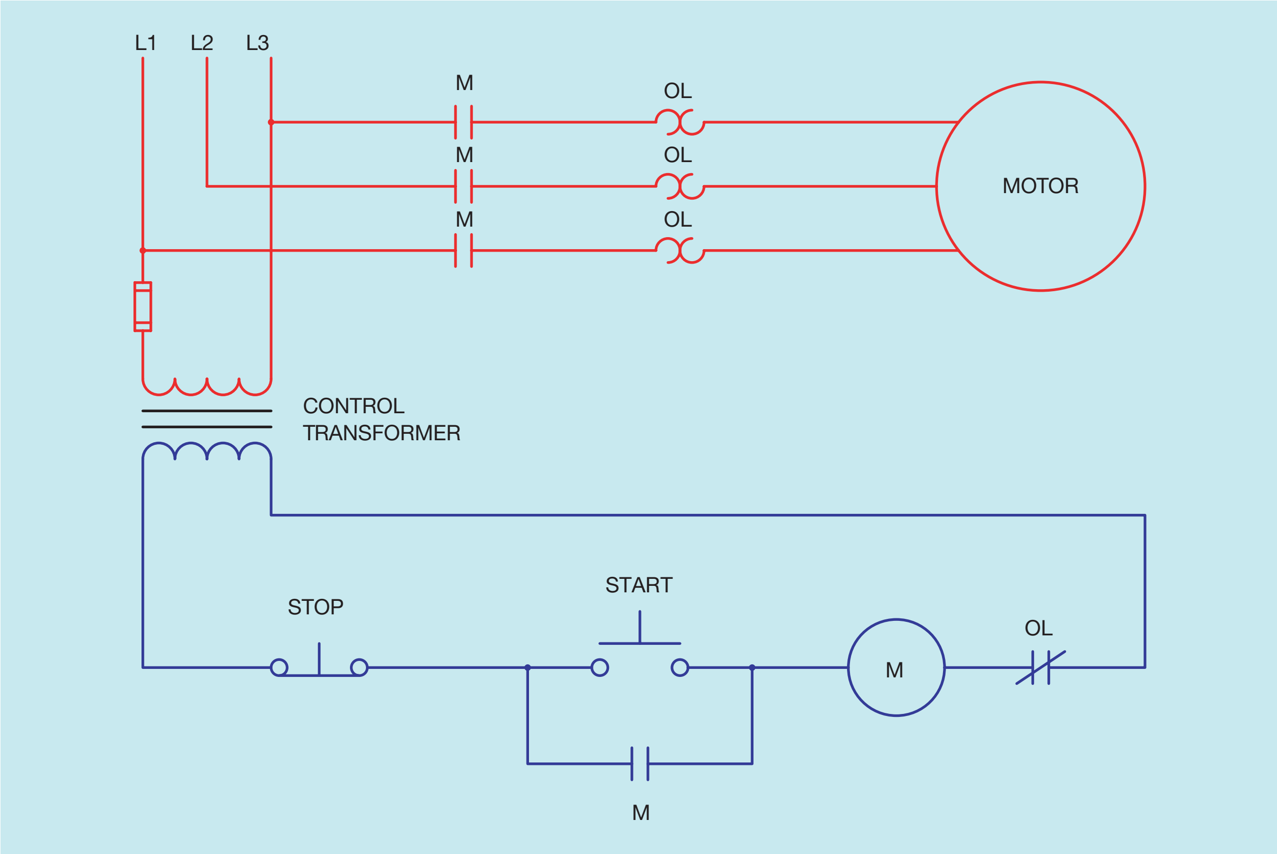


Figure 18–7 A basic three-wire start-stop control circuit. (Source: Delmar/Cengage Learning.)

Review Questions

1. What are the two major types of control circuits?
2. How is it possible for a two-wire control circuit to control the operation of a three-phase motor?
3. Refer to the schematic shown in Figure 18–4. What type of switch is the thermostat?
   a. normally open temperature switch.
   b. normally closed temperature switch.
   c. normally open held closed temperature switch.
   d. normally closed held open temperature switch.
4. Refer to the schematic shown in Figure 18–4. What type of switch is the low water switch?
   a. normally open float switch.
   b. normally closed float switch.
   c. normally open held closed float switch.
   d. normally closed held open float switch.
5. What generally characterizes a three-wire control circuit?
6. Explain the function of a holding contact.
7. How are holding contacts connected?

CHAPTER 19

SCHEMATICS AND WIRING DIAGRAMS (CIRCUIT #1)

OBJECTIVES

After studying this chapter, the student will be able to:

- Interpret schematic diagrams.
- Interpret wiring diagrams.
- Connect control circuits using schematic and wiring diagrams.
- Discuss the operation of circuit #1.

Schematic and wiring diagrams are the written language of control circuits. Maintenance electricians must be able to interpret schematic and wiring diagrams to install control equipment or troubleshoot existing control circuits. Schematic diagrams are also known as line diagrams and ladder diagrams. *Schematic diagrams show components in their electrical sequence without regard to physical location.* Schematics are used more than any other type of diagram to connect or troubleshoot a control circuit.

Wiring diagrams show a picture of the control components with connecting wires. Wiring diagrams are sometimes used to install new control circuits, but they are seldom used for troubleshooting existing circuits. Figure 19–1A shows a schematic diagram of a start-stop, push-button circuit. Figure 19–1B shows a wiring diagram of the same circuit.

When reading schematic diagrams, the following rules should be remembered.

A. Read a schematic as you would a book—from top to bottom and from left to right.

B. Contact symbols are shown in their de-energized or off position.

C. When a relay is energized, all the contacts controlled by that relay change position. If a contact is shown normally open on the schematic, it will close when the coil controlling it is energized.

The three circuits shown in this and following chapters are used to illustrate how to interpret the logic of a control circuit using a schematic diagram.

Circuit #1, shown in Figure 19–2A, is an alarm silencing circuit. The purpose of the circuit is to sound

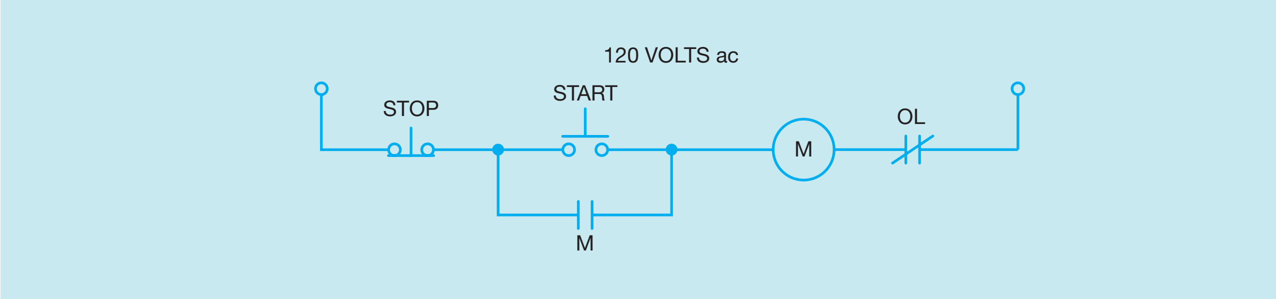


Figure 19–1A Schematic diagram of a start-stop push-button station. (Source: Delmar/Cengage Learning.)

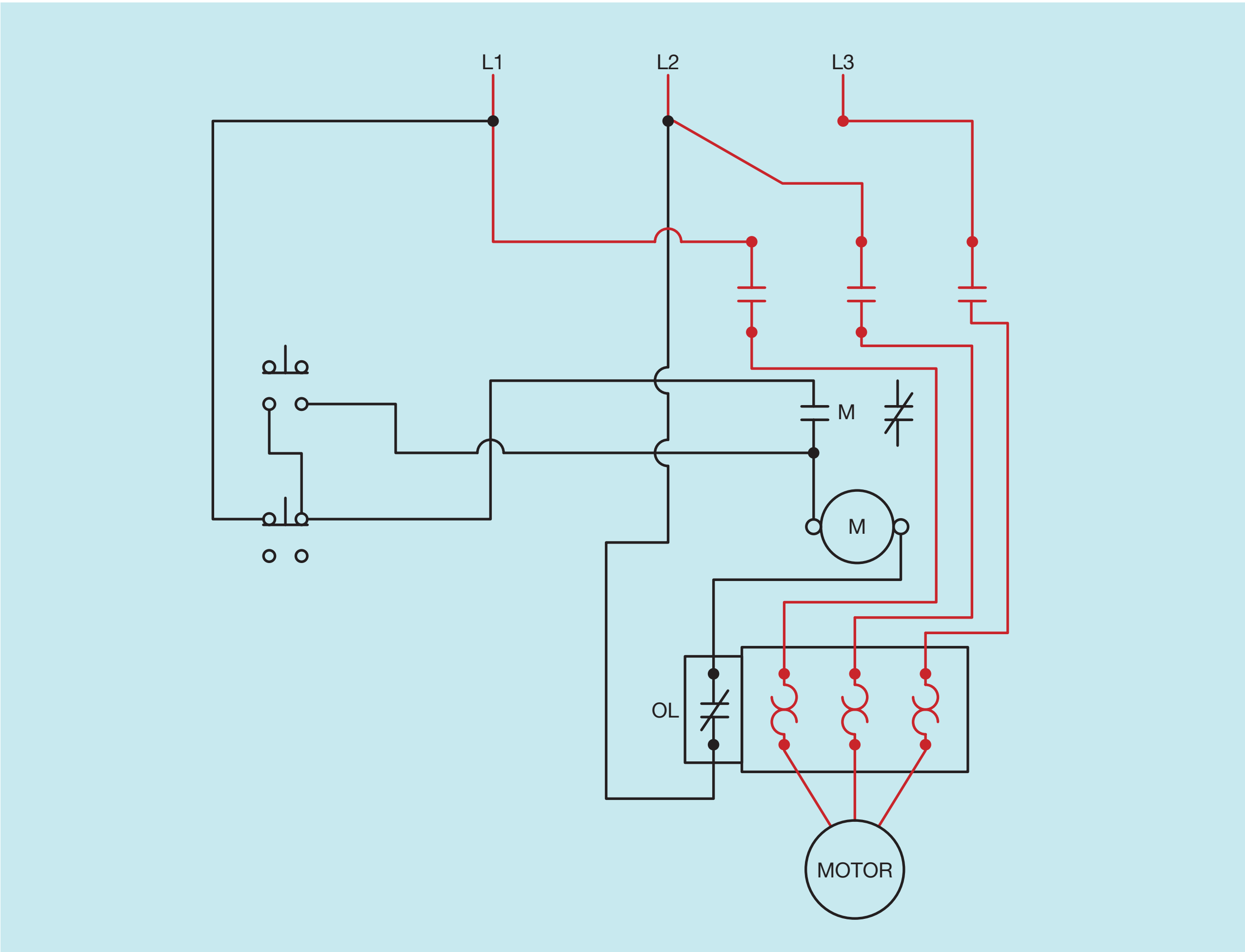


Figure 19–1B Wiring diagram of a start-stop push-button station. (Source: Delmar/Cengage Learning.)

a horn and turn on a red warning light when the pressure of a particular system becomes too great. After the alarm has sounded, the RESET button can be used to turn the horn off, but the red warning light must remain on until the pressure in the system drops to a safe level. Notice that no current can flow in the system because of the open pressure switch, PS.

If the pressure rises high enough to cause pressure switch PS to close, current can flow through the normally closed S contact to the horn. Current can also flow

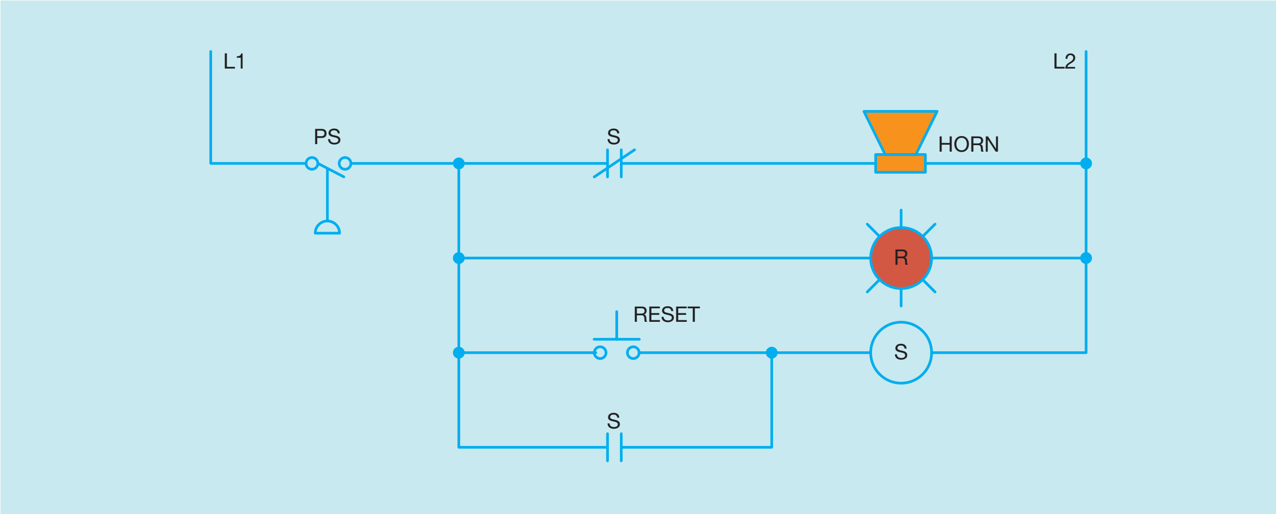


Figure 19–2A Circuit #1. Alarm silencing circuit. (Source: Delmar/Cengage Learning.)

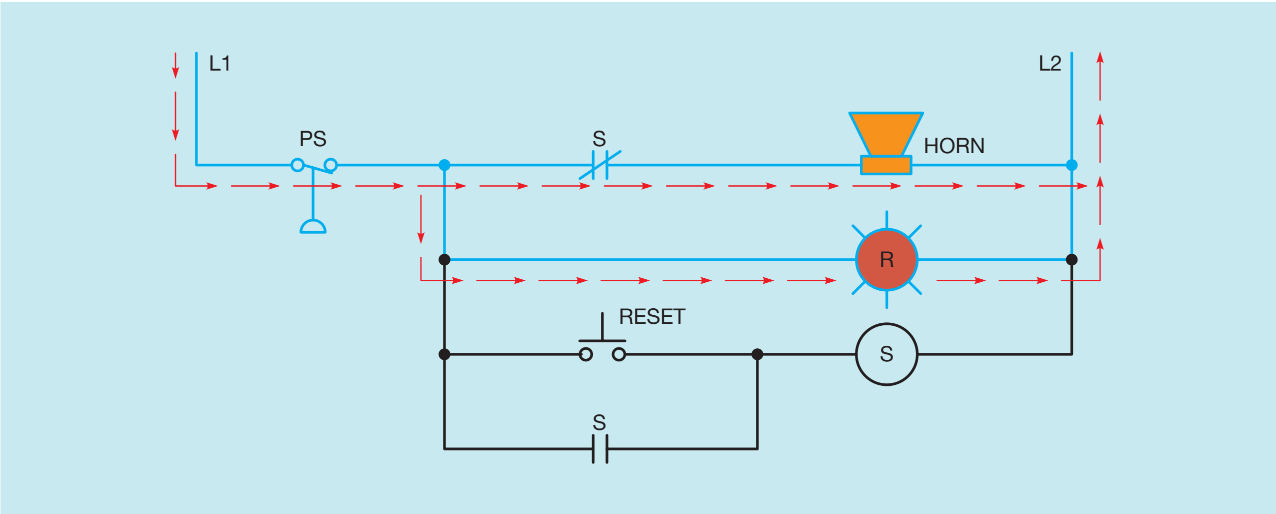


Figure 19–2B Pressure switch closes. (Source: Delmar/Cengage Learning.)

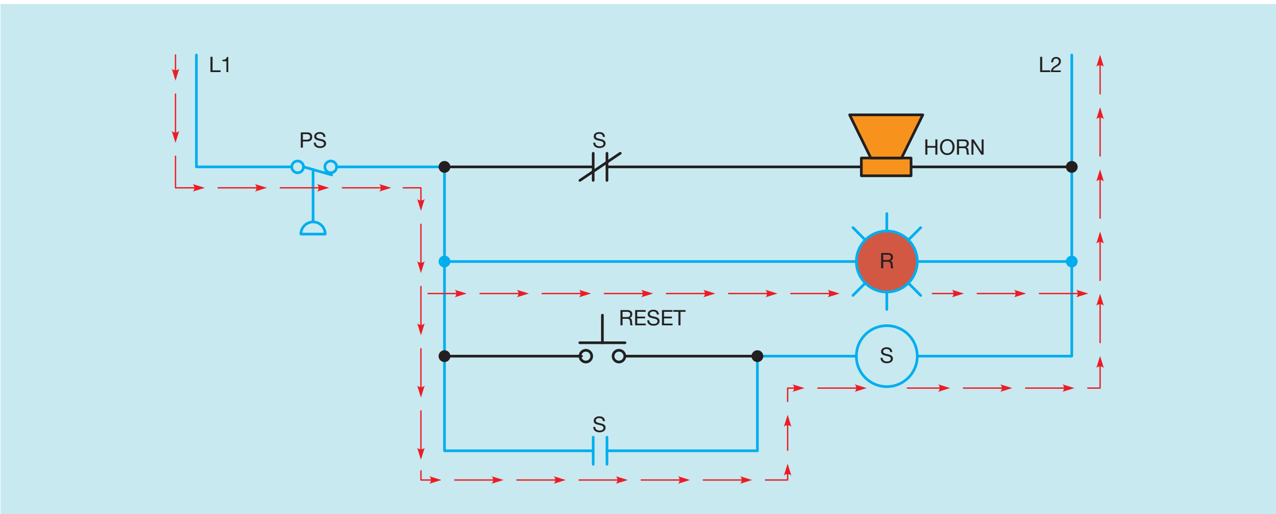


Figure 19–2C The alarm has been silenced but the warning light remains on. (Source: Delmar/Cengage Learning.)

through the red warning light. Current cannot, however, flow through the normally open RESET button or the normally open S contact (Figure 19–2B).

If the reset button is pushed, a circuit is completed through the S relay coil. When relay coil S energizes, the normally closed S contact opens and the normally open S contact closes. When the normally closed S contact opens, the circuit to the horn is broken. This causes the horn to turn off. The normally open S contact is used as a holding contact to maintain current to the coil of the relay when the RESET button is released (Figure 19–2C).

The red warning light will remain turned on until the pressure switch opens again. When the pressure switch opens, the circuit is broken and current flow through the system stops. This causes the red warning light to turn off, and it de-energizes the coil of relay S. When relay S de-energizes, both of the S contacts return to their original position. The circuit is now back to the same condition it was in in Figure 19–2A.

Review Questions

1. Define a schematic diagram.
2. Define a wiring diagram.
3. Referring to circuit #1 (Figure 19–2A), explain the operation of the circuit if pressure switch PS was connected normally closed instead of normally open.

CHAPTER 20

TIMED STARTING FOR THREE MOTORS (CIRCUIT #2)

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of circuit #2.
- Troubleshoot circuit #2 using the schematic.

A machine contains three large motors. The current surge to start all three motors at the same time is too great for the system. Therefore, when the machine is to be started, there must be a delay of 10 seconds between the starting of each motor. Circuit #2, shown in Figure 20–1, is a start-stop, push-button control that controls three motor starters and two time-delay relays. The circuit is designed so that an overload on any motor will stop all motors.

When the START button is pressed, a circuit is completed through the START button, M1 motor starter coil, and TR1 relay coil. When coil M1 energizes, motor #1 starts and auxiliary contact M1, which is parallel to the START button, closes. This contact maintains the current flow through the circuit when the START button is released (Figure 20–2).

After a 10-second interval, contact TR1 closes. When this contact closes, a circuit is completed through motor starter coil M2 and timer relay coil TR2. When coil M2 energizes, motor #2 starts (Figure 20–3).

Ten seconds after coil TR2 energizes, contact TR2 closes. When this contact closes, a circuit is completed to motor starter coil M3, which causes motor #3 to start (Figure 20–4).

If the STOP button is pressed, the circuit to coils M1 and TR1 is broken. When motor starter Ml de-energizes, motor #1 stops and auxiliary contact Ml opens. TR1 is an on-delay relay; therefore, when coil TR1 is de-energized, contact TR1 opens immediately.

When contact TR1 opens, motor starter M2 de-energizes, which stops motor #2, and coil TR2 de-energizes. Since TR2 is an on-delay relay, contact

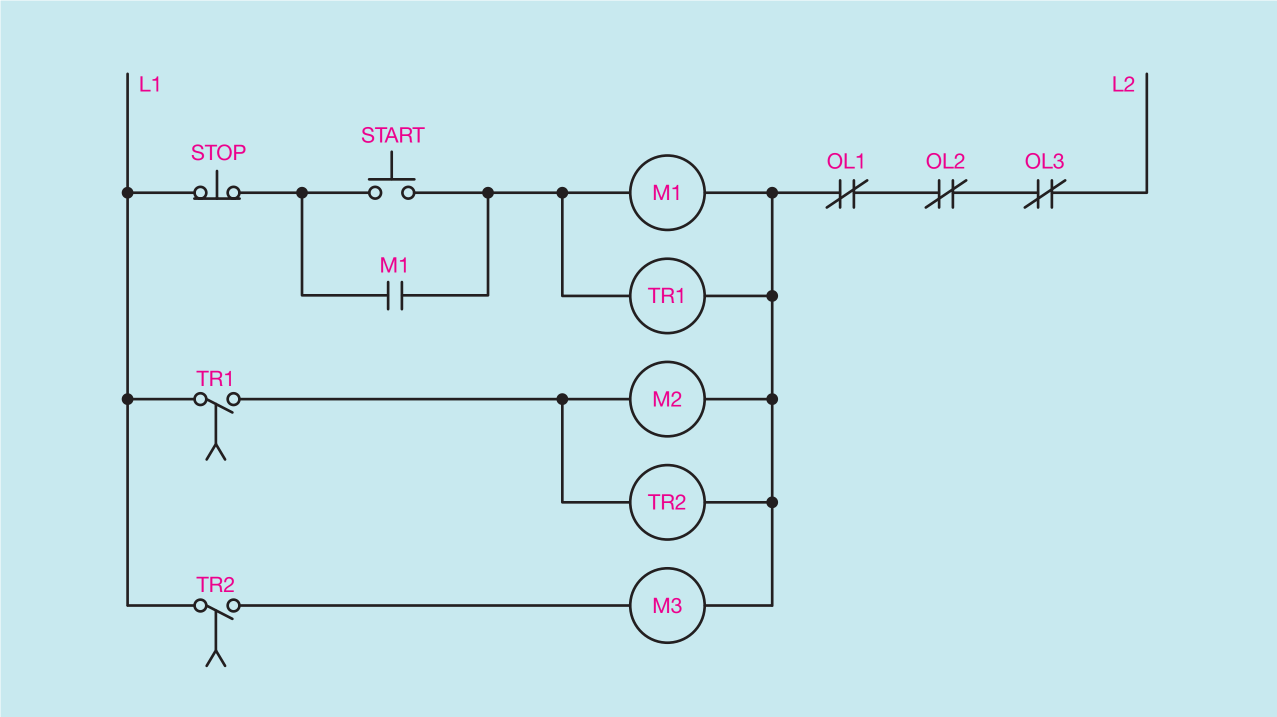


Figure 20–1 Circuit #2. Time delay starting for three motors. (Source: Delmar/Cengage Learning.)

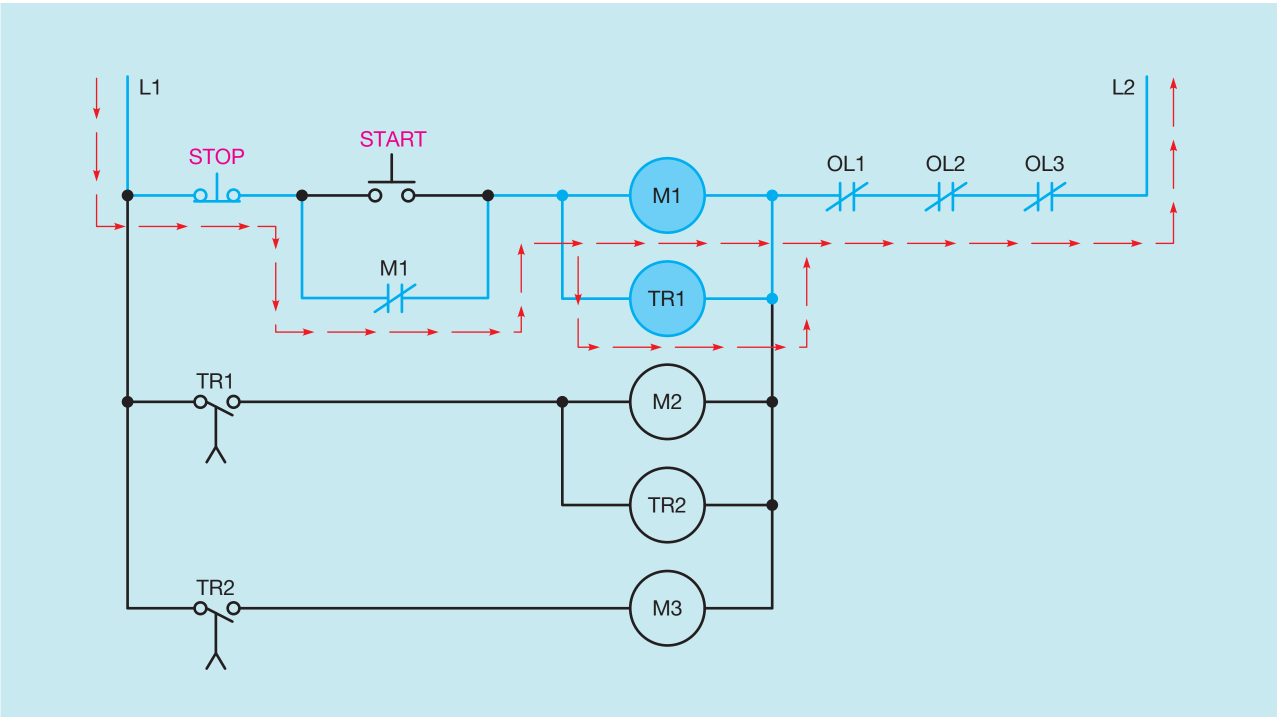


Figure 20–2 M1 motor starter and TR1 timer relay turn on. (Source: Delmar/Cengage Learning.)

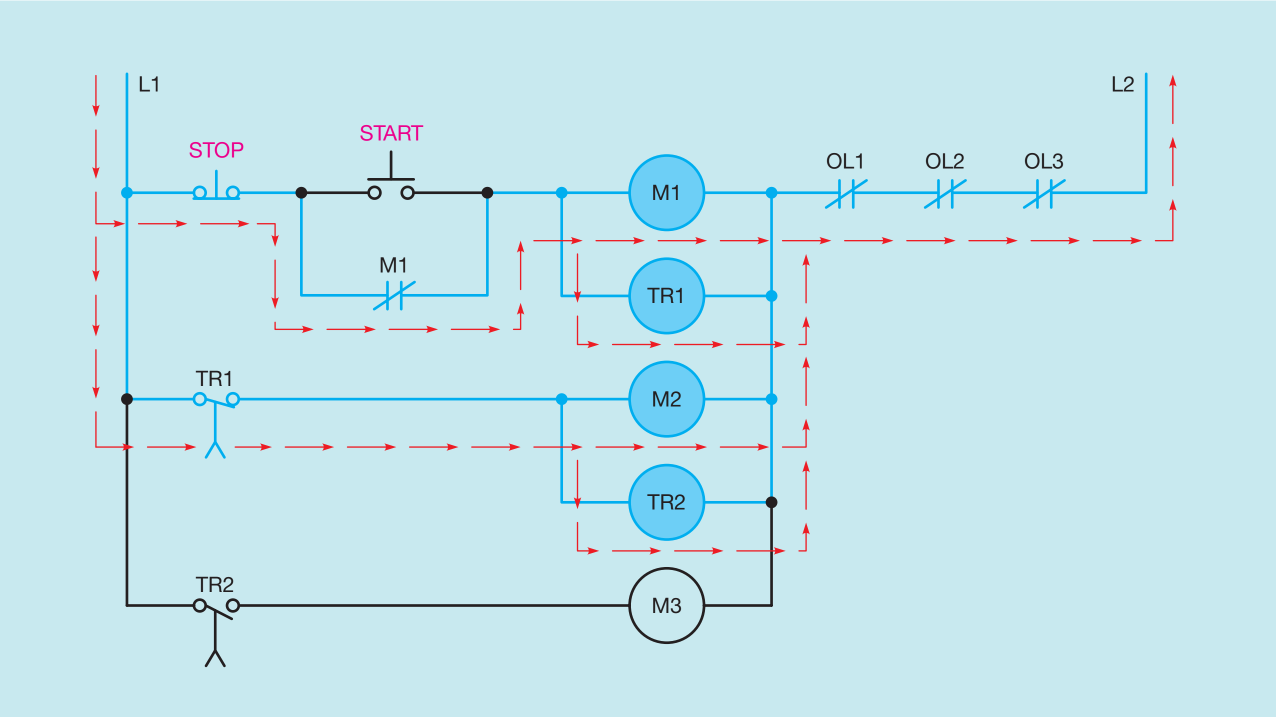


Figure 20–3 Motor 2 and TR2 have energized. (Source: Delmar/Cengage Learning.)

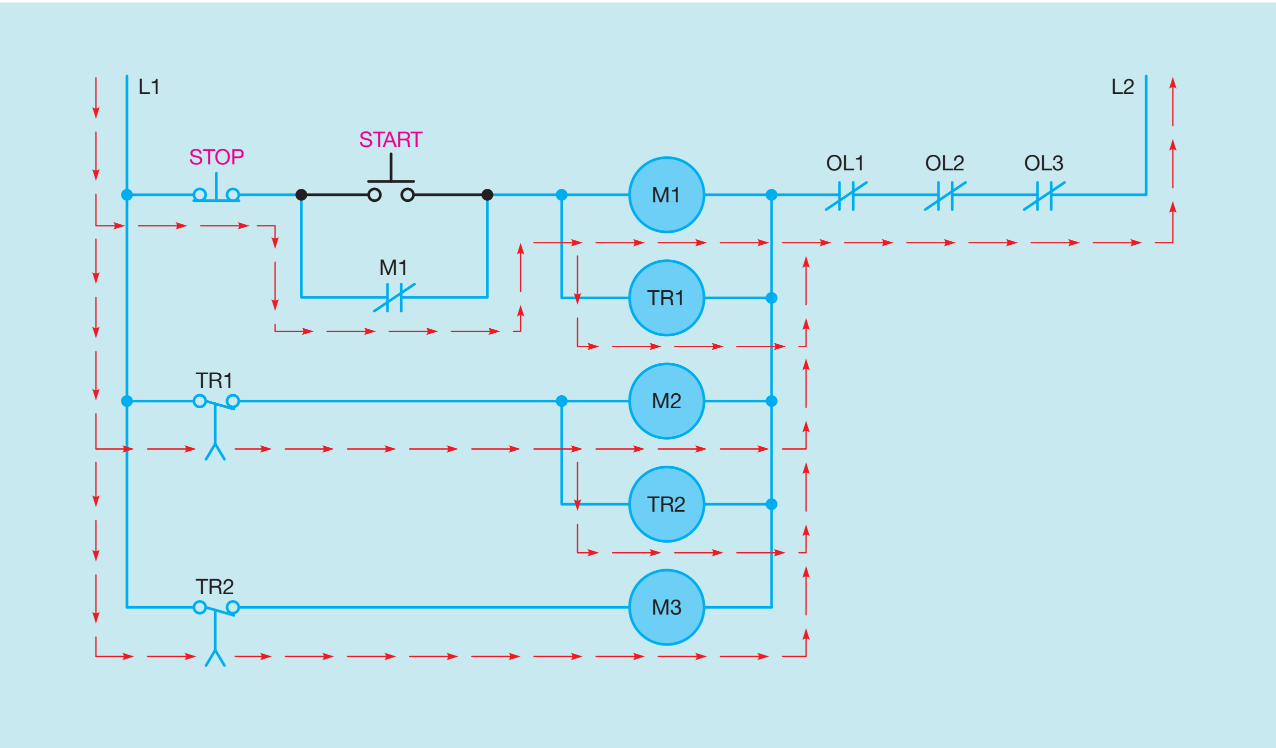


Figure 20–4 Motor 3 has energized. (Source: Delmar/Cengage Learning.)

TR2 opens immediately. This breaks the circuit to motor starter M3. When motor starter M3 de-energizes, motor #3 stops. Although it takes several seconds to explain what happens when the STOP button is pressed, the action of the relays is almost instantaneous. If one of the overload contacts opens while the circuit is energized, the effect is the same as pressing the STOP button. After the circuit stops, all contacts return to their normal positions, and the circuit is the same as the original circuit shown in Figure 20–1.

Review Questions

(Refer to circuit 20–1.)

1. Explain the operation of circuit #2 (Figure 20–1) if contact M1 did not close.
2. Explain the operation of circuit #2 (Figure 20–1) if relay coil TR2 were burned out.
3. Refer to circuit #2, shown in Figure 20–1. Assume that both times are set for a delay of 5 seconds. When the START button is pressed, motor #1 starts running immediately. After a delay of 10 seconds, motor #3 starts running, but motor #2 never starts. Which of the following could cause this problem?
   a. TR1 coil is open.
   b. M2 starter coil is open.
   c. TR2 coil is open.
   d. OL2 contact is open.
4. Refer to circuit #2, shown in Figure 20–1. Assume that the timers are set for a delay of 5 seconds. When the START button is pressed nothing happens. No motors start running for a period of 1 minute. Which of the following could **not** cause this problem?
   a. M1 holding contacts did not close.
   b. the STOP push-button is open.
   c. OL1 contact is open.
   d. M2 coil is open.

CHAPTER 21

FLOAT SWITCH CONTROL OF A PUMP AND PILOT LIGHTS (CIRCUIT #3)

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of circuit #3.
- Troubleshoot circuit #3 using the schematic.

In circuit #3, a float switch is used to operate a pump motor. The pump is used to fill a tank with water. When the tank is low on water, the float switch activates the pump motor and turns a red pilot light on. When the tank is filled with water, the float switch turns the pump motor and red pilot light off, and turns an amber pilot light on to indicate that the pump motor is not running. If the pump motor becomes overloaded, an overload relay stops the pump motor only.

The requirements for this circuit indicate that a float switch is to be used to control three different items: a red pilot light, a motor starter, and an amber pilot light. However, most pilot devices, such as float switches, pressure switches, and limit switches, seldom contain more than two contacts. When the circuit requires these pilot devices to use more contacts than they contain, it is common practice to let a set of contacts on the pilot device operate a control relay. The contacts of the control relay can be used as needed to fulfill the requirements of the circuit.

The float switch in Figure 21–1 is used to operate a control relay labeled FSCR. The contacts of the control relay are used to control the motor starter and the two pilot lights.

In the circuit shown in Figure 21–2, current can flow through the normally closed FSCR contact to the red pilot light, and through a second normally closed FSCR contact to the coil of motor starter M1. When motor starter M1 energizes, the pump motor starts and begins to fill the tank with water. As water rises in the tank, the float of float switch FS rises also. When the tank is sufficiently filled, the float switch contact closes and energizes relay FSCR (Figure 21–3).

When the coil of relay FSCR energizes, all FSCR contacts change. The normally closed contacts open and the normally open contact closes. When the normally

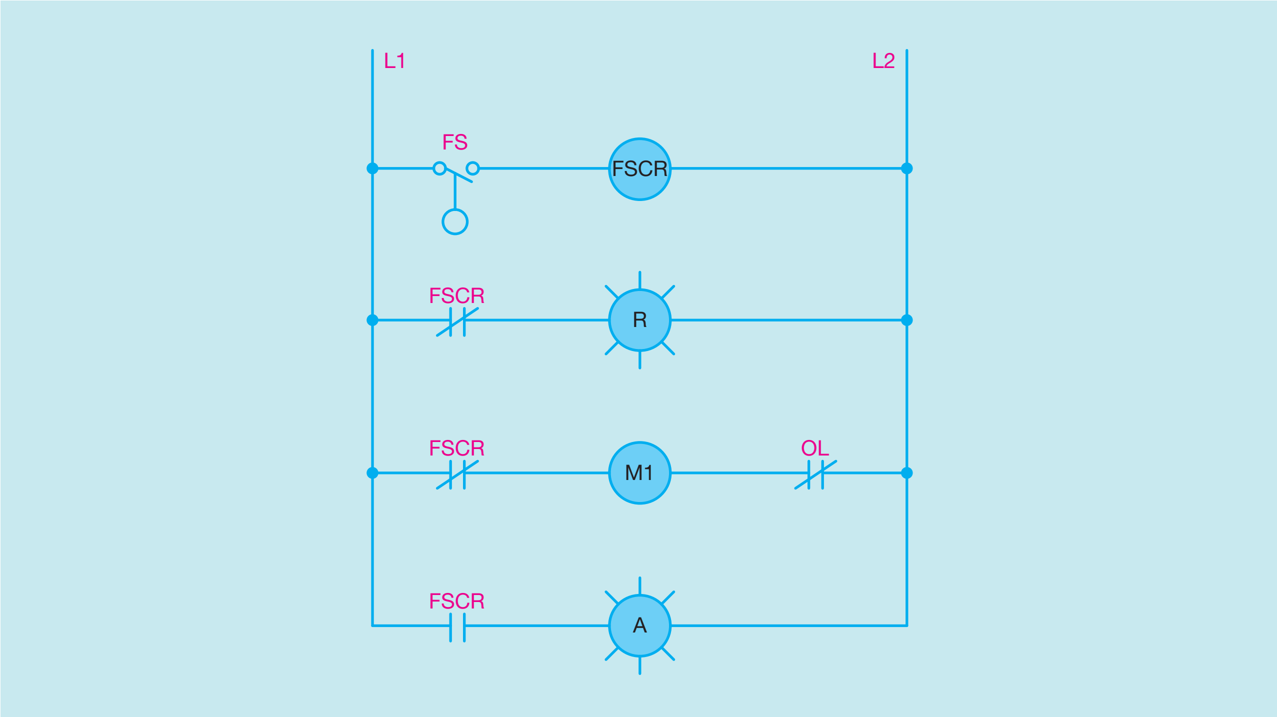


Figure 21–1 Circuit #3. Float switch used to operate a control relay. (Source: Delmar/Cengage Learning.)

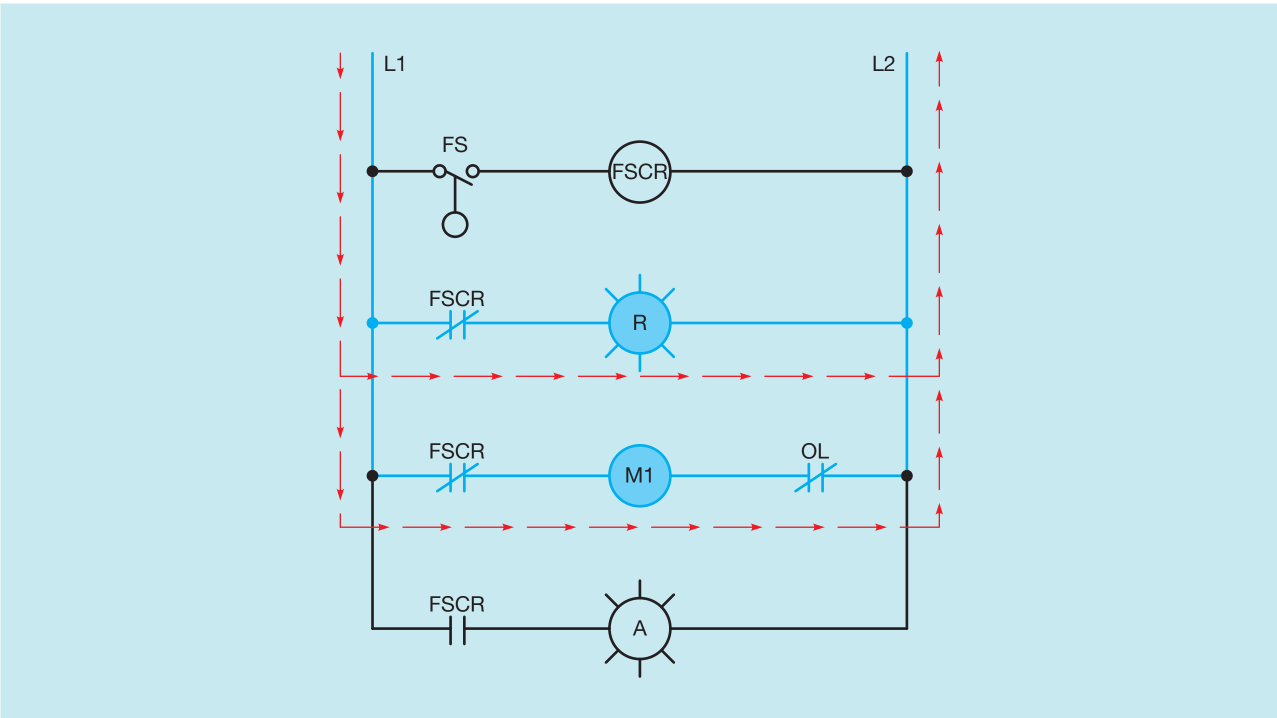


Figure 21–2 Warning light and pump motor have energized. (Source: Delmar/Cengage Learning.)

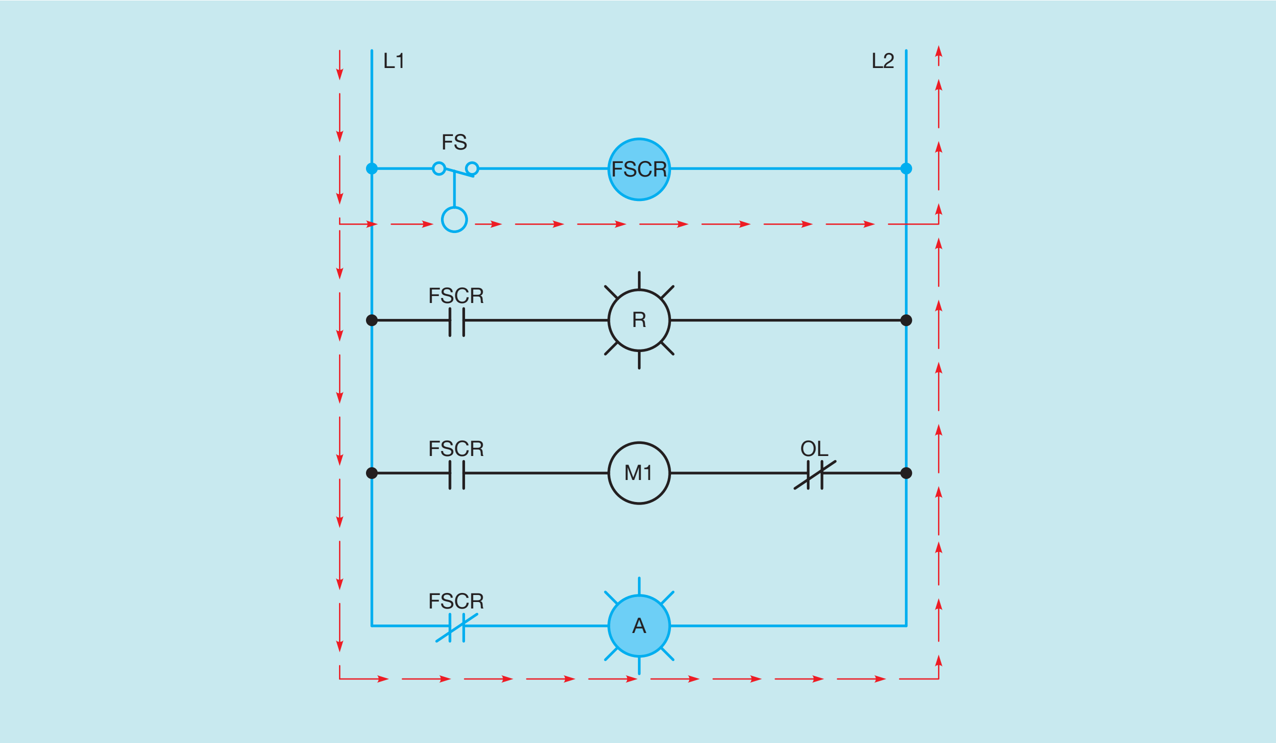


Figure 21–3 Float switch energized FSCR relay. (Source: Delmar/Cengage Learning.)

closed contacts open, the circuits to the red pilot light and to coil M1 are broken. When motor starter M1 de-energizes, the pump motor stops. When the normally open FSCR contact closes, current flows to the amber pilot light. When the pump motor turns off, the water level begins to drop in the tank. When the water level drops low enough, the float switch opens and de-energizes relay coil FSCR. When relay FSCR de-energizes, all FSCR contacts return to their normal positions as shown in Figure 21–1. If the pump motor is operating and the overload relay opens the overload contact, only the motor starter will be de-energized. The pilot lights will continue to operate.

Review Questions

(Refer to circuit 21–1.)

1. Explain the operation of the circuit shown in Figure 21–1 if float switch FS were connected normally closed instead of normally open.
2. Explain the operation of the circuit shown in Figure 21–1 if relay coil M1 were burned out.

CHAPTER 22

DEVELOPING A WIRING DIAGRAM (CIRCUIT #1)

OBJECTIVES

After studying this chapter, the student will be able to:

- Interpret a wiring diagram.
- Develop a wiring diagram from a schematic diagram.
- Connect a control circuit using a wiring circuit diagram.

Wiring diagrams will now be developed for the three circuits just discussed. The method used for developing wiring diagrams is the same as the method used for installing new equipment. To illustrate this principle, the components of the system will be drawn on paper and connections will be made to the various contacts and coils. Using a little imagination, it will be possible to visualize actual relays and contacts mounted in a panel, and wires connecting the various components.

Figure 22–1 shows the schematic for the alarm silencing circuit from Chapter 19, and Figure 22–2 shows the components of the system. The connection of the circuit is more easily understood with the aid of a simple numbering system. The rules for this system are as follows:

A. Each time a component is crossed, the number must change.

B. Number all connected components with the same number.

C. Never use a number set more than once.

Figure 22–3 shows the schematic of the alarm silencing circuit with numbers placed beside each component. Notice that a 1 has been placed beside L1 and one side of the pressure switch. The pressure switch is a component. Therefore, the number must change when the pressure switch is crossed. The other side of the pressure switch is numbered with a 2. A 2 is also placed on one side of the normally closed S contact, one side of the red warning light, one side of the normally open RESET push button, and one side of the normally open S contact. All of these components are connected electrically; therefore, each has the same number.

When the normally closed S contact is crossed, the number is changed. The other side of the normally

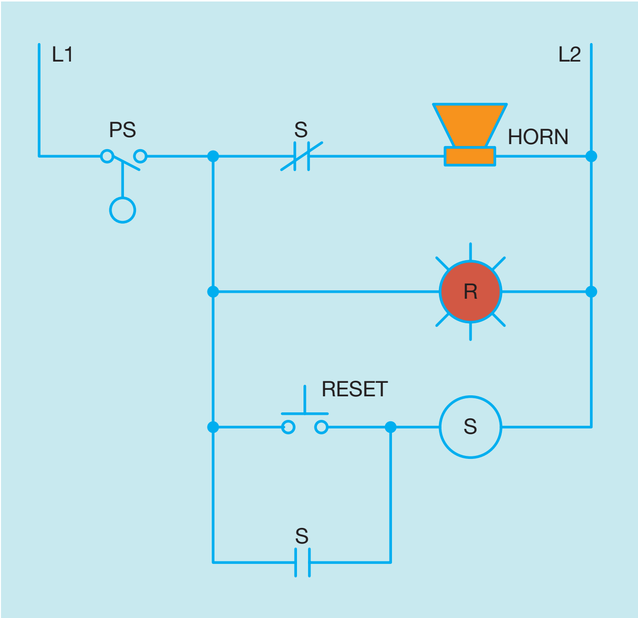


Figure 22–1 Circuit #1. Alarm silencing circuit. (Source: Delmar/Cengage Learning.)

closed S contact is now a 3, and one side of the horn is a 3. The other side of the horn is connected to L2. The other side of the red warning light and one side of relay coil S are also connected to L2. All of these points are labeled with a 4. The other side of the normally open RESET button, the other side of the normally open S contact, and the other side of relay coil S are numbered with a 5.

The same numbers that are used to label the schematic in Figure 22–3 are used to label the components shown in Figure 22–4. L1 in the schematic is labeled with a 1; therefore, 1 is used to label L1 on the wiring diagram in Figure 22–4. One side of the pressure switch in the schematic is labeled with a 1 and the other side is labeled with a 2. The pressure switch in the wiring diagram is shown with three terminals. One terminal is labeled C for common, one is labeled NO for normally open, and one is labeled NC for normally closed. This is a common contact arrangement used on many pilot devices and control relays (see Figure 5–2). In the schematic the pressure switch is connected as a normally open device; therefore, terminals C and

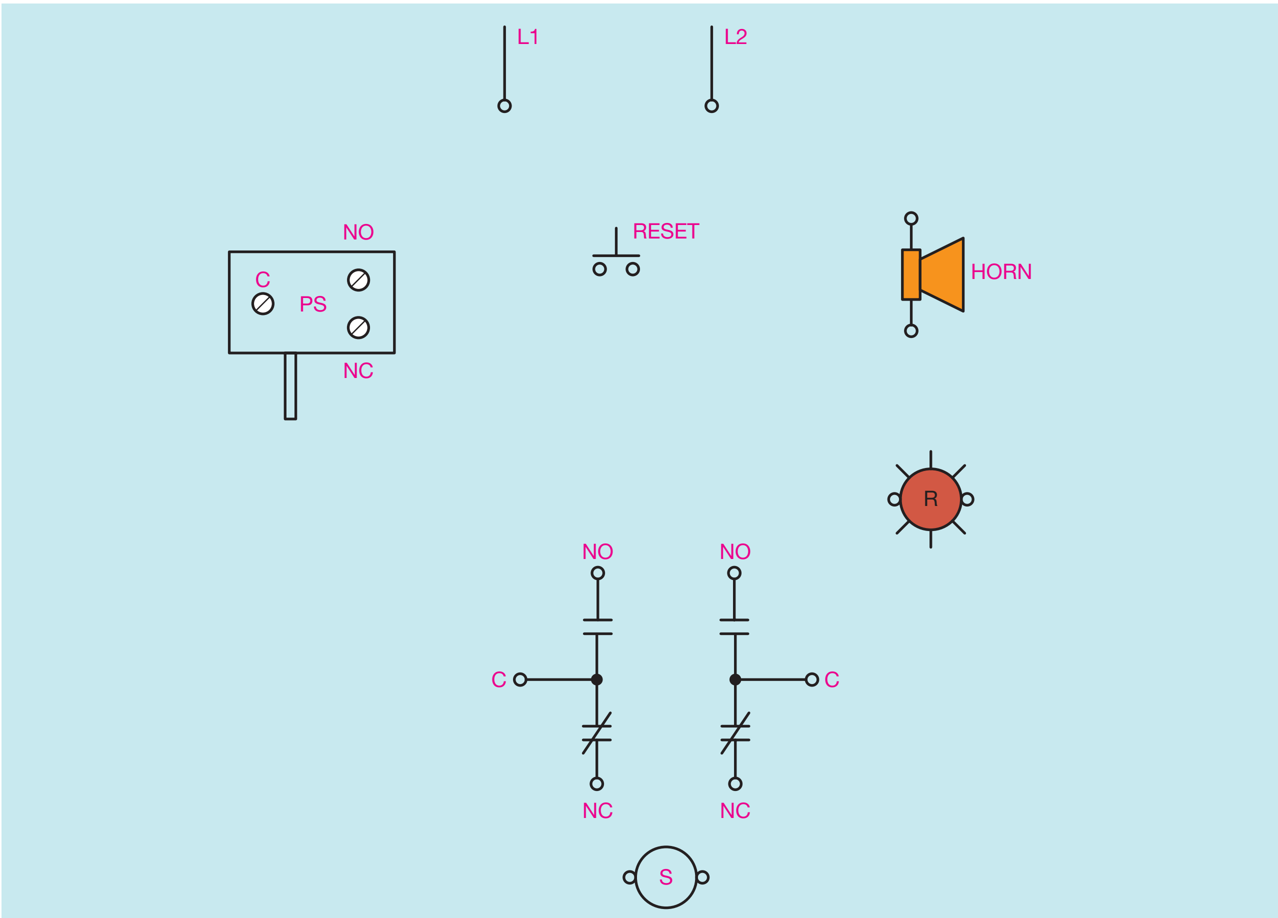


Figure 22–2 Circuit components. (Source: Delmar/Cengage Learning.)

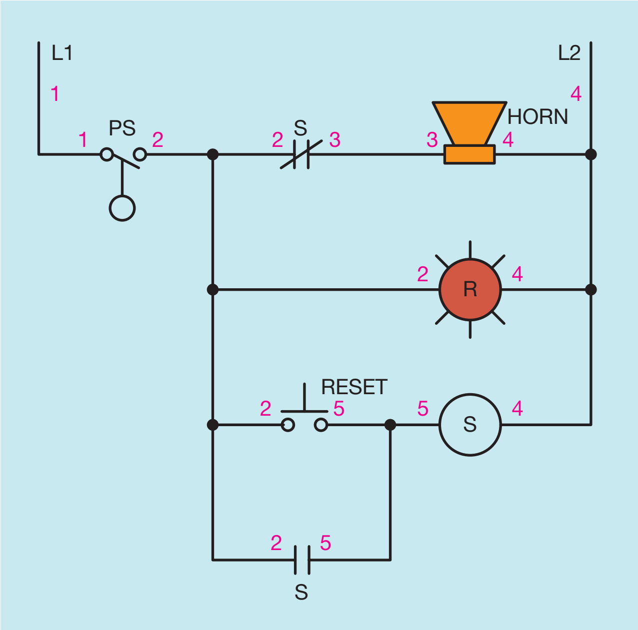


Figure 22–3 Numbers aid in circuit connection. (Source: Delmar/Cengage Learning.)

NO will be used. A 1 is placed by terminal C and a 2 is placed beside terminal NO. Notice that a 2 has also been placed beside one side of the normally open RESET button, one side of the normally closed contact located on relay S, one side of the normally open contact located on relay S, and one side of the red warning light. A 3 is placed beside the common terminal of relay contact S which is used to produce a normally closed contact, and beside one of the terminal connections of the horn. A 4 is placed beside L2, the other terminal of the horn, the other side of the red warning light, and one side of relay coil S. A 5 is placed on the other side of relay coil S, the other side of the normally open RESET button, and on the common terminal of relay contact S, which is used as a normally open contact.

Notice that the numbers used to label the components of the wiring diagram are the same as the numbers used to label the components of the schematic. For instance, the pressure switch in the schematic is shown as being normally open and is labeled with a 1 and a 2. The pressure switch in the wiring diagram is labeled

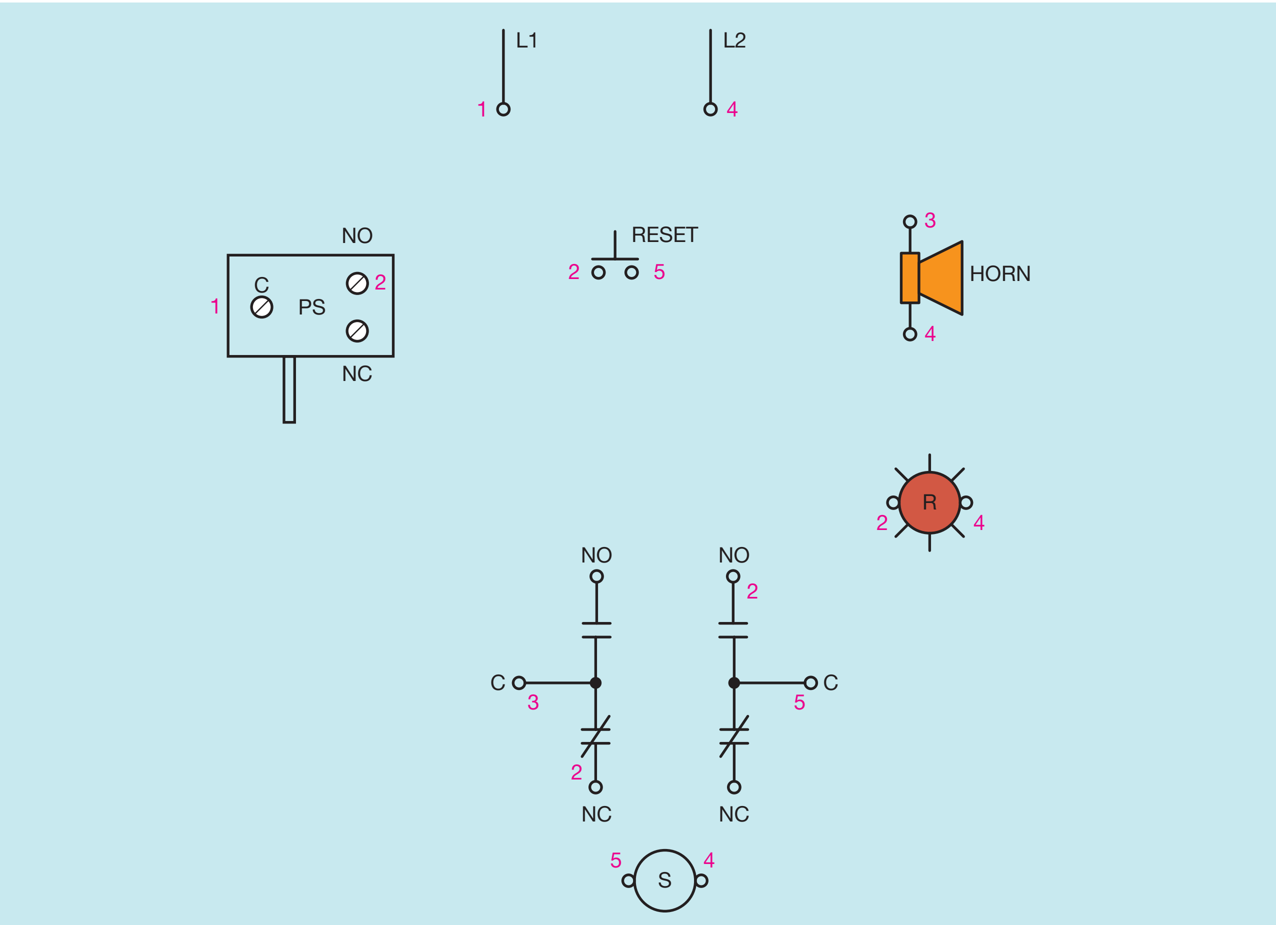


Figure 22–4 Circuit components have been numbered to match the schematic. (Source: Delmar/Cengage Learning.)

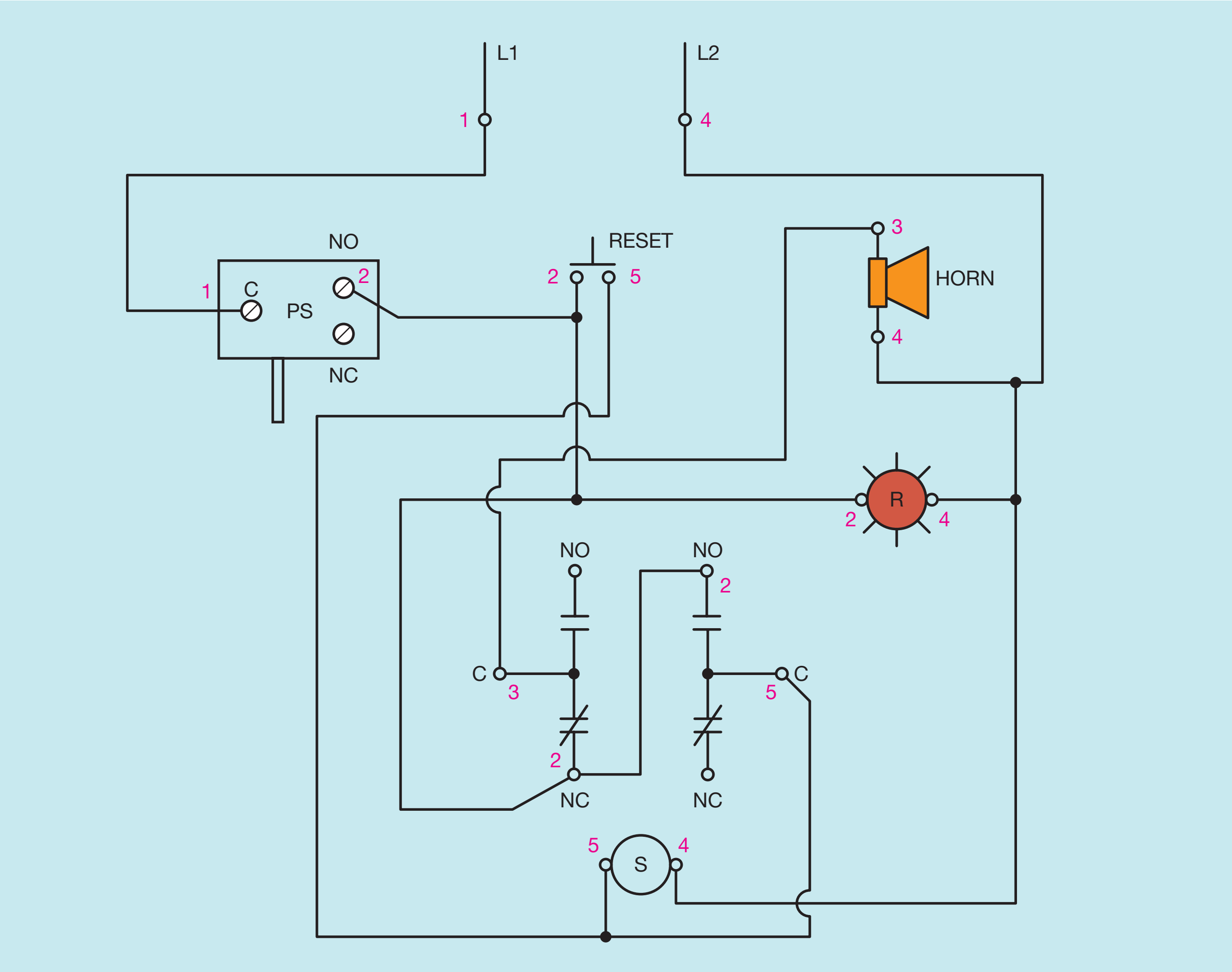


Figure 22–5 Final wiring is done by connecting numbers. (Source: Delmar/Cengage Learning.)

with a 1 beside the common terminal and a 2 beside the NO terminal. The normally closed S contact in the schematic is labeled with a 2 and a 3. Relay S in the wiring diagram has a normally closed contact labeled with a 2 and a 3. The numbers used to label the components in the wiring diagram correspond to the numbers used to label the same components in the schematic.

After labeling the components in the wiring diagram with the proper numbers, it is simple to connect the circuit (Figure 22–5). Connection of the circuit is made by connecting like numbers. For example, all of the components labeled with a 1 are connected, all of those labeled with a 2 are connected, all of the 3s are connected, all of the 4s are connected, and all of the 5s are connected.

Review Questions

1. Why are numbers used when developing a wiring diagram from a schematic diagram?
2. The float switch in Figure 22–1 is:
   a. Normally closed
   b. Normally open
   c. Normally closed held open
   d. Normally open held closed
3. The circuit in Figure 22–1 is designed to sound an alarm if the liquid level rises to a high enough level. What change would have to be made in the circuit so that it would sound an alarm if the liquid level dropped below a certain point?

CHAPTER 23

DEVELOPING A WIRING DIAGRAM (CIRCUIT #2)

OBJECTIVES

After studying this chapter, the student will be able to:

- Develop a wiring diagram for circuit #2 using the schematic.
- Connect this circuit.

Circuit #2, shown in Figure 23–1, is the same as the schematic shown in Figure 20–1, except it has been labeled with numbers. Figure 23–2 shows the components of the wiring diagram. The numbers used to label the components in the wiring diagram correspond to the numbers in the schematic. For instance, the schematic shows the numbers 1 and 8 beside normally open contact TR1. The wiring diagram also shows the numbers 1 and 8 beside normally open contact TR1. The numbers used with each component shown on the schematic have been placed beside the proper component shown in the wiring diagram.

Figure 23–3 shows the wiring diagram with connected wires. Notice that the wiring diagram shows motor connections while the schematic does not. Although it is a common practice to omit motor connections in control schematics, wiring diagrams do show the motor connections.

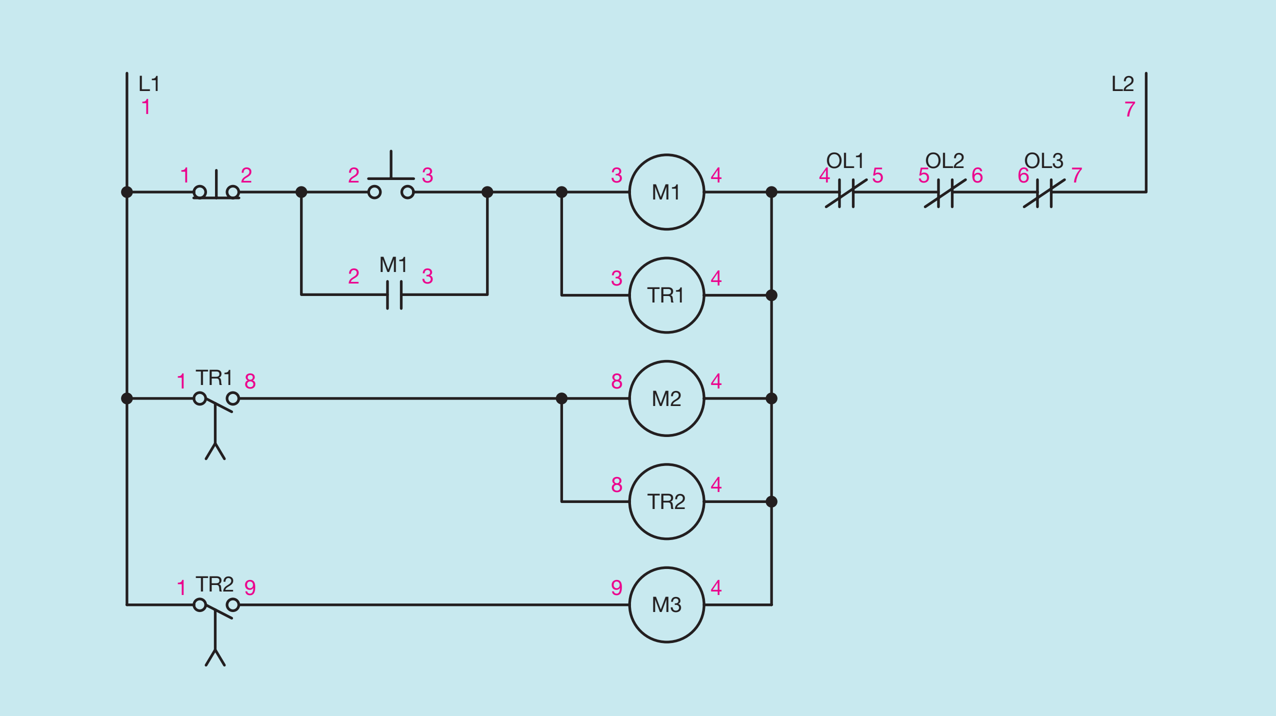


Figure 23–1 Circuit #2. Schematic with components numbered. (Source: Delmar/Cengage Learning.)

Review Question

1. Referring to the circuit shown in Figure 23–1, would it be possible to change the components that have been numbered with an 8 to a number 9, and the components that have been numbered with a 9 to a number 8, without affecting the operation of the circuit?

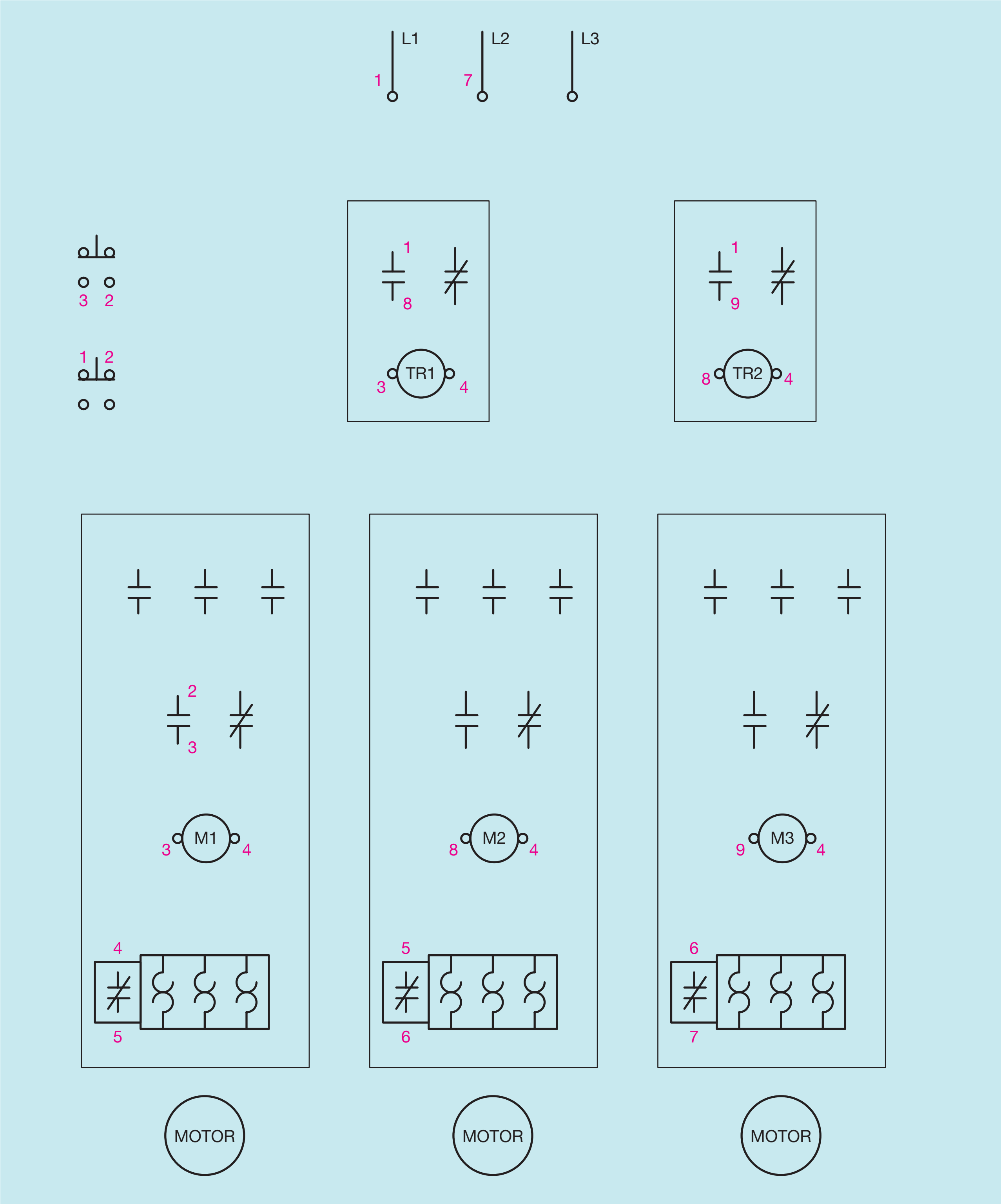


Figure 23–2 Components have been numbered to match the schematic. (Source: Delmar/Cengage Learning.)

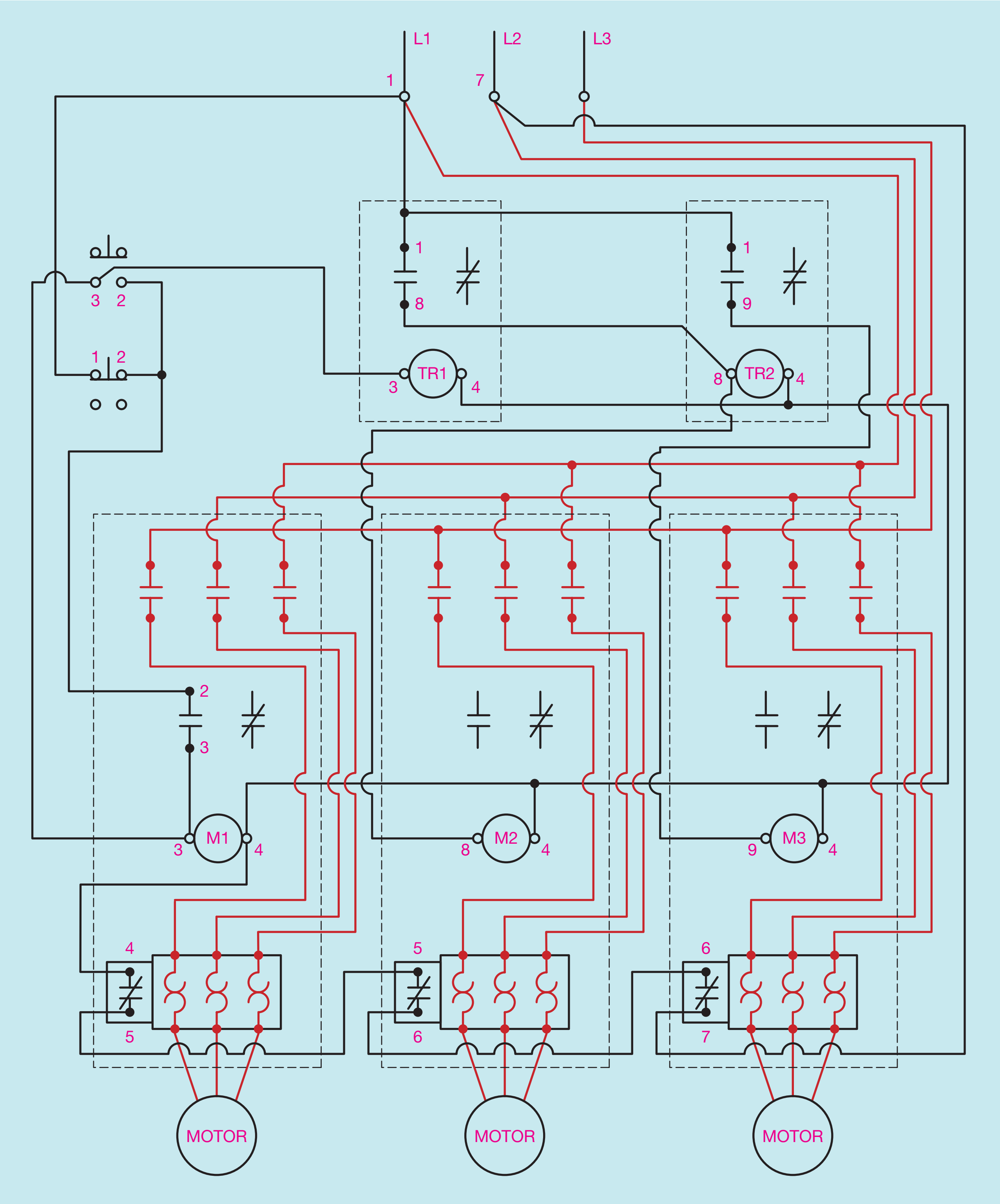


Figure 23–3 Wire connections are made by connecting like numbers. (Source: Delmar/Cengage Learning.)

CHAPTER 24

DEVELOPING A WIRING DIAGRAM (CIRCUIT #3)

OBJECTIVES

After studying this chapter, the student will be able to:

- Develop a wiring diagram for circuit #3 using the schematic.
- Connect this circuit.

Figure 24–1 shows the same schematic as Figure 21–1, except that Figure 24–1 has been labeled with numbers. Figure 24–2 shows the components of the wiring diagram labeled with numbers that correspond to the numbered components shown in the schematic. Figure 24–3 shows the wiring diagram with connected wires.

The same method has been used to number the circuits in the last few chapters. Although most control schematics are numbered to aid the electrician in troubleshooting, several methods are used. Regardless of the method used, all numbering systems use the same principles. An electrician who learns this method of numbering a schematic will have little difficulty understanding a different method.

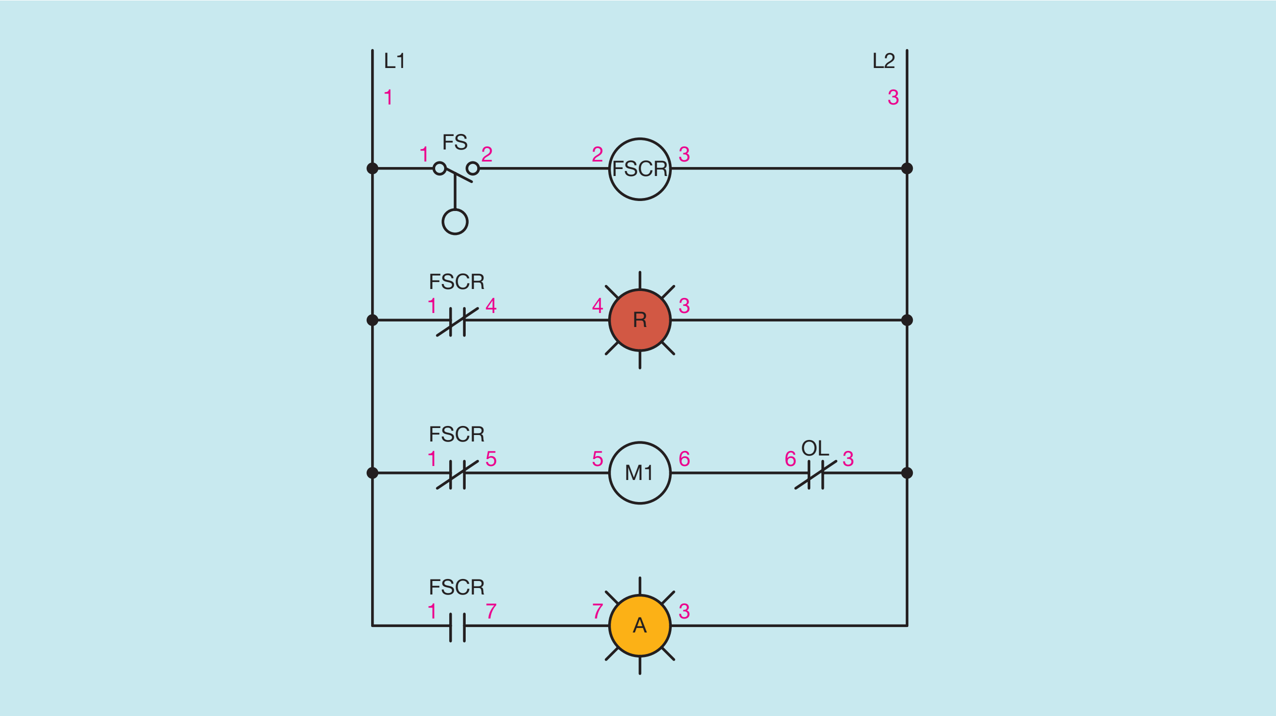


Figure 24–1 Schematic with components numbered. (Source: Delmar/Cengage Learning.)

Review Question

1. Are numbering systems other than the one described in this text used to develop wiring diagrams from schematic diagrams?

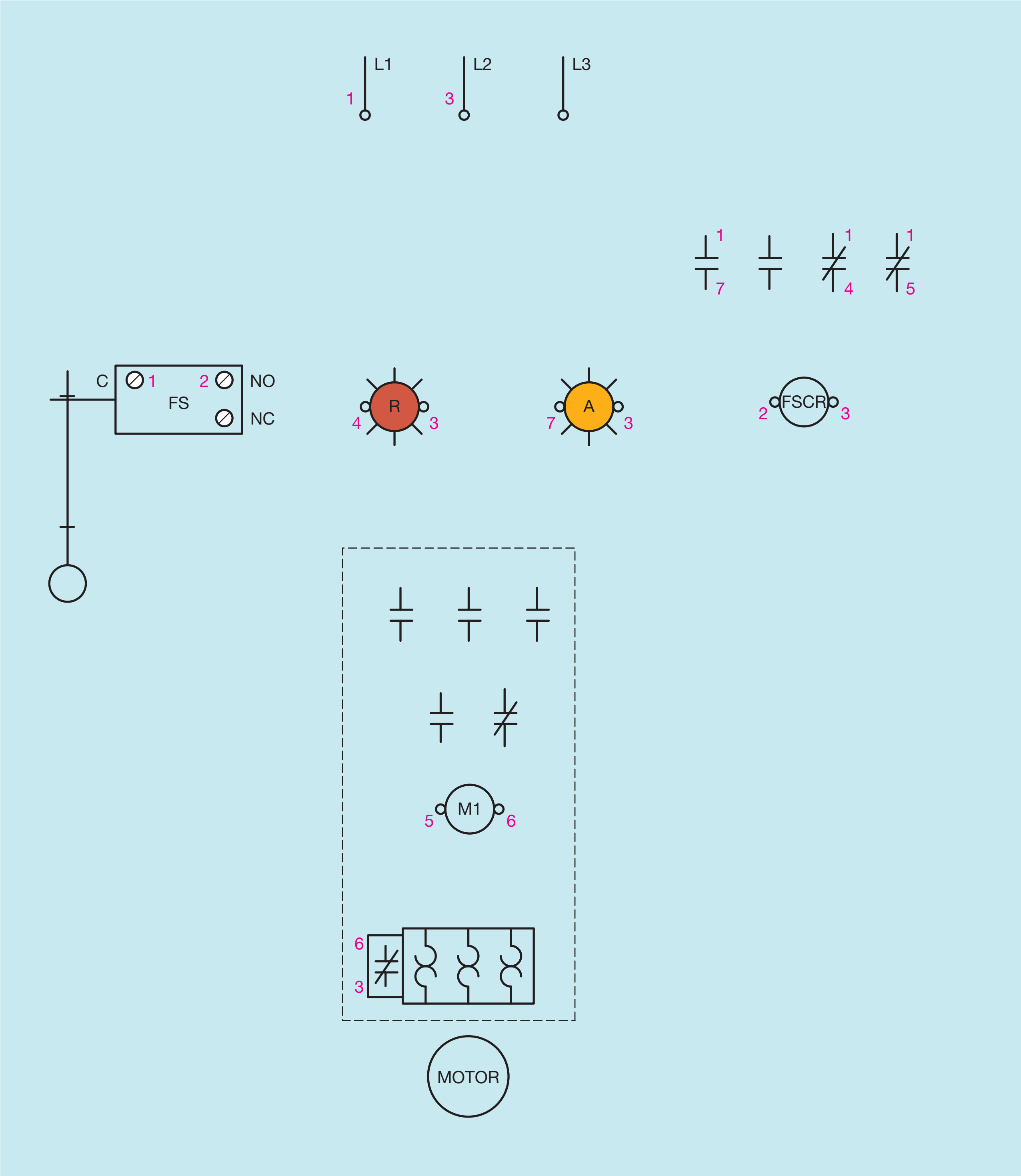


Figure 24–2 Components have been numbered to correspond with the schematic. (Source: Delmar/Cengage Learning.)

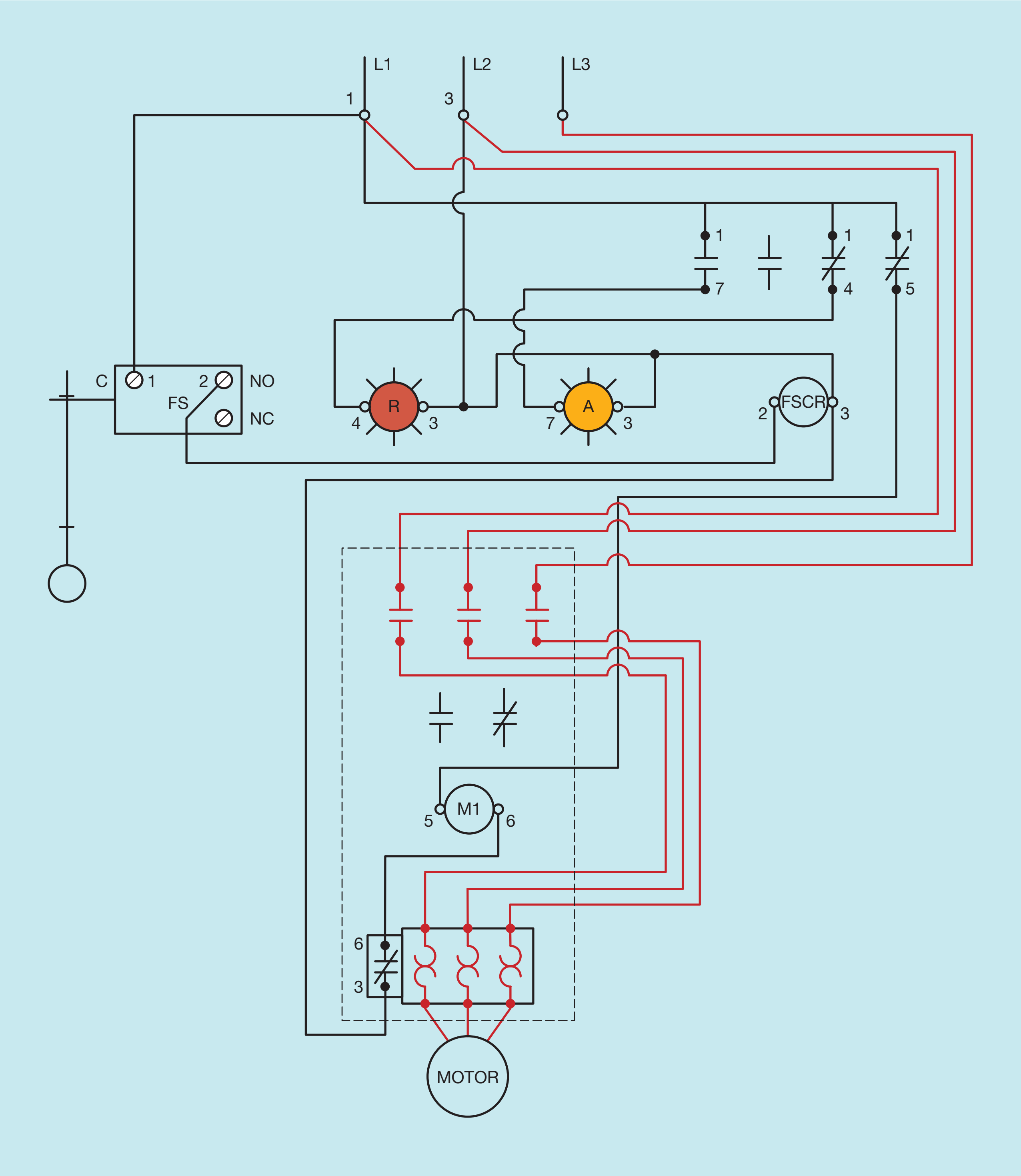


Figure 24–3 Wire connections are made by connecting like numbers. (Source: Delmar/Cengage Learning.)

CHAPTER 25

READING LARGE SCHEMATIC DIAGRAMS

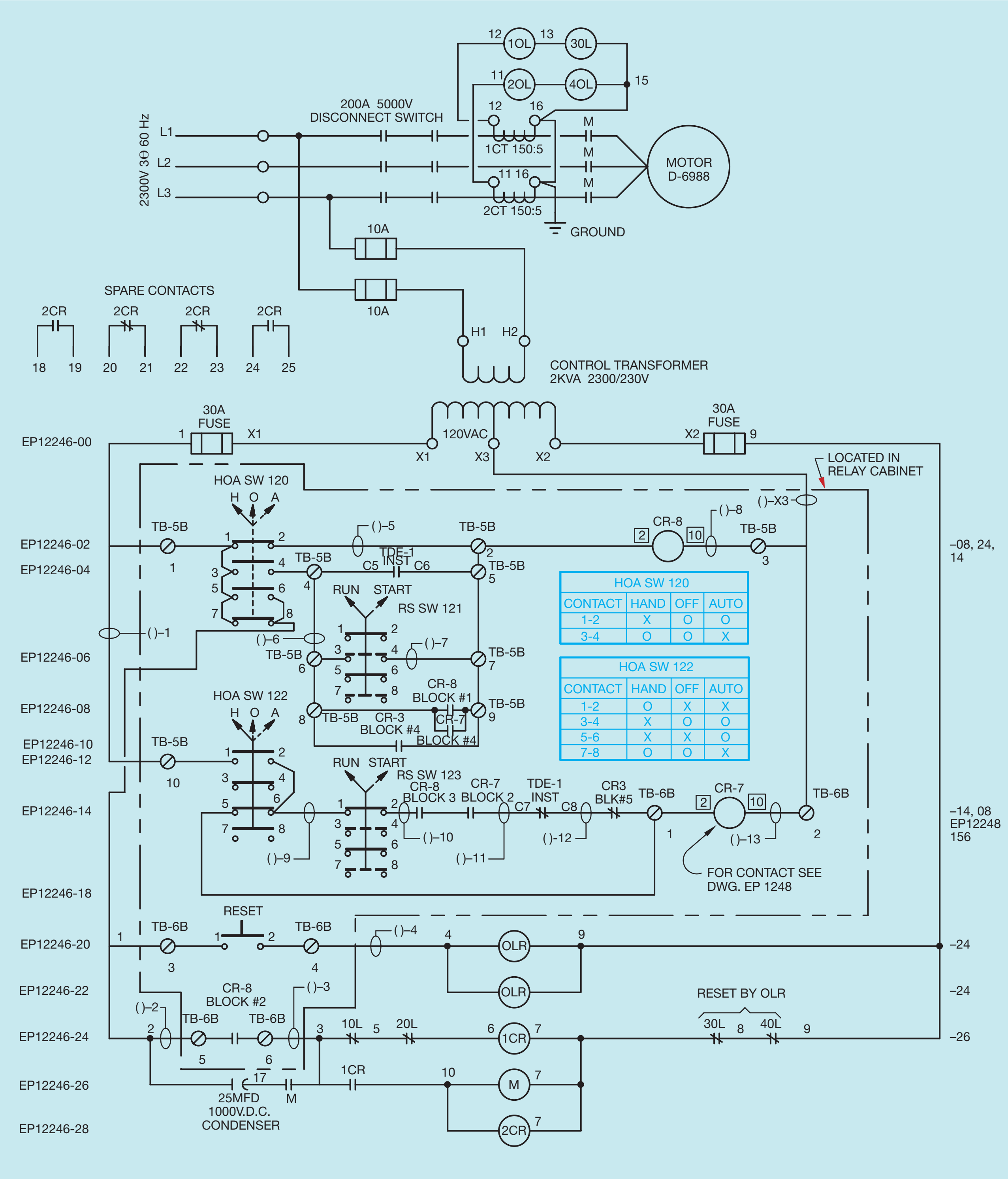
OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss notations written on large schematics.
- Find contacts that are controlled by specific coils on different lines.
- Find contacts that are controlled by specific coils on different electrical prints.

The schematics presented in this text so far have been small and intended to teach circuit logic and how basic control systems operate. Schematics in industry, however, are often much more complicated and may contain several pages. Notation is generally used to help the electrician interpret the meaning of certain components and find contacts that are controlled by coils. The schematic shown in Figure 25–1 is part of a typical industrial control schematic. Refer to this schematic to locate the following information provided about the control system.

1. At the top left-hand side find the notation: (2300V 3θ 60 Hz). This indicates that the motor is connected to a 2300 volt, three-phase, 60 hertz power line (Figure 25–2).
2. To the right of the first notation, locate the notation: (200A 5000V DISCONNECT SWITCH). This indicates that there is a 200 ampere disconnect switch, rated at 5000 volts, that can be used to disconnect the motor from the power line. Also notice that there are six contacts for this switch, two in each line. This is common for high voltage disconnect switches.
3. At the top of the schematic, locate the two current transformers, 1CT and 2CT. These two current transformers are used to detect the amount of motor current. Current transformers produce an output current of 5 amperes under a short circuit condition. The notation beside each CT indicates that it has a ratio of 150 to 5. The secondary of 1CT is connected to 1OL and 3OL. The secondary of 2CT is connected to 2OL and 4OL. Overload coils 1OL and 3OL are connected in series, which forces each to have the same current flow. Also note that coil symbols (not heater symbols) are used for the overloads. This indicates that these overload relays are magnetic, rather than thermal.



HOA SW 120			
CONTACT	HAND	OFF	AUTO
1-2	X	O	O
3-4	O	O	X

HOA SW 122			
CONTACT	HAND	OFF	AUTO
1-2	O	X	X
3-4	X	O	O
5-6	X	X	O
7-8	O	O	X

Figure 25–1 Typical industrial schematic diagram. (Source: Delmar/Cengage Learning.)

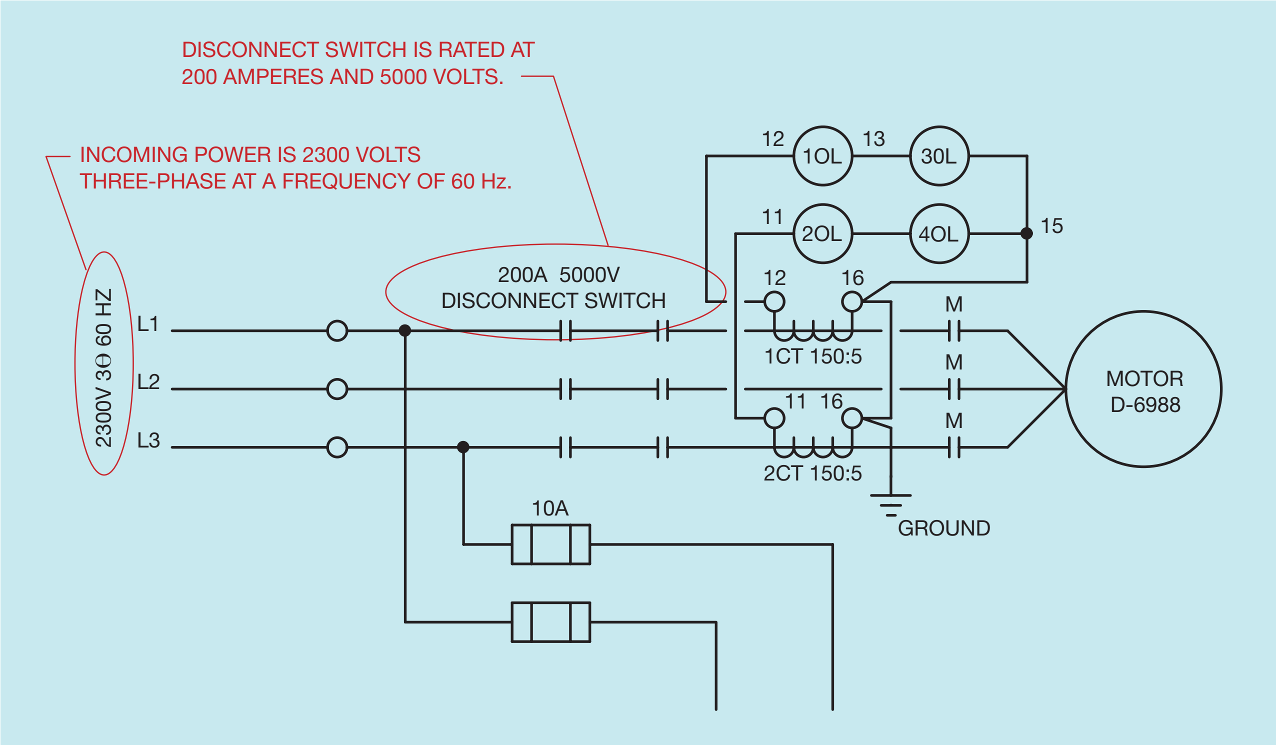


Figure 25–2 (Source: Delmar/Cengage Learning.)

4. Locate the two 10 ampere fuses connected to the primary of the control transformer (Figure 25–3). The control transformer is rated at 2 kilovolt-amperes (2000 volt-amperes). The high voltage winding is rated at 2300 volts and the secondary winding is rated at 230 volts. Also note that the secondary winding contains a center tap (X3). The center tap can be used to provide 120 volts from either of the other X terminals. Terminals X1 and X2 are connected to 30 ampere fuses.

5. To the left of the 30 ampere fuse connected to terminal X1, locate the notation (EP12246-00) (Figure 25–4). This notation indicates that you are looking at Electrical Print 12246, and line 00. Most multi-page schematics will use some form of notation similar to this to indicate the page and line number you are viewing.

6. On line number EP12246-02, locate the HAND-OFF-AUTOMATIC switch labeled HOA SW 120. Also locate the contact chart for this switch just to the right of the center of the schematic. The chart indicates connection between specific terminals for different settings of the switch. The X indicates connection between terminals and O indicates no connection. Notice that in the HAND position, there is connection between terminals 1 and 2. There is no connection between terminals 3 and 4. In the OFF position, there is no connection between any of the terminals. In the AUTO position, there is connection between terminals 3 and 4 but no connection between terminals 1 and 2. Referring back to the switch itself, notice that there are three arrows drawn at the top of the switch. One arrow points to H, one points to O, and one points to A. The line connected to the arrowhead pointed at H is shown as a solid line. The lines connected to the other two arrowheads are shown as broken or dashed. The solid line represents the position the switch is set in for the contact arrangement shown on the schematic. The schematic indicates that at the present time there is a connection between terminals 1 and 2, and no connection between terminals 3 and 4. This is consistent with the contact chart for this switch.

7. Locate the RUN-START switch (RS SW 121) to the right and below HOA SW 120. A contact chart is not shown for this switch. Since there are only two

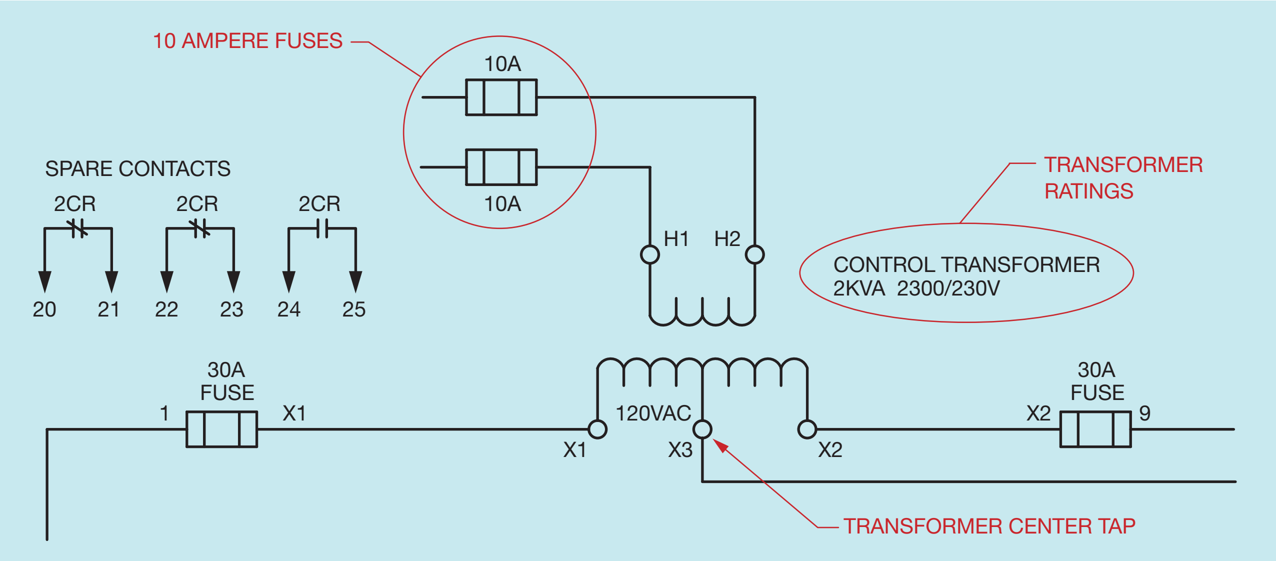


Figure 25–3 (Source: Delmar/Cengage Learning.)

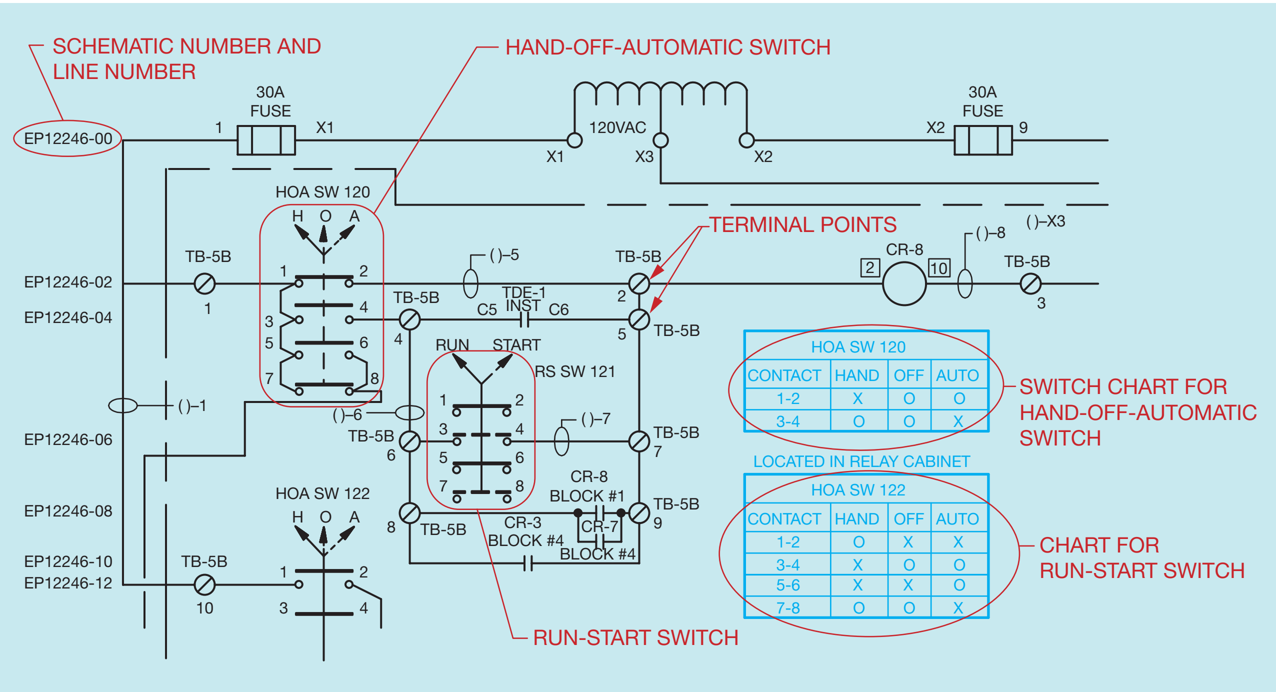


Figure 25–4 (Source: Delmar/Cengage Learning.)

positions for this switch, a different method is employed to indicate contact position for the different switch positions. Notice that arrowheads at the top of the switch are pointing at the RUN and START positions. The line drawn to the RUN position is solid and the line drawn to the START position is shown as broken or dashed. The schematic shows a solid line between switch terminals 1 and 2, and 5 and 6. Dashed lines are shown between terminals 3 and 4, and 7 and 8. When the switch is set in the

RUN position, there is a connection between terminals 1 and 2, and 5 and 6. When the switch is in the START position, there is a connection between terminals 3 and 4, and 7 and 8.

8. On line 02, there are three terminals marked TB-5B. These indicate terminal block points. Locate the terminal with 2 drawn beside it. This wire position is located on screw terminal #2 of terminal point 5B. Another terminal block point is shown below it. This terminal location is screw terminal #5 of terminal point 5B.
9. Find relay coil CR-8 on line 02 (Figure 25–5). CR stands for Control Relay. Notice that the numbers 2 and 10 on each side of the coil are shown inside a square box. The square box indicates that these are terminal numbers for the relay and should not be confused with wire numbers. Terminals 2 and 10 are standard coil connections for relays designed to fit into an eleven-pin tube socket. If you were trying to physically locate this relay, the pin numbers would be a strong hint as to what you are trying to find.
10. Beside pin number 10 of relay coil CR-8 is a circle with a line connected to it. The line goes to a symbol that looks like ()–8. This indicates a test point. Test points are often placed at strategic points to aid in troubleshooting when it becomes necessary.
11. At the far right-hand side of line 02 is the notation (-08, 24, 14). These numbers indicate the lines on the schematic where contacts controlled by relay coil CR-8 can be found. Find the contacts labeled CR-8 on these lines of the schematic.
12. Locate coil CR-7 on line 14 (Figure 25–1 and Figure 25–6). At the far right-hand side, find the notation (-14, 08, EP12248 156). This notation again indicates the places where contacts controlled by coil CR-7 can be found. CR-7 contacts are located on lines 14 and 08 in this schematic and on line 156 of Electrical Print #12248.
13. At the right side of the schematic between lines 00 and 02 is the notation LOCATED IN RELAY CABINET. An arrow is pointing at a dashed line. This gives the physical location of such control components as starters, relays, and terminal blocks. Push buttons, HOA switches, pilot lights, and so on are generally located on a control terminal where an operator has access to them.

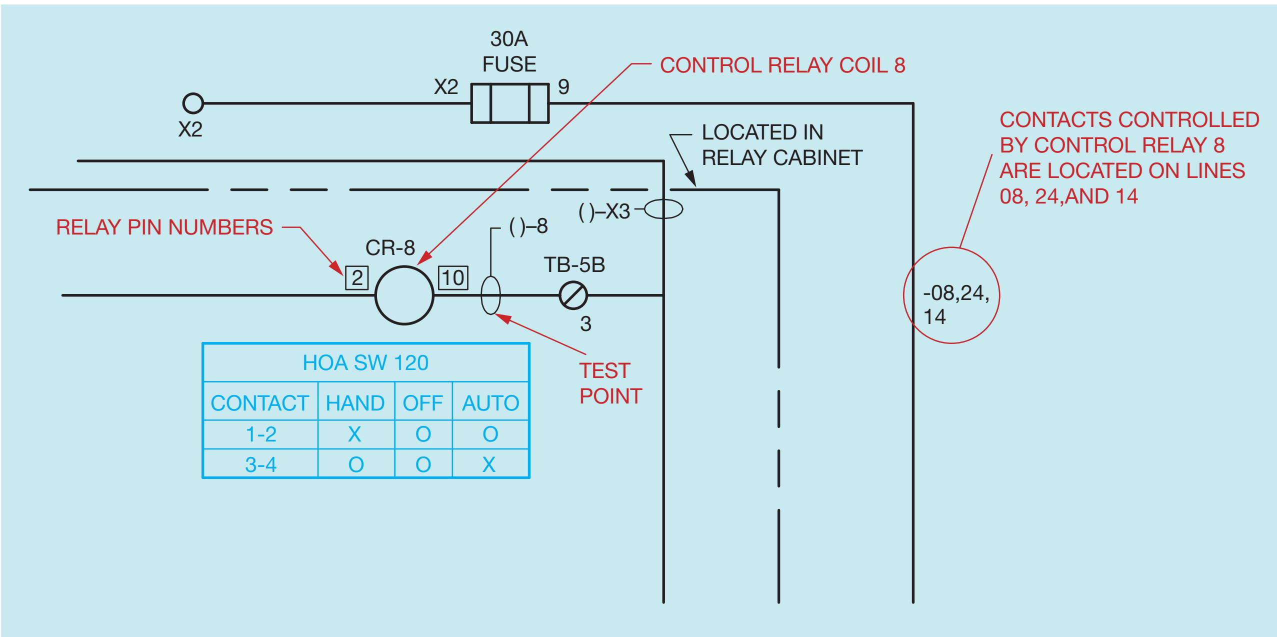


Figure 25–5 (Source: Delmar/Cengage Learning.)

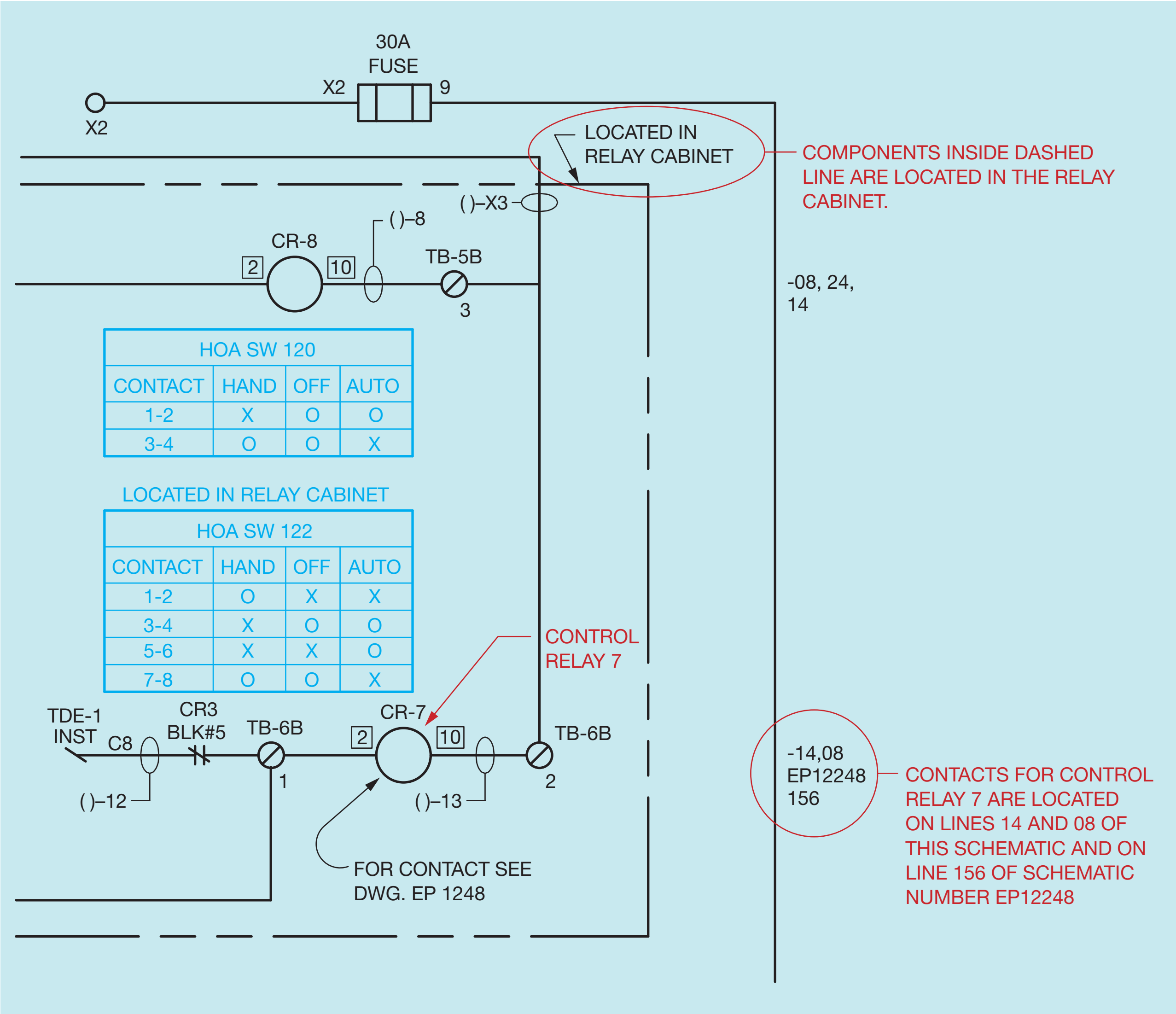


Figure 25–6 (Source: Delmar/Cengage Learning.)

These are notations that are common to many industrial control schematics. Nothing is standard, however. Many manufacturers use their own numbering and notation system, specific to their company. Some use the NEMA symbols that are discussed in this text and others do not. With practice and an understanding of basic control logic and schematics, most electricians can determine what these different symbols mean and the way they are used in a circuit. The old saying “Practice makes perfect” certainly applies to reading schematic diagrams.

Review Questions

Refer to Figure 25–1 to answer the following questions.

1. When switch HOA SW 122 is in the OFF position, which contacts have connection between them?
2. How much voltage will be applied to coil 1CR when it is energized?
3. Referring to switch RS SW 123, in what position must the switch be set to make connection between terminals 3 and 4?
4. What are the terminal numbers for the two normally open spare contacts controlled by coil 2CR?
5. How much voltage is applied to coil CR-7 when it is energized?
6. What contact(s) is/are located between screw numbers 8 and 9 of terminal block 5B?
7. Between which terminal block and screw numbers is relay coil CR-7 located?
8. Assume that HOA SW 120 has been set in the AUTO position. List four ways by which coil CR-8 could be energized.
9. In what position must switch HOA SW 123 be set to make connection between terminals 3 and 4?
10. If one of the magnetic overload relays opens its contact, how can it be reset?

CHAPTER 26

INSTALLING CONTROL SYSTEMS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the installation of control circuits.
- Use the number system on a schematic diagram to troubleshoot a circuit.

Wiring diagrams can be misleading in that they show all components grouped together. In actual practice, the control relays and motor starters may be located in one cabinet, the push buttons and pilot lights in a control panel, and pilot devices such as limit switches and pressure switches may be located on the machine itself (Figure 26–1). Most control systems use a relay cabinet to house the control relays and motor starters. Wiring is brought to the relay cabinet from the push buttons and pilot lights located in the control panel, and from the pilot devices located on the machine. All of the connections are made inside the relay cabinet.

Relay cabinets generally contain rows of terminal strips. These terminal strips are used as connection points between the control wiring inside the cabinet and inputs or outputs to the machine or control panel. Most terminal strips are designed so that connection points can be numbered. This type of system can be more costly to install, but it will more than pay for the extra cost in time saved when troubleshooting. For example, assume that an electrician desires to check limit switch LS15 to see if its contacts are open or closed. Limit switch LS15 is located on the machine, but assume that in the schematic one side of the limit switch is number 25 and the other side of the limit switch is number 26. If numbers 25 and 26 can be located on the terminal strip, the electrician can check the limit switch from the relay cabinet without having to go to the machine and remove the cover from the limit switch. The electrician will only have to connect the probes of a voltmeter across terminals 25 and 26. If the voltmeter indicates the control voltage of the circuit, the limit switch contacts are open. If the voltmeter indicates 0 volts, the limit switch contacts are closed.

Part of a typical ladder diagram is shown in Figure 26–2. Wire numbers have been placed on the schematic. Connections to the components using a terminal strip are shown in Figure 26–3. An industrial diagram showing terminal block connections is shown in Figure 26–4.

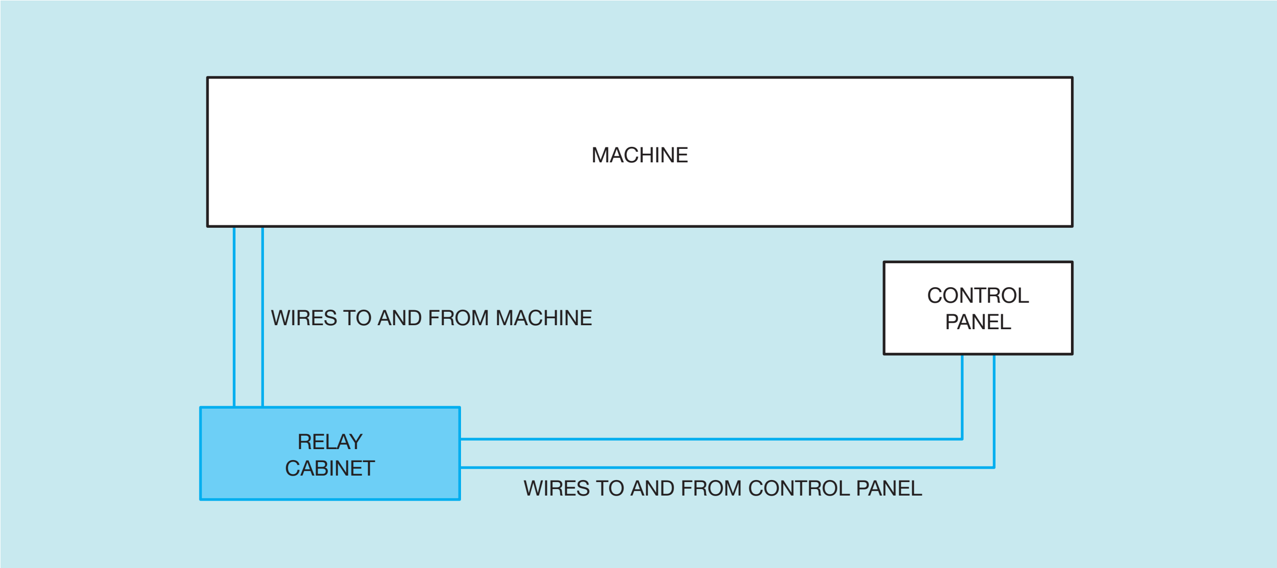


Figure 26–1 Most wire connections are made inside the relay cabinet. (Source: Delmar/Cengage Learning.)

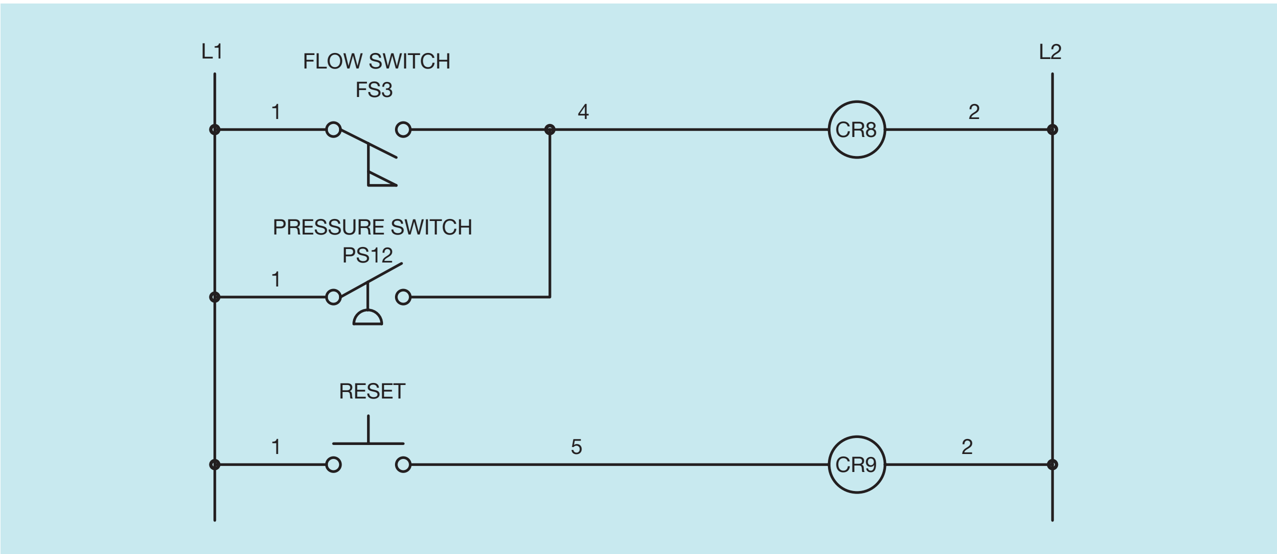


Figure 26–2 Part of a typical ladder or schematic diagram. (Source: Delmar/Cengage Learning.)

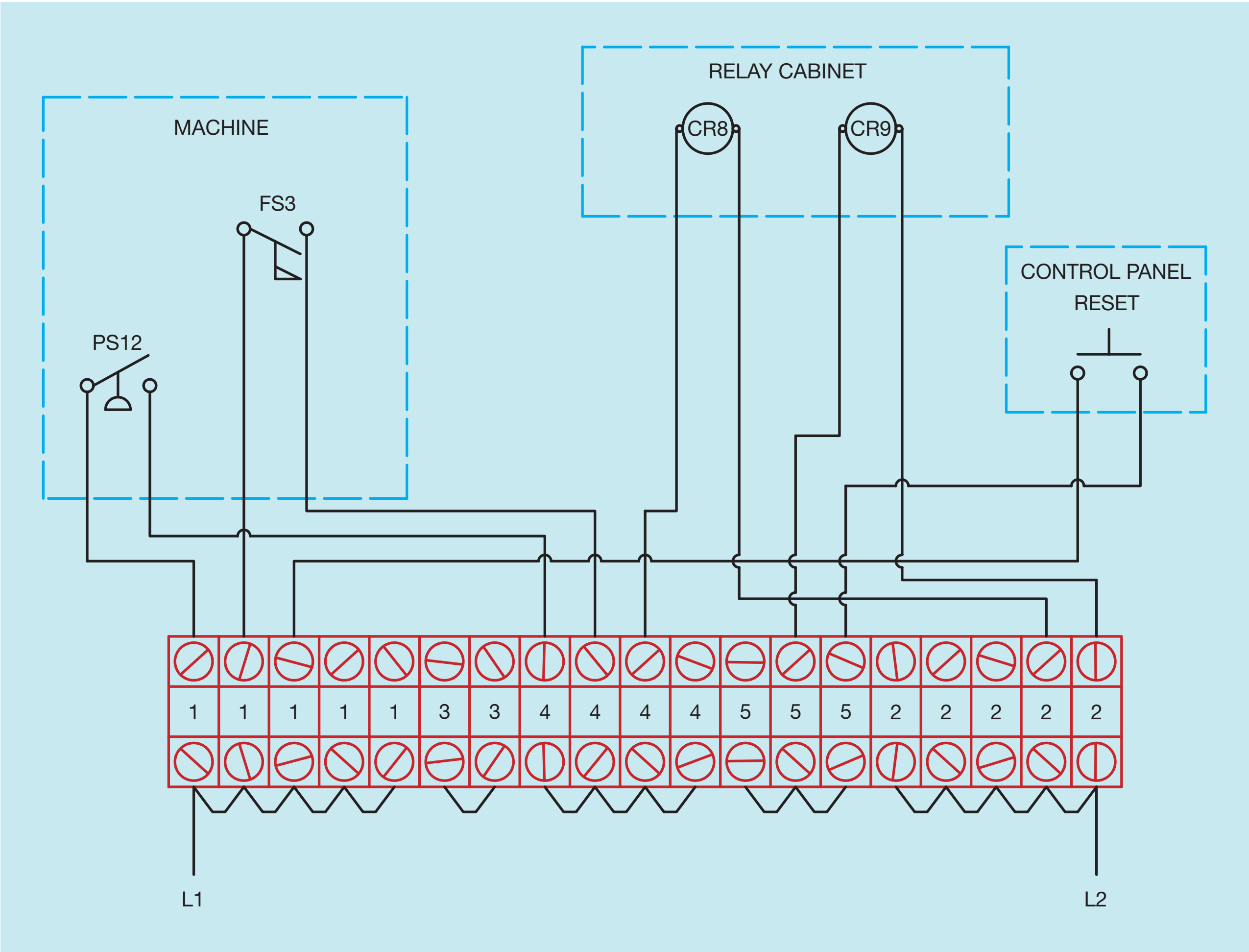


Figure 26–3 Typical connections using a terminal strip. (Source: Delmar/Cengage Learning.)

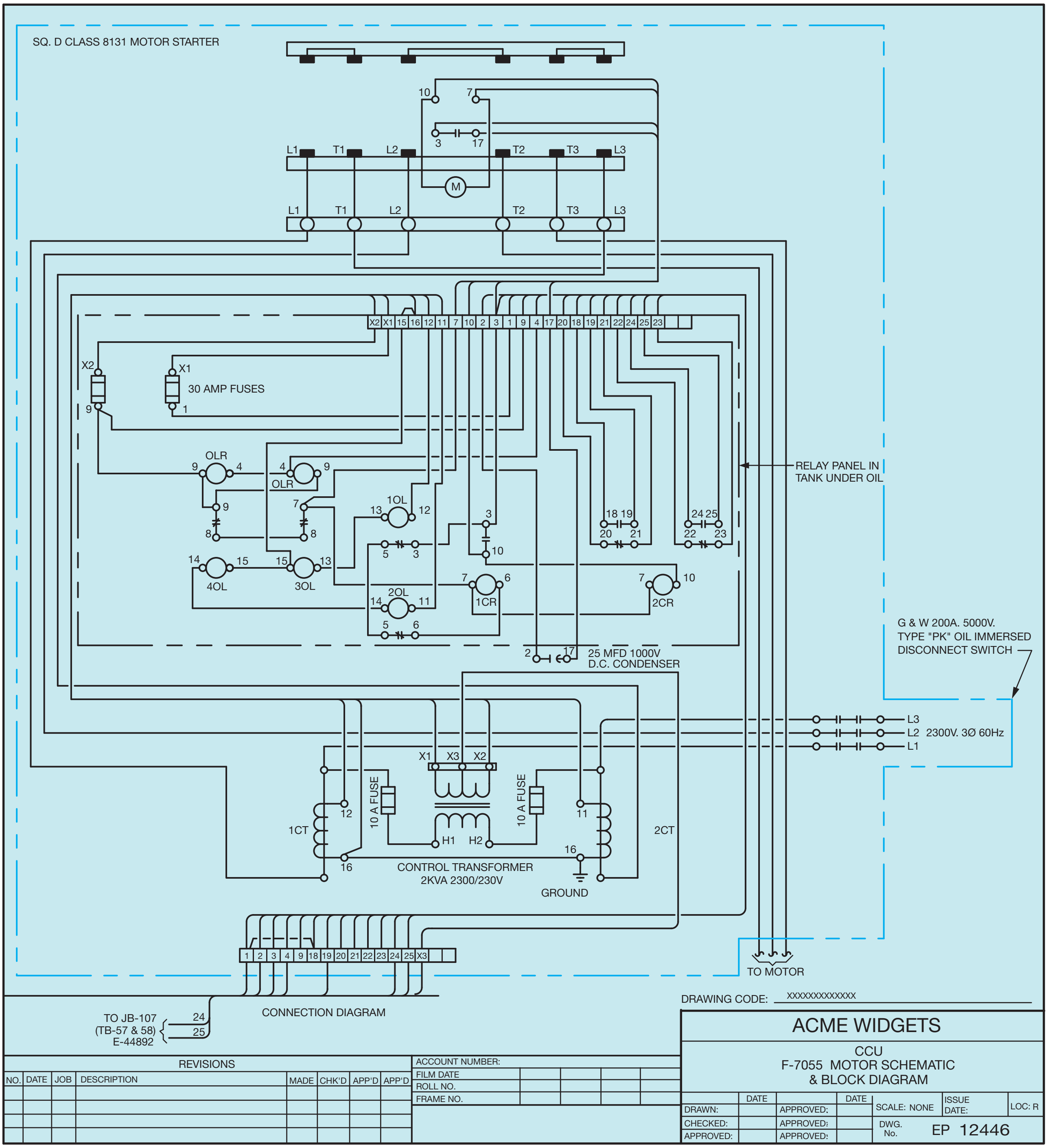


Figure 26–4 Industrial diagram showing terminal block connections. (Source: Delmar/Cengage Learning.)

Review Questions

1. Define a schematic diagram.
2. Define a wiring diagram.
3. Are symbols in a schematic shown in their energized or de-energized condition?
4. Draw the standard NEMA symbol for the following components.
   a. Float switch (NO)
   b. Limit switch (NC)
   c. Normally open push button
   d. Relay coil
   e. Overload contact
5. You are an electrician working in an industrial plant. Your job is to connect the components shown in Figure 26–3 to the terminal strip. Should switch FS3 be connected normally open or normally closed? Explain your answer.
6. Should switch PS12 be connected normally open or normally closed? Explain your answer.

CHAPTER 27

HAND-OFF-AUTOMATIC CONTROLS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of a hand-off-automatic control switch.
- Connect a hand-off-automatic control circuit.
- Recognize hand-off-automatic switches on a schematic diagram.

Hand-off-automatic controls are used to permit an operator to select between automatic or manual operation of a motor. The circuit shown in Figure 27–1 permits a motor to be operated by a float switch or to be run manually. The switch is shown as a single-pole double-throw switch with a center Off position.

Another symbol for a hand-off-automatic switch is shown in Figure 27–2. This switch is shown to contain two separate sets of contacts. One set is labeled 1-2 and the other is labeled 3-4. The switch chart indicates that when the switch is in the Off position, there is no connection between any of the contacts. When set in the Hand position, connection is made between terminals 1 and 2. When set in the Automatic position, connection is made between terminals 3 and 4. This circuit is the control for a large fan that pulls air through a building. The motor in this example is water cooled: it requires a flow of cooling water when running. Starter M1 controls the fan motor, and starter M2 controls a pump used to circulate water through the motor. Flow switch FS1 detects the flow of water to insure that the fan motor cannot run if there is no flow of cooling water. A warning lamp indicates that there is no flow of water when the circuit is energized.

When the hand-off-automatic switch is set in the Hand position, connection is made between terminals 1 and 2. This permits the motor to be controlled by a start-stop push-button station. In this mode, the fan will run continuously until the Stop button is pressed. When the HOA switch is placed in the Auto position, a thermostat controls the action of the fan. A combination push-button station with a hand-off-automatic switch and pilot lamp is shown in Figure 27–3.

The flow switch shown in Figure 27–2 employs two separate contacts, one normally open and the other normally closed. The dashed line indicates that the two switches are mechanically connected. When one switch changes position the other switch changes position also. If a flow switch with two separate switches cannot be obtained, it is possible to use a single-pole

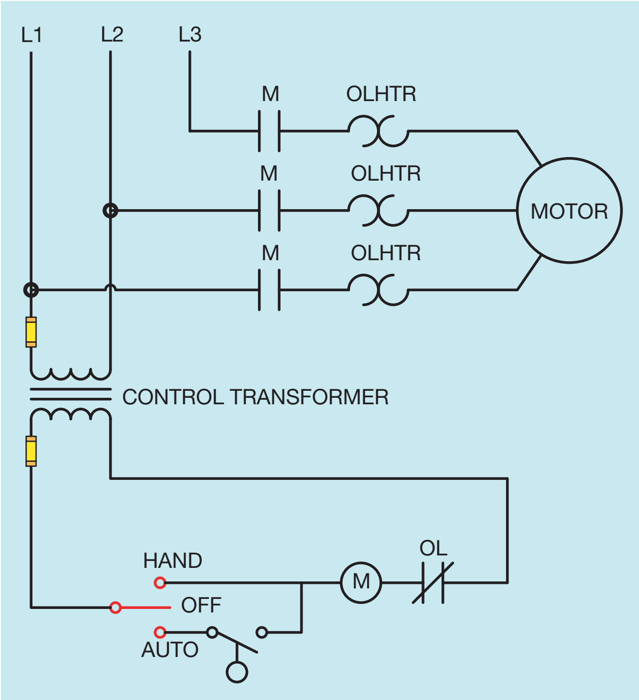


Figure 27–1 Hand-off-automatic switch provides manual control of a motor or control can be provided by a float switch. (Source: Delmar/Cengage Learning.)

Figure 27–3 Push-button control station with hand-off-auto switch and pilot light. (Source: Delmar/Cengage Learning.)

double-throw switch with a common terminal, a normally open terminal, and a normally closed terminal in this circuit. Notice that one terminal of both the normally open switch and normally closed switch are

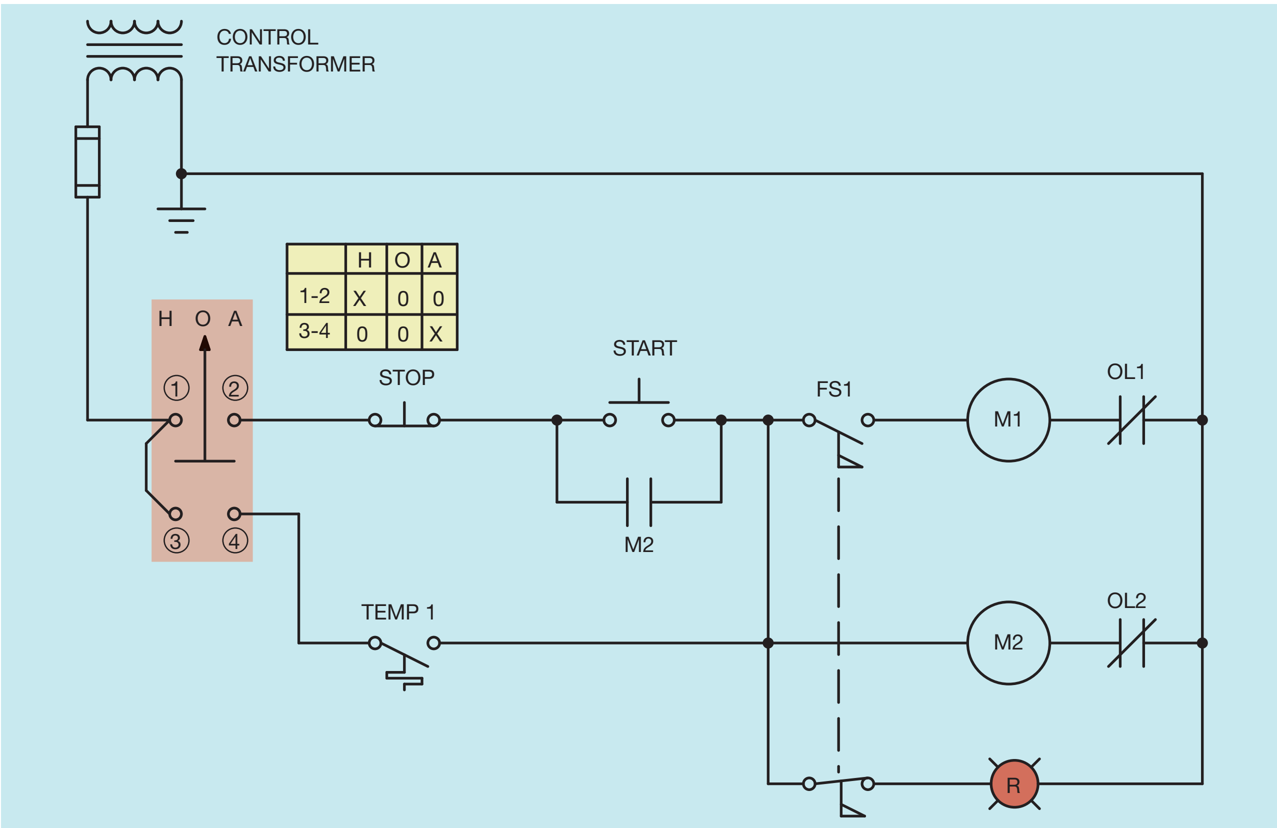


Figure 27–2 A water-cooled motor must have a flow of water before it is permitted to run. (Source: Delmar/Cengage Learning.)

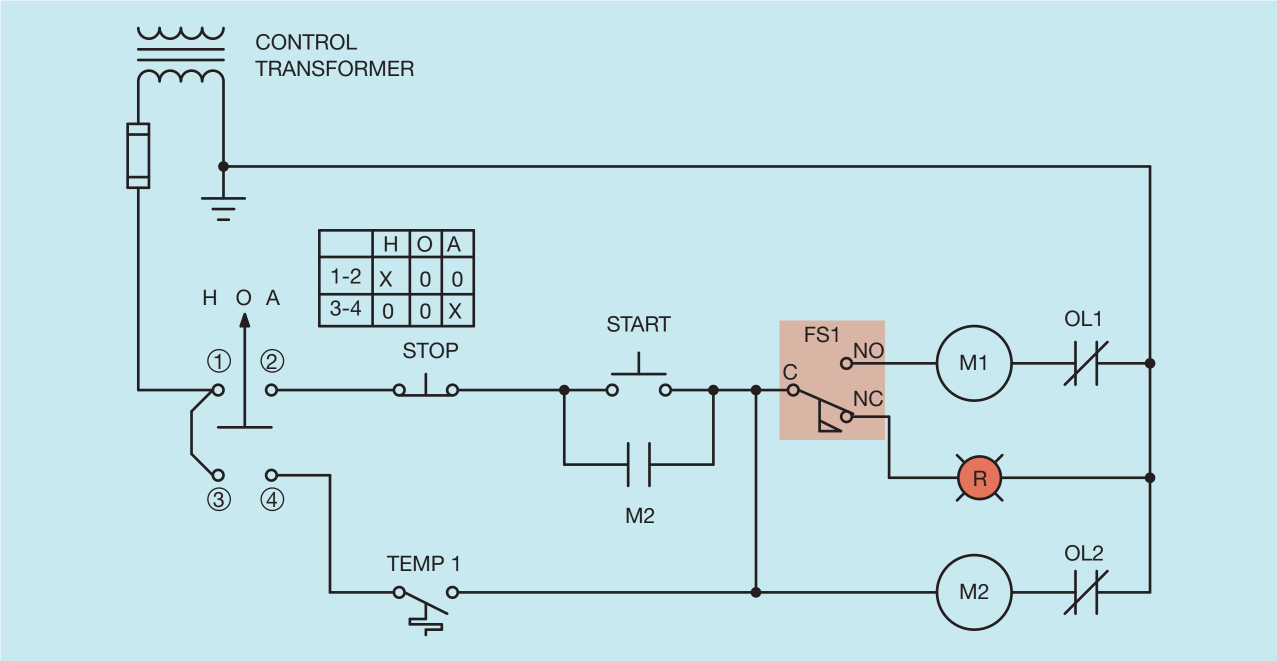


Figure 27–4 A flow with two separate switches has been replaced with a single-pole double-throw switch. (Source: Delmar/Cengage Learning.)

connected together. This forms a common point for both switches and could be used as the common terminal for a flow switch that contains a single-pole double-throw switch, Figure 27–4. Although the circuit shown in Figure 27–4 looks different than the circuit in Figure 27–2, electrically they are the same and will operate in the same manner.

Review Questions

1. Refer to the circuit shown in Figure 27–2. Would it be possible to replace the hand-off-auto switch in this circuit with a hand-off-auto switch that contained a common terminal and center Off position like the HOA switch shown in Figure 27–1? Explain your answer.
2. Refer to the circuit shown in Figure 27–2. Would the temperature have to increase or decrease to permit the fan to turn on?
3. Refer to the circuit shown in Figure 27–2. Which starter controls the holding contacts connected in parallel with the start push button?
4. Refer to the circuit shown in Figure 27–4. Assume that the HOA switch is in the Hand position and that the motor is running. Now assume that OL1 opens its contacts. Would this cause the pump motor to stop operating? Explain your answer.
5. Refer to the circuit shown in Figure 27–2. Assume that the HOA switch is in the Hand position and that the motor is running. Now assume that OL2 opens its contacts. Would this stop the operation of the fan motor? Explain your answer.
6. Refer to the circuit shown in Figure 27–4. Assume that the HOA switch is in the Auto position. Also assume the fan is running. Now assume that the fan stops running and the red warning light turns on. Which of the following could cause this condition?
   a. OL1 contacts are open
   b. Temp 1 switch is open
   c. OL2 contacts are open
   d. The HOA switch has been moved to the Off position
7. Refer to the circuit shown in Figure 27–2. Assume that the HOA switch is set in the Hand position.

When the Start button is pressed, the red warning lamp lights. When the Start button is released, the light turns off but the fan motor does not start. Each time the Start button is pressed, the warning lamp lights for as long as the Start button is held down, but it goes out each time the Start button is released, and the fan does not start. Which of the following could cause this condition?

a. Temp 1 switch is open
b. M2 starter coil is open
c. M1 starter coil is open
d. The Stop push button is open

CHAPTER 28

MULTIPLE PUSH-BUTTON STATIONS

OBJECTIVES

After studying this chapter, the student will be able to:

- Place wire numbers on a schematic diagram.
- Place corresponding numbers on control components.
- Draw a wiring diagram from a schematic diagram.
- Connect a control circuit using two stop and two start push buttons.
- Discuss how components are to be connected to perform the functions of start or stop for a control circuit.

There may be times when it is desirable to have more than one start-stop push-button station to control a motor. In this chapter, the basic start-stop push-button control circuit will be modified to include a second stop and start push button.

When a component is used to perform the function of **stop** in a control circuit, it will generally be a normally closed component and be connected in series with the motor starter coil. In this example, a second Stop push button is to be added to the existing start-stop control circuit shown in Figure 28–1. The second push button will be added to the control circuit by connecting it in series with the existing Stop push button.

When a component is used to perform the function of **start,** it is generally normally open and connected in parallel with the existing start button (Figure 28–2). If either Start button is pressed, a circuit will be completed to M coil. When M coil energizes, all M contacts change position. The three load contacts connected between the three-phase power line and the motor close to connect the motor to the line. The normally open auxiliary contact connected in parallel with the two Start buttons closes to maintain the circuit to M coil when the Start button is released.

Developing a Wiring Diagram

Now that the circuit logic has been developed in the form of a schematic diagram, a wiring diagram will be drawn from the schematic. The components needed

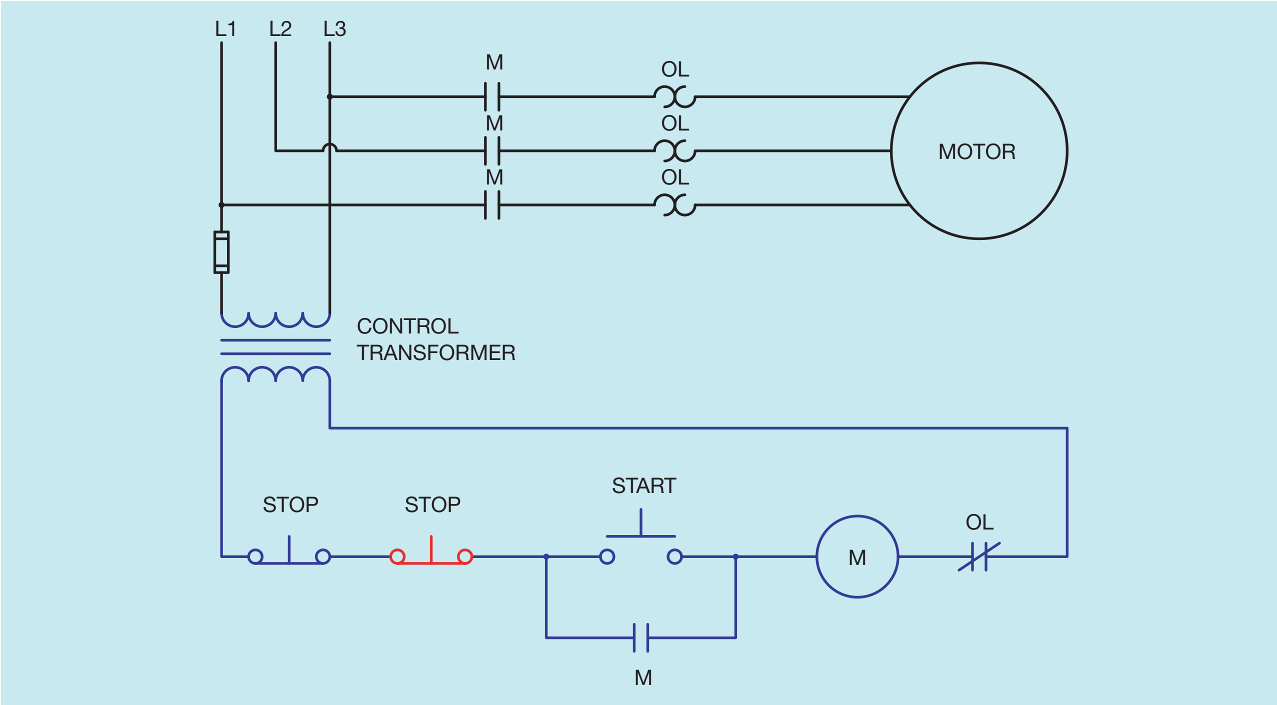


Figure 28–1 A second Stop push button is added to the circuit. (Source: Delmar/Cengage Learning.)

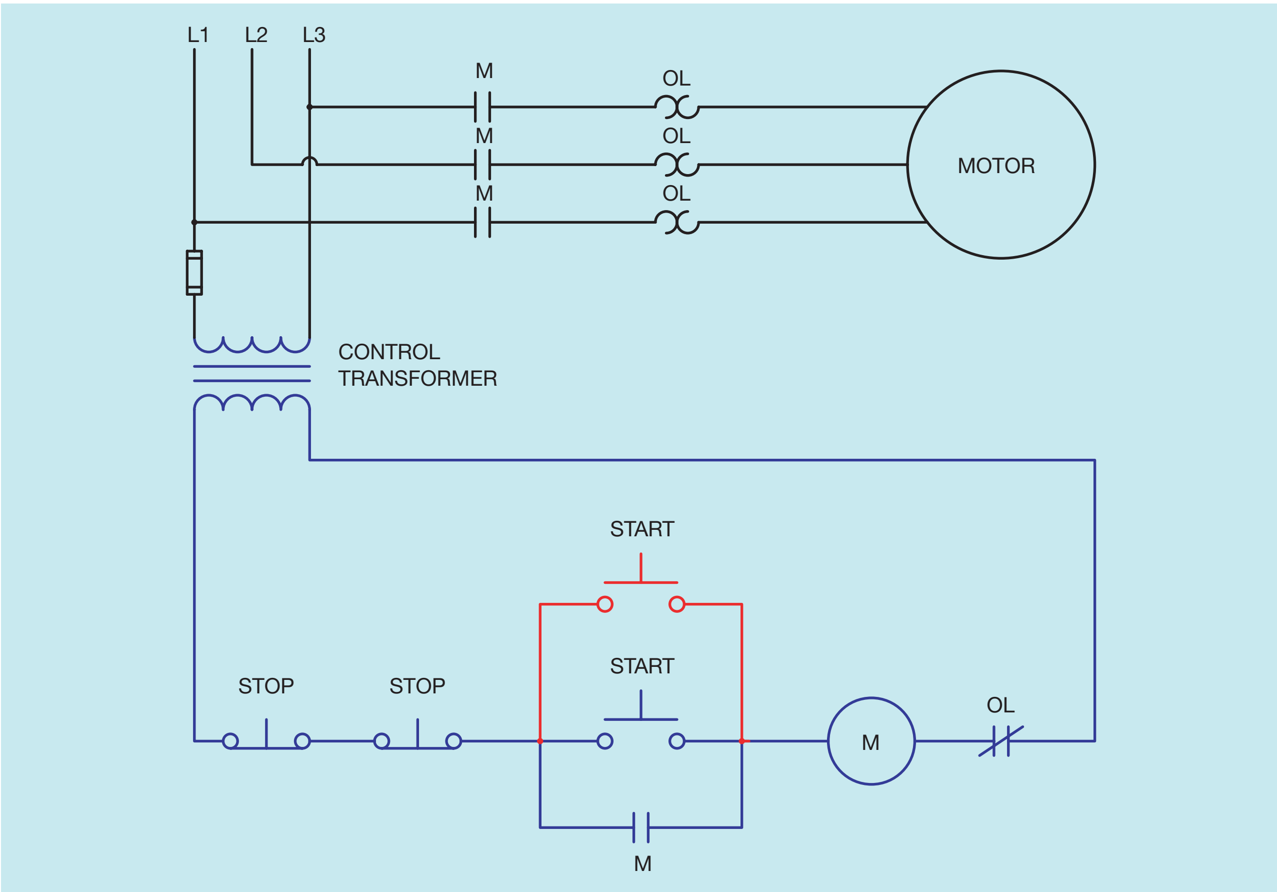


Figure 28–2 A second Start push button is added to the circuit. (Source: Delmar/Cengage Learning.)

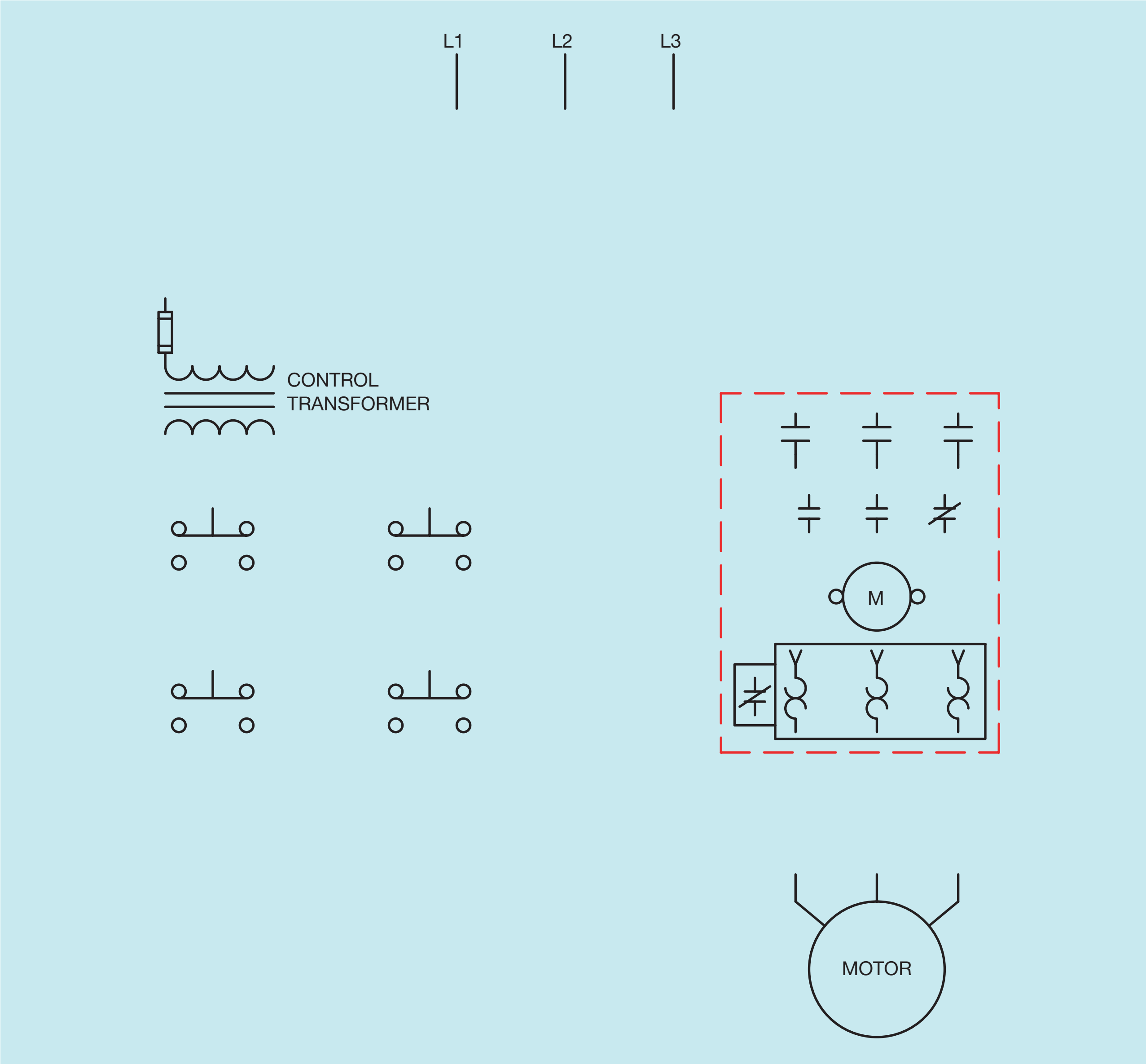


Figure 28–3 Components needed to construct the circuit. (Source: Delmar/Cengage Learning.)

to connect this circuit are shown in Figure 28–3. Following the same procedure discussed in chapter 22, wire numbers are placed on the schematic diagram (Figure 28–4). After wire numbers are placed on the schematic, corresponding numbers are placed on the control components (Figure 28–5).

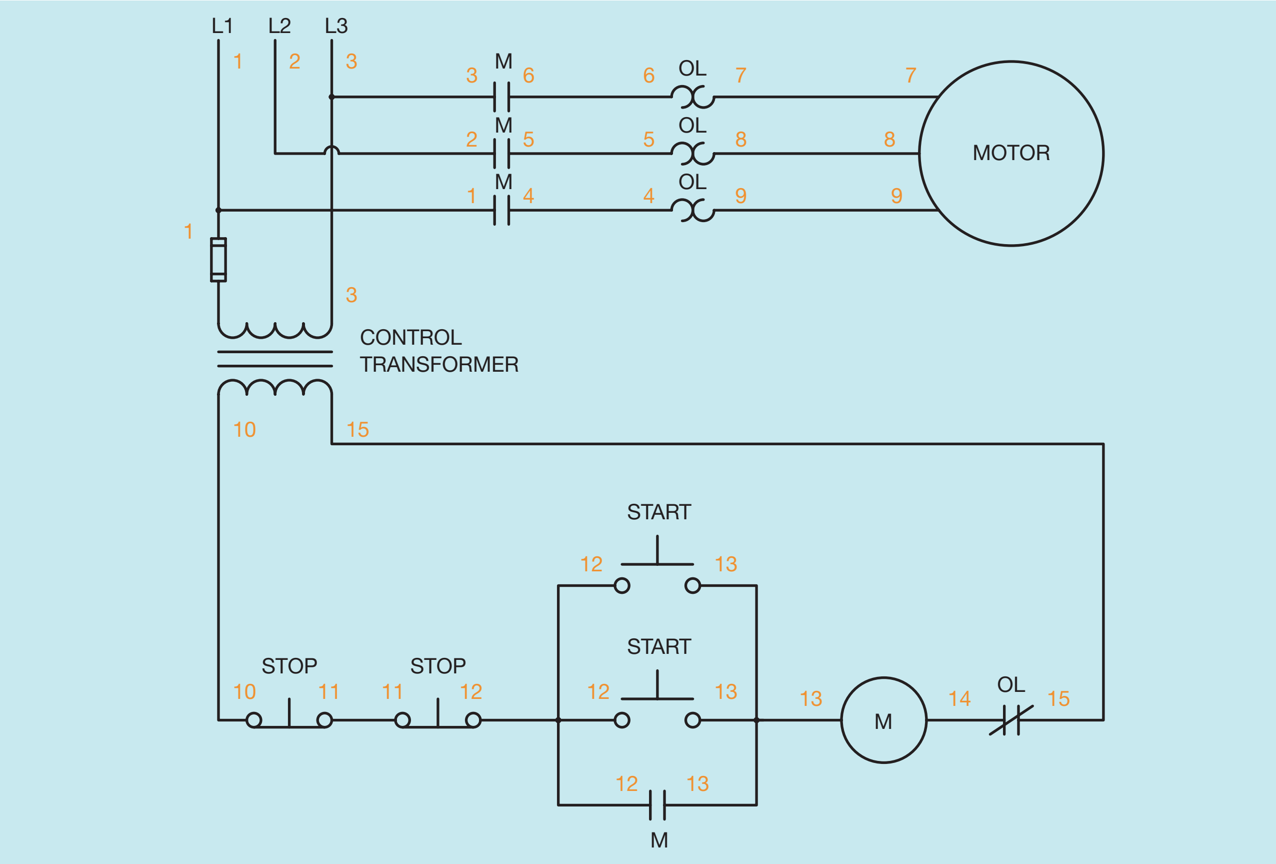


Figure 28–4 Numbers are placed on the schematic. (Source: Delmar/Cengage Learning.)

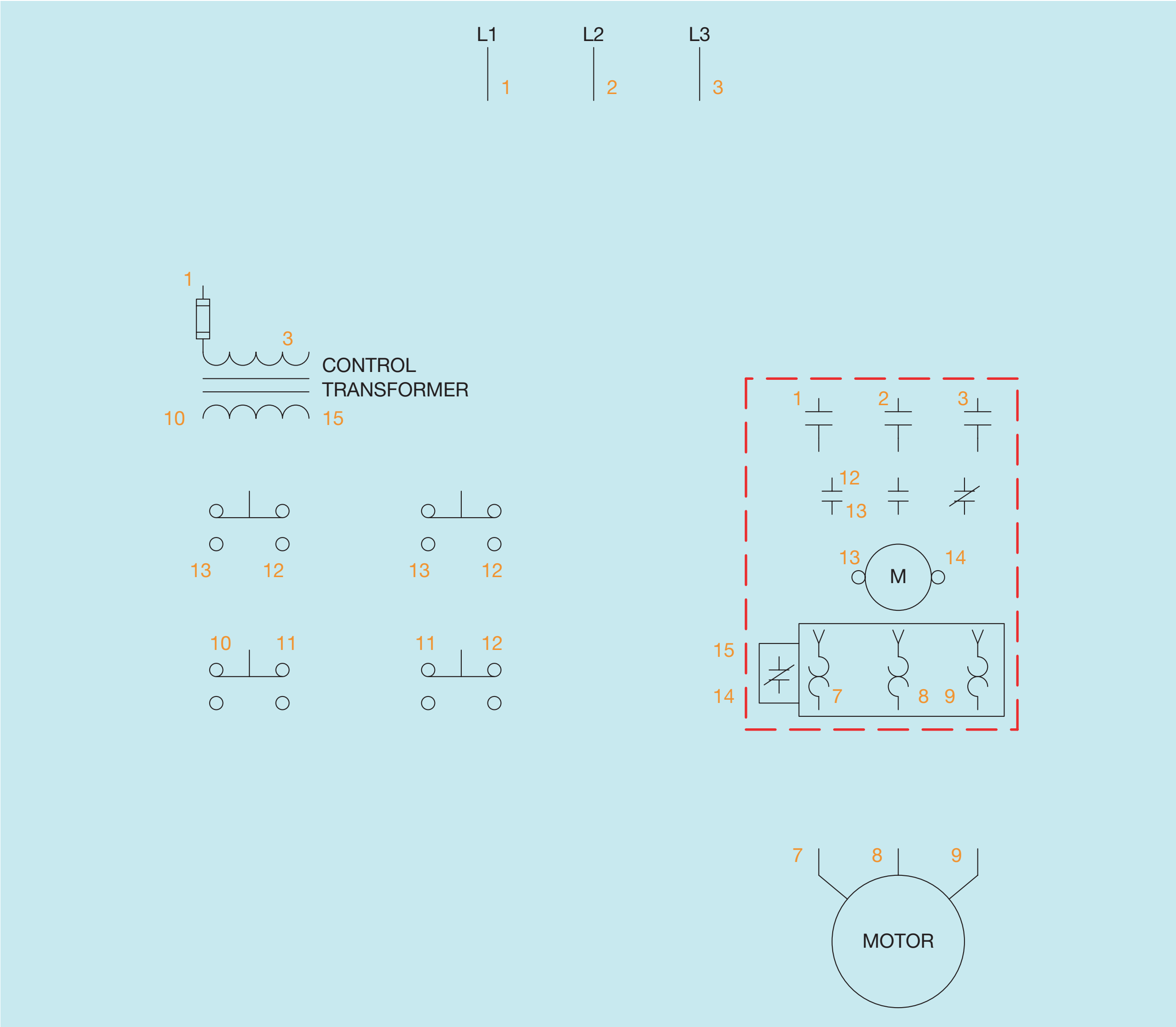


Figure 28–5 Numbers are placed by the corresponding component. (Source: Delmar/Cengage Learning.)

Review Questions

1. When a component is to be used for the function of **start,** is the component generally normally open or normally closed?
2. When a component is to be used for the function of **stop,** is the component generally normally open or normally closed?
3. The two stop push buttons in Figure 28–2 are connected in series with each other. What would be the action of the circuit if they were to be connected in parallel as shown in Figure 28–6?
4. What would be the action of the circuit if both start buttons were to be connected in series as shown in Figure 28–7?

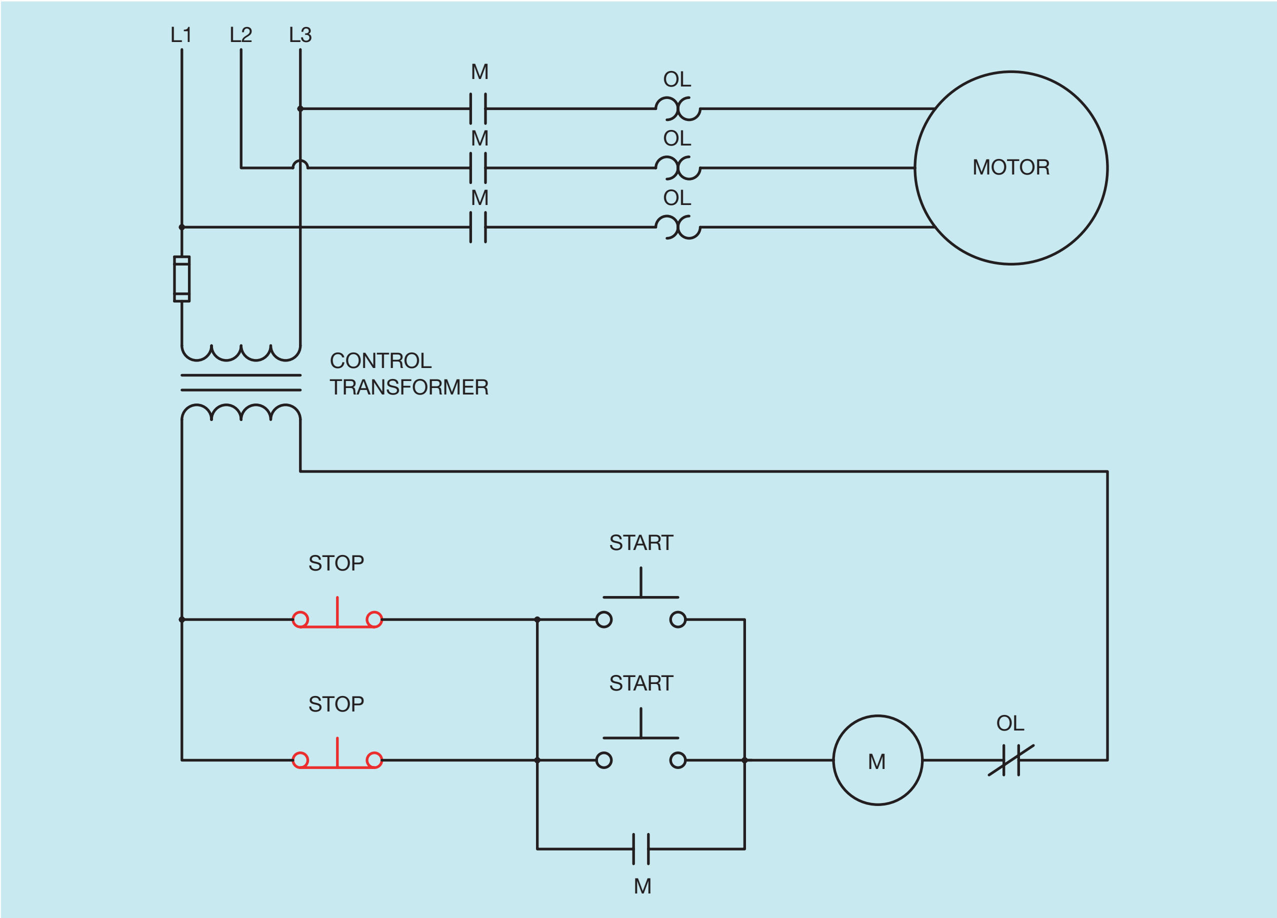


Figure 28–6 Stop buttons have been connected in parallel. (Source: Delmar/Cengage Learning.)

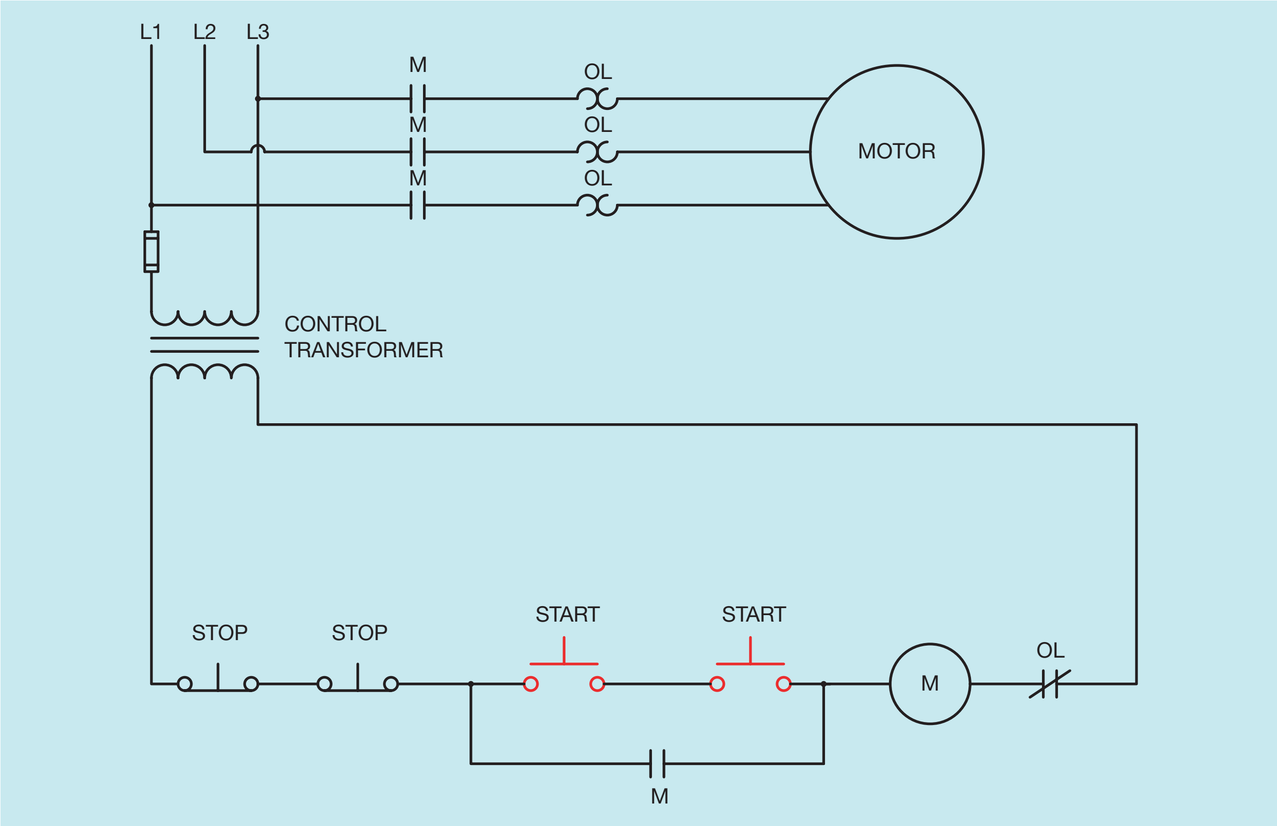


Figure 28–7 Start buttons have been connected in series. (Source: Delmar/Cengage Learning.)

CHAPTER 29
FORWARD-REVERSE CONTROL

OBJECTIVES

After completing this chapter, the student should be able to:

- Discuss cautions that must be observed in reversing circuits.
- Explain how to reverse a three-phase motor.
- Discuss interlocking methods.
- Connect a forward-reverse motor control circuit.

The direction of rotation of any three-phase motor can be reversed by changing any two motor T leads (Figure 29–1). Since the motor is connected to the power line regardless of which direction it operates, a separate contactor is needed for each direction. If the reversing starters adhere to NEMA standards, T leads 1 and 3 will be changed (Figure 29–2). Since only one motor is in operation, however, only one overload relay is needed to protect the motor. True reversing controllers contain two separate contactors and one overload relay. Some reversing starters will use one separate contactor and a starter with a built-in overload relay. Others use two separate contactors and a separate overload relay. A vertical reversing starter with overload relay is shown in Figure 29–3, and a horizontal reversing starter without overload relay is shown in Figure 29–4.

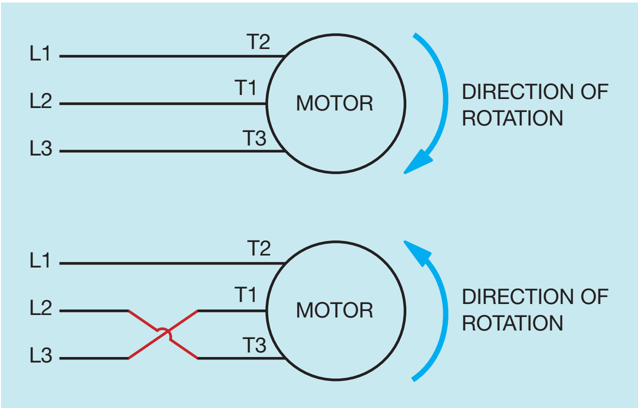


Figure 29–1 The direction of rotation of any three-phase motor can be changed by reversing connection to any two motor T leads. (Source: Delmar/Cengage Learning.)

Interlocking

Interlocking prevents some action from taking place until some other action has been performed. In the case of reversing starters, interlocking is used to prevent both contactors from being energized at the same time. This would result in two of the three phase lines being shorted together. Interlocking forces one contactor to be de-energized before the other one can be energized. There are three methods that can be employed to assure interlocking. Many reversing controls use all three.

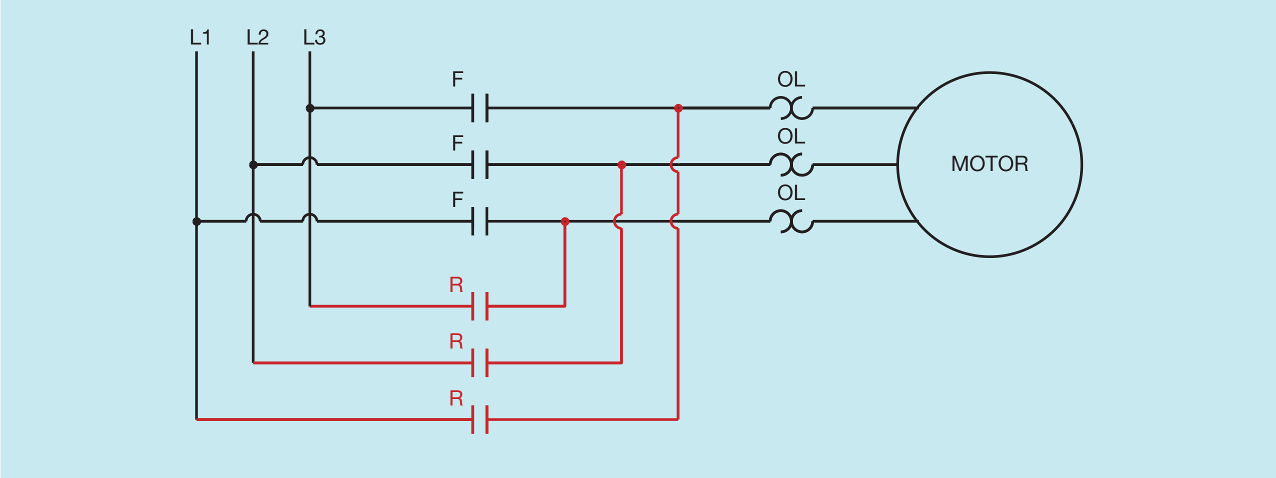


Figure 29–2 Magnetic reversing starters generally change T leads 1 and 3 to reverse the motor. (Source: Delmar/Cengage Learning.)

Mechanical Interlocking

Most reversing controllers contain mechanical interlocks as well as electrical interlocks. Mechanical interlocking is accomplished by using the contactors to operate a mechanical lever that prevents the other contactor from closing while one is energized. Mechanical interlocks are supplied by the manufacturer and are built into reversing starters. In a schematic diagram, mechanical interlocks are shown as dashed lines from each coil joining at a solid line (Figure 29–5).

Electrical Interlocking

Two methods of electrical interlocking are available. One method is accomplished with the use of double acting push buttons (Figure 29–6). The dashed lines drawn between the push buttons indicate that they are mechanically connected. Both push buttons will pushed at the same time. The normally closed part of the FORWARD push button is connected in series with R coil, and the normally closed part of the REVERSE push button is connected in series with F coil. If the motor should be running in the forward direction and the REVERSE push button is pressed, the normally closed part of the push button will open and disconnect F coil from the line before the normally open part closes to energize R coil. The normally closed section of either push button has the same effect on the circuit as pressing the STOP button.

The second method of electrical interlocking is accomplished by connecting the normally closed auxiliary contacts on one contactor in series with the coil of the other contactor (Figure 29–7). Assume that the FORWARD push button is pressed and F coil energizes. This causes all F contacts to change position. The three F load contacts close and connect the motor to the line. The normally open F auxiliary contact closes to maintain the circuit when the FORWARD push button is released, and the normally closed F auxiliary contact connected in series with R coil opens (Figure 29–8).

If the opposite direction of rotation is desired, the STOP button must be pressed first. If the REVERSE push button were to be pressed first, the now open F auxiliary contact connected in series with R coil would prevent a complete circuit from being established. Once the STOP button has been pressed, however, F coil de-energizes and all F contacts return to their normal position. The REVERSE push button can now be pressed to energize R coil (Figure 29–9). When R coil energizes, all R contacts change position. The three R load contacts close and connect the motor to the line. Notice, however, that two of the motor T leads are connected to different lines. The normally closed R auxiliary contact opens to prevent the possibility of F coil being energized until R coil is de-energized.

Developing a Wiring Diagram

The same basic procedure is used to develop a wiring diagram from the schematic as was followed in the previous chapters. The components needed to construct

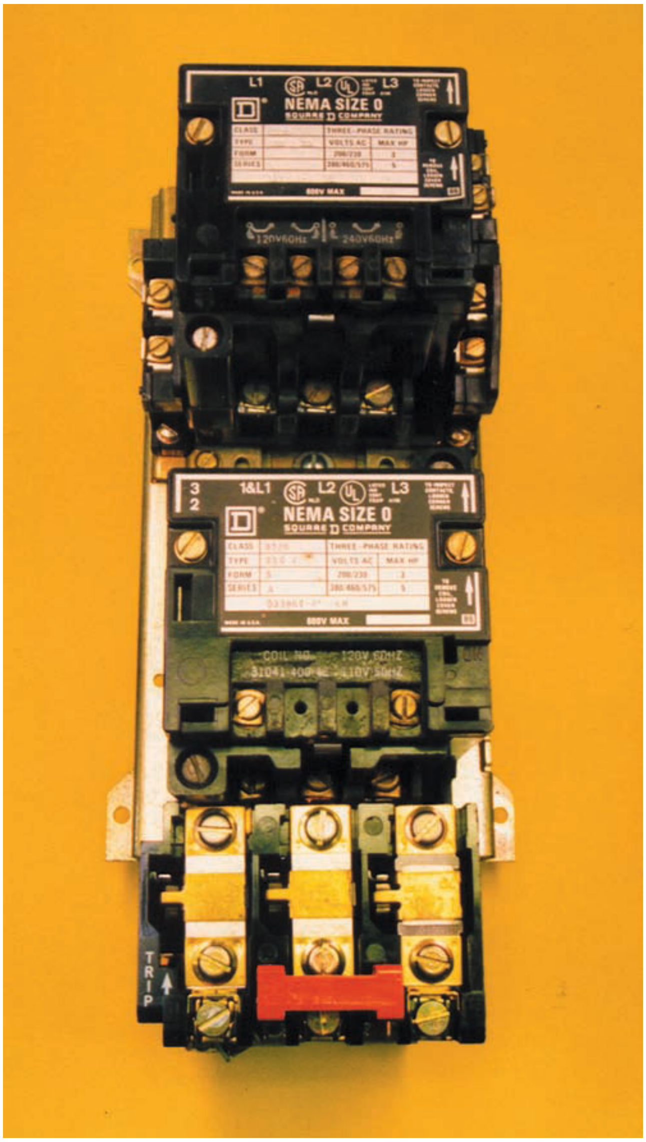


Figure 29–3 Vertical reversing starter with overload relay. (Source: Delmar/Cengage Learning.)

this circuit are shown in Figure 29–10. In this example, assume that two contactors and a separate three-phase overload relay are to be used.

The first step is to place wire numbers on the schematic diagram. A suggested numbering sequence is shown in Figure 29–11. The next step is to place the wire numbers beside the corresponding components of the wiring diagram (Figure 29–12).

Reversing Single-Phase Split-Phase Motors

To reverse the direction of rotation of a single-phase split-phase motor, either the starting winding leads or running winding leads, but not both, are interchanged. A schematic diagram of a forward-reverse control for a single-phase split-phase motor is shown in Figure 29–13. Notice that the control section is the same as that used for reversing three-phase motors. In this example, run winding lead T1 will always be connected to L1, and T4 will always be connected to L2. The start winding leads, however, will be changed. When the forward contactor is energized, start winding lead T5 will be connected to L1, and T8 will be connected to L2. When the reverse contactor is energized, start winding lead T5 will be connected to L2, and T8 will be connected to L1.

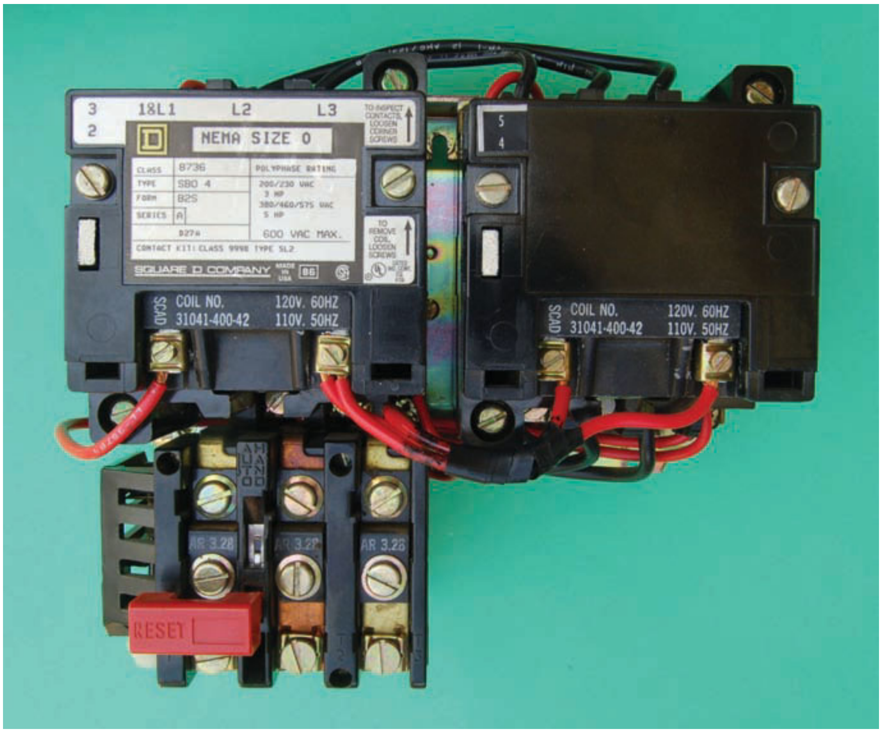


Figure 29–4 Horizontal reversing starter. (Source: Delmar/Cengage Learning.)

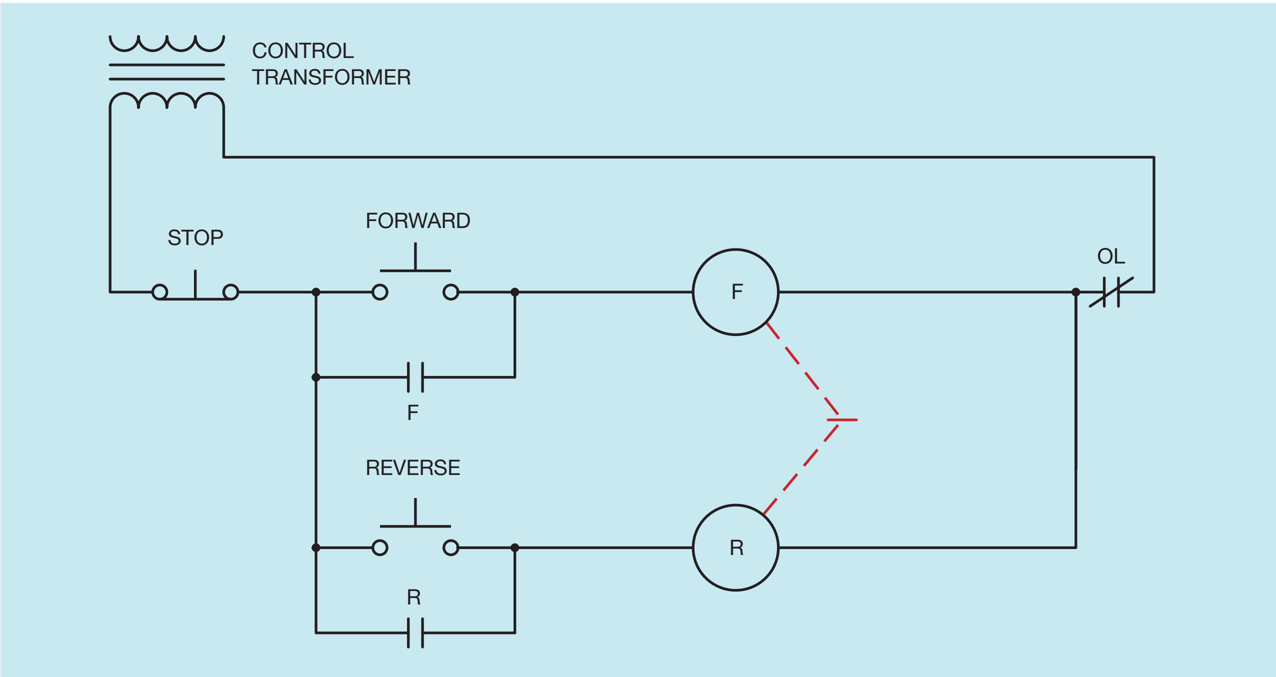


Figure 29–5 Mechanical interlocks are indicated by dashed lines extending from each coil. (Source: Delmar/Cengage Learning.)

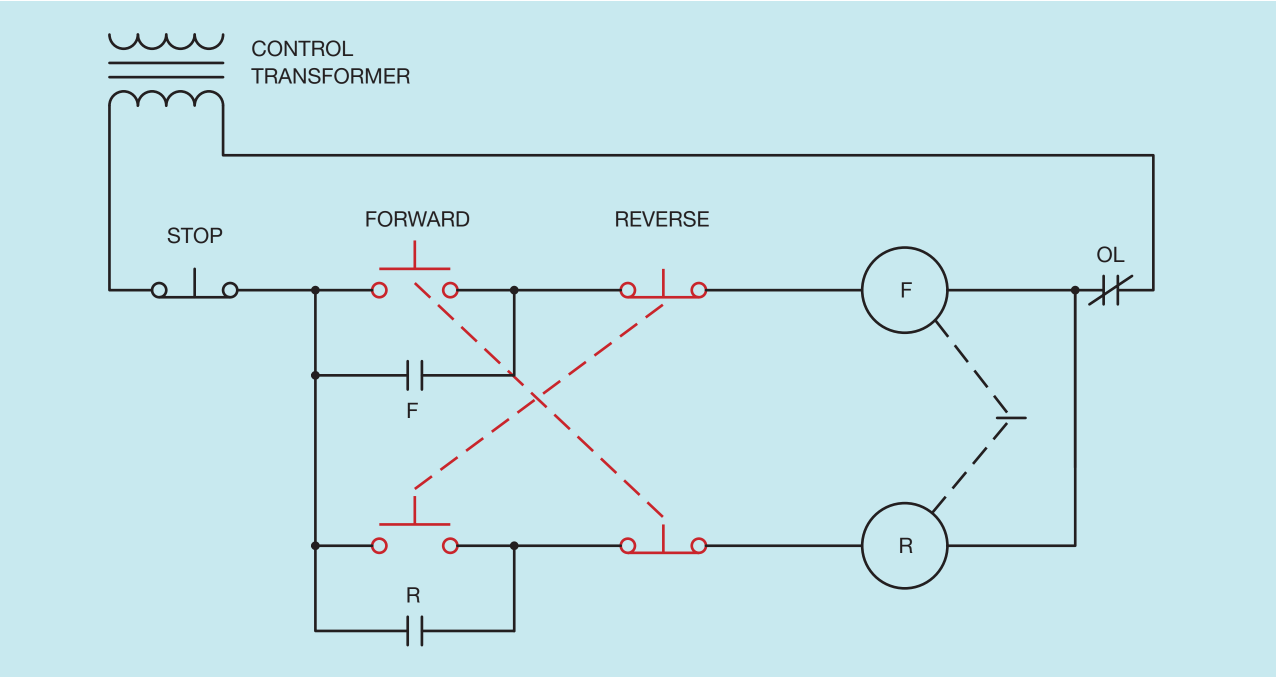


Figure 29–6 Interlocking with double acting push buttons. (Source: Delmar/Cengage Learning.)

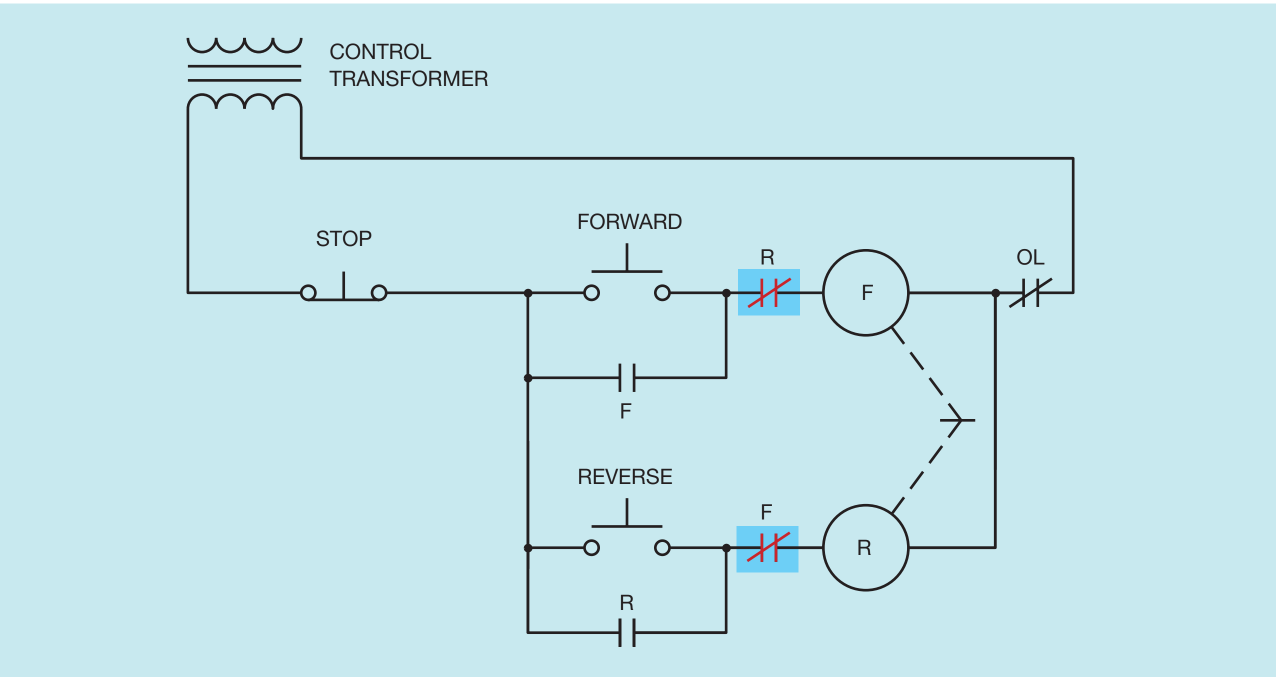


Figure 29–7 Electrical interlocking is also accomplished with normally closed auxiliary contacts. (Source: Delmar/Cengage Learning.)

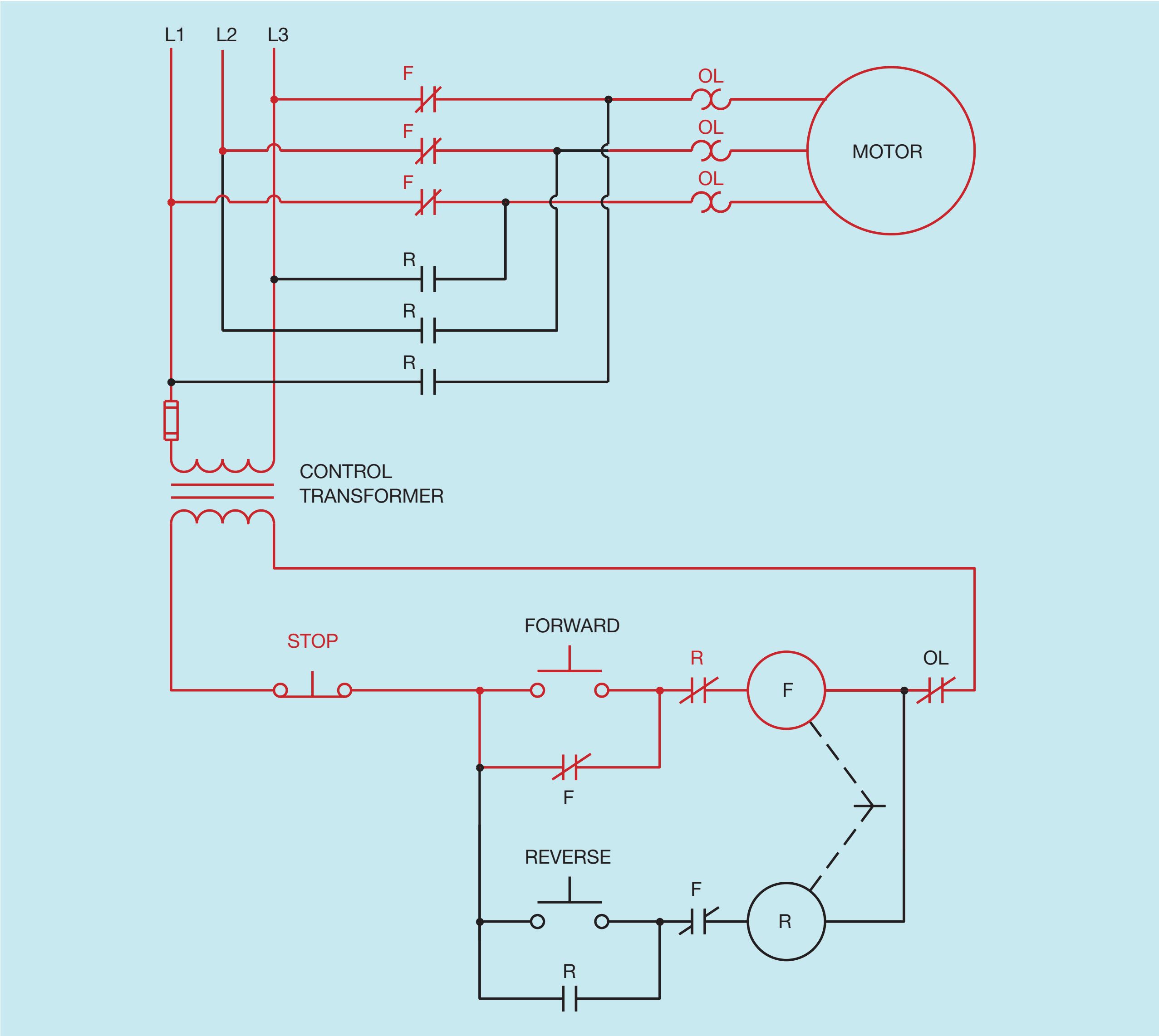


Figure 29–8 Motor operating in the forward direction. (Source: Delmar/Cengage Learning.)

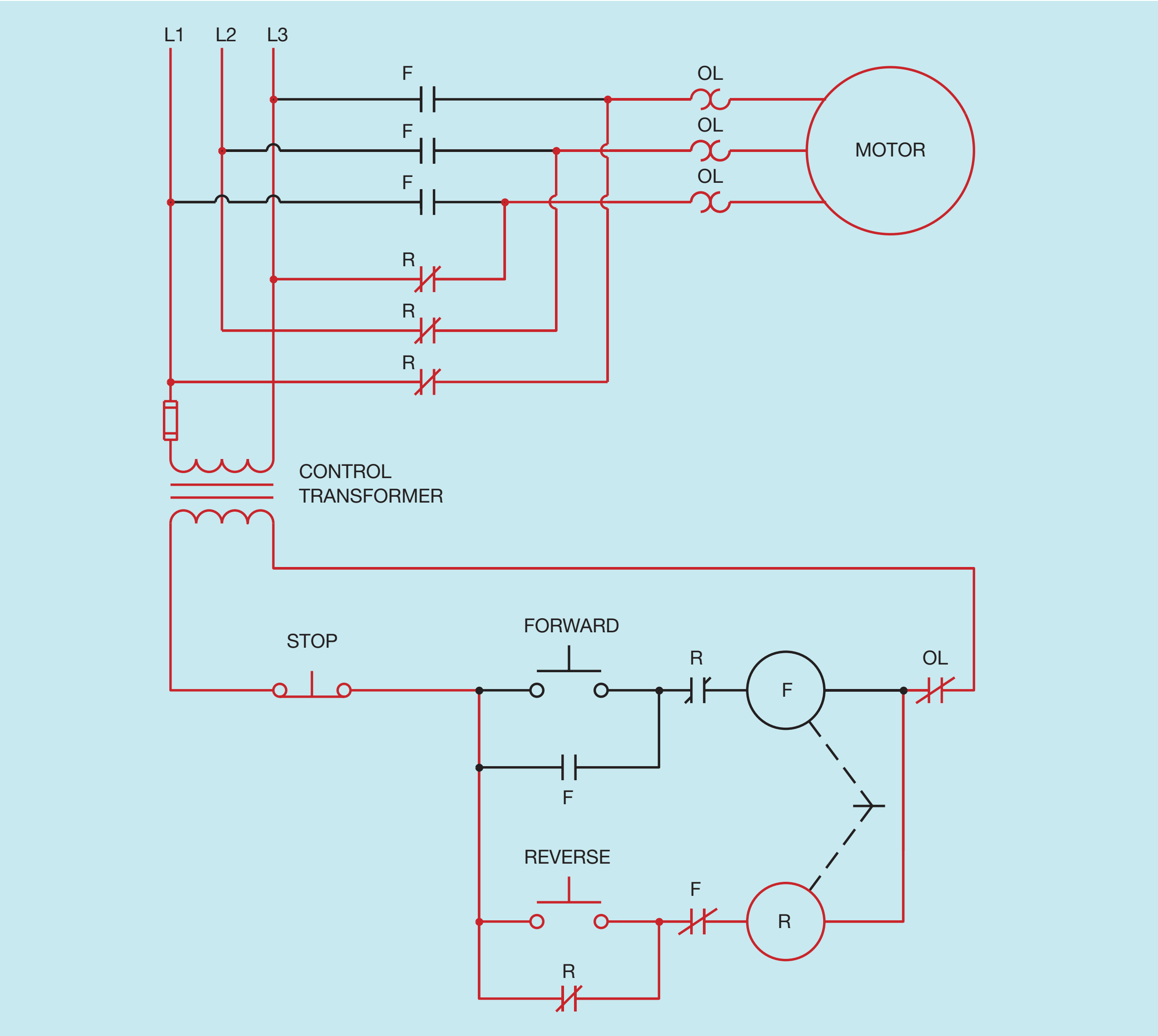


Figure 29–9 Motor operating in the reverse direction. (Source: Delmar/Cengage Learning.)

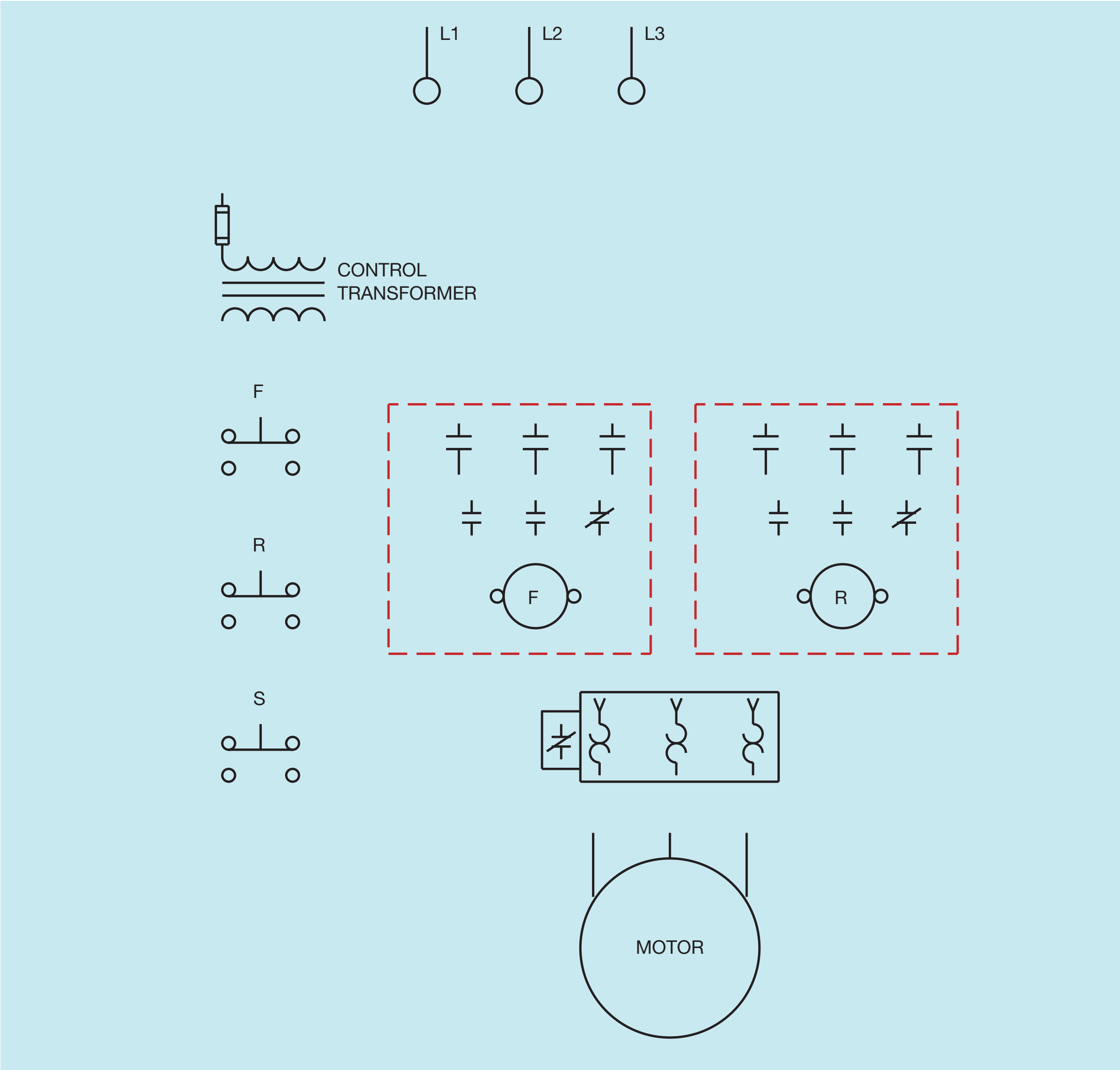


Figure 29–10 Components needed to construct a reversing control. (Source: Delmar/Cengage Learning.)

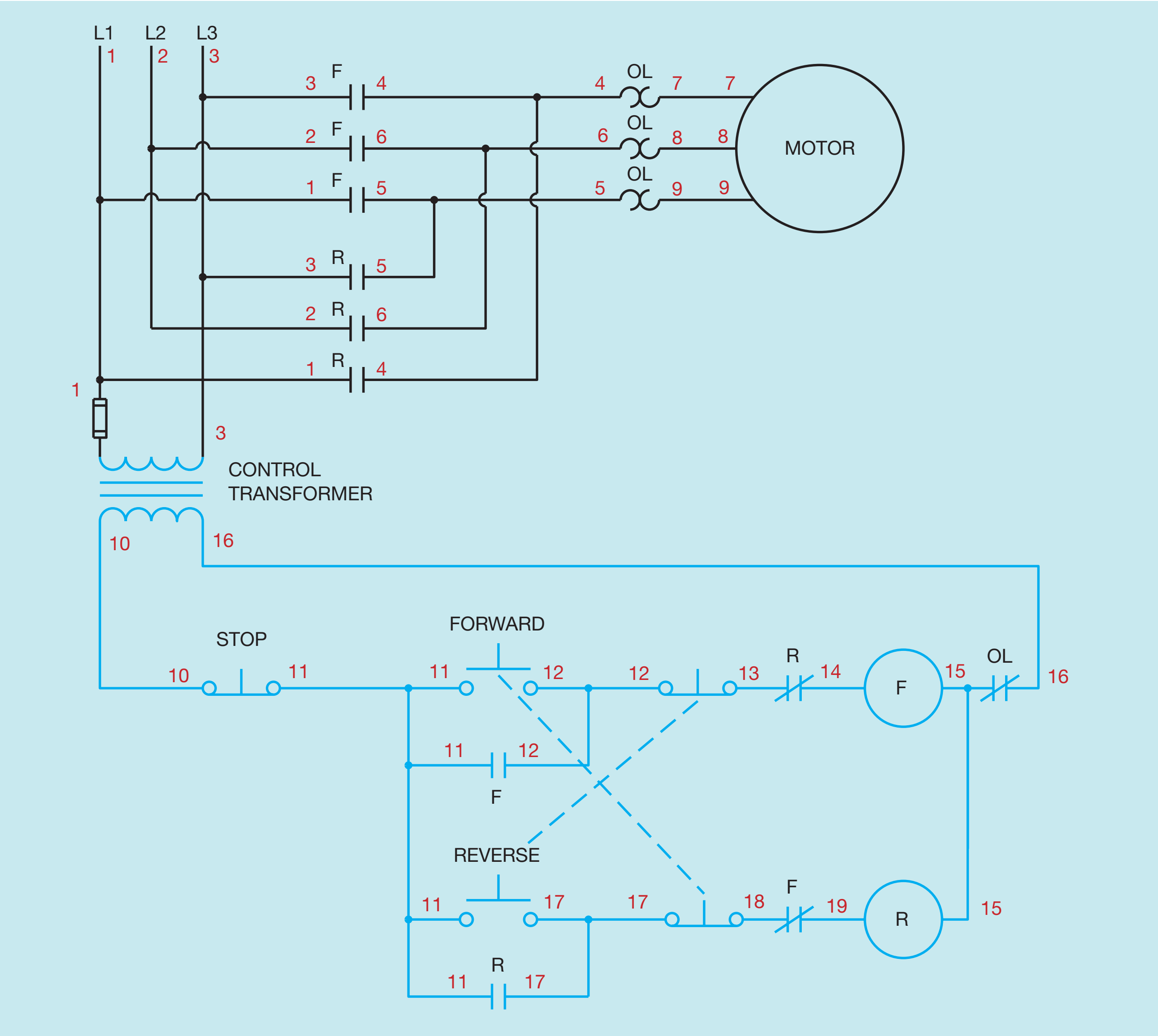


Figure 29–11 Placing numbers on the schematic. (Source: Delmar/Cengage Learning.)

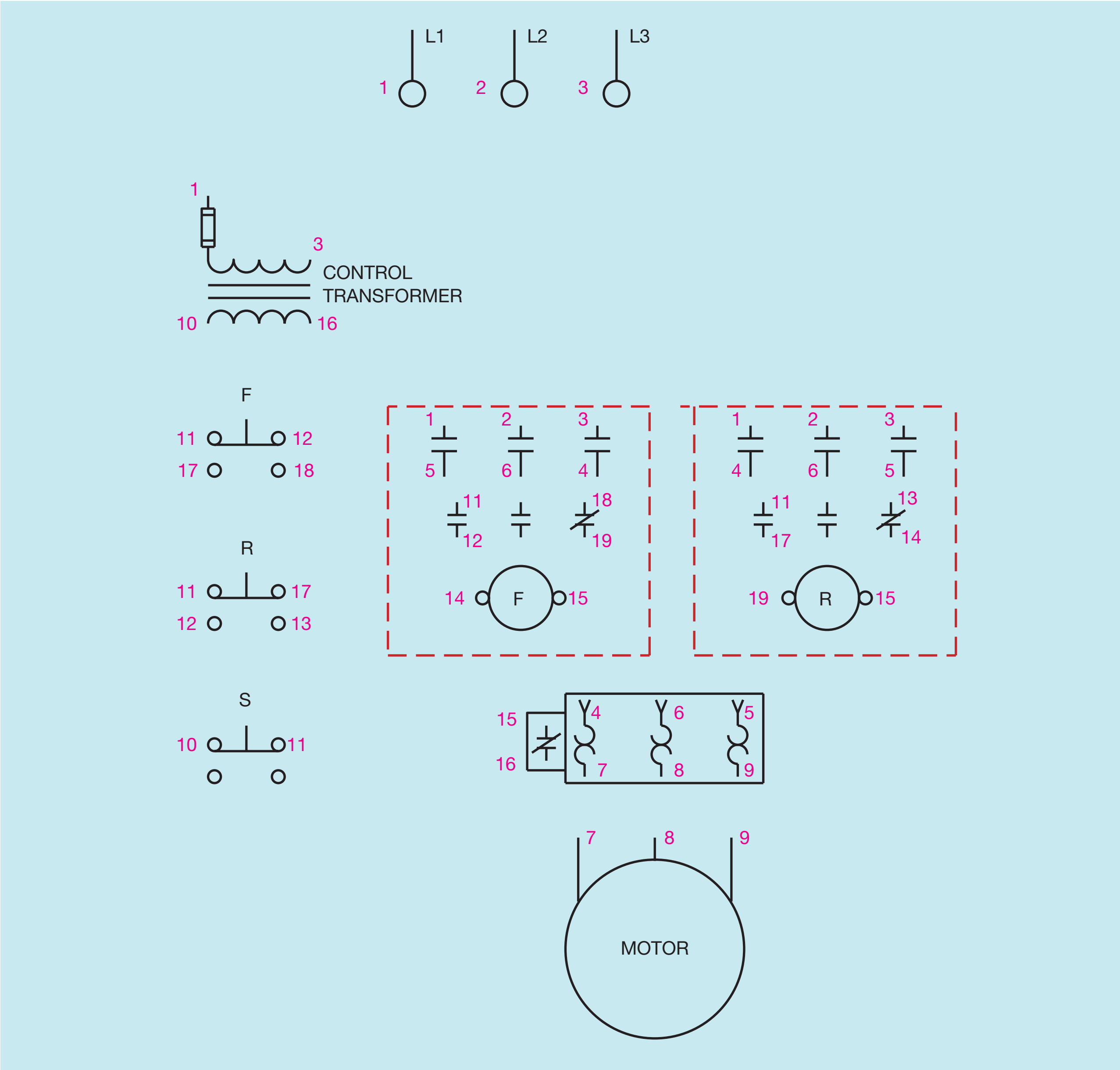


Figure 29–12 Components needed to construct a reversing control circuit. (Source: Delmar/Cengage Learning.)

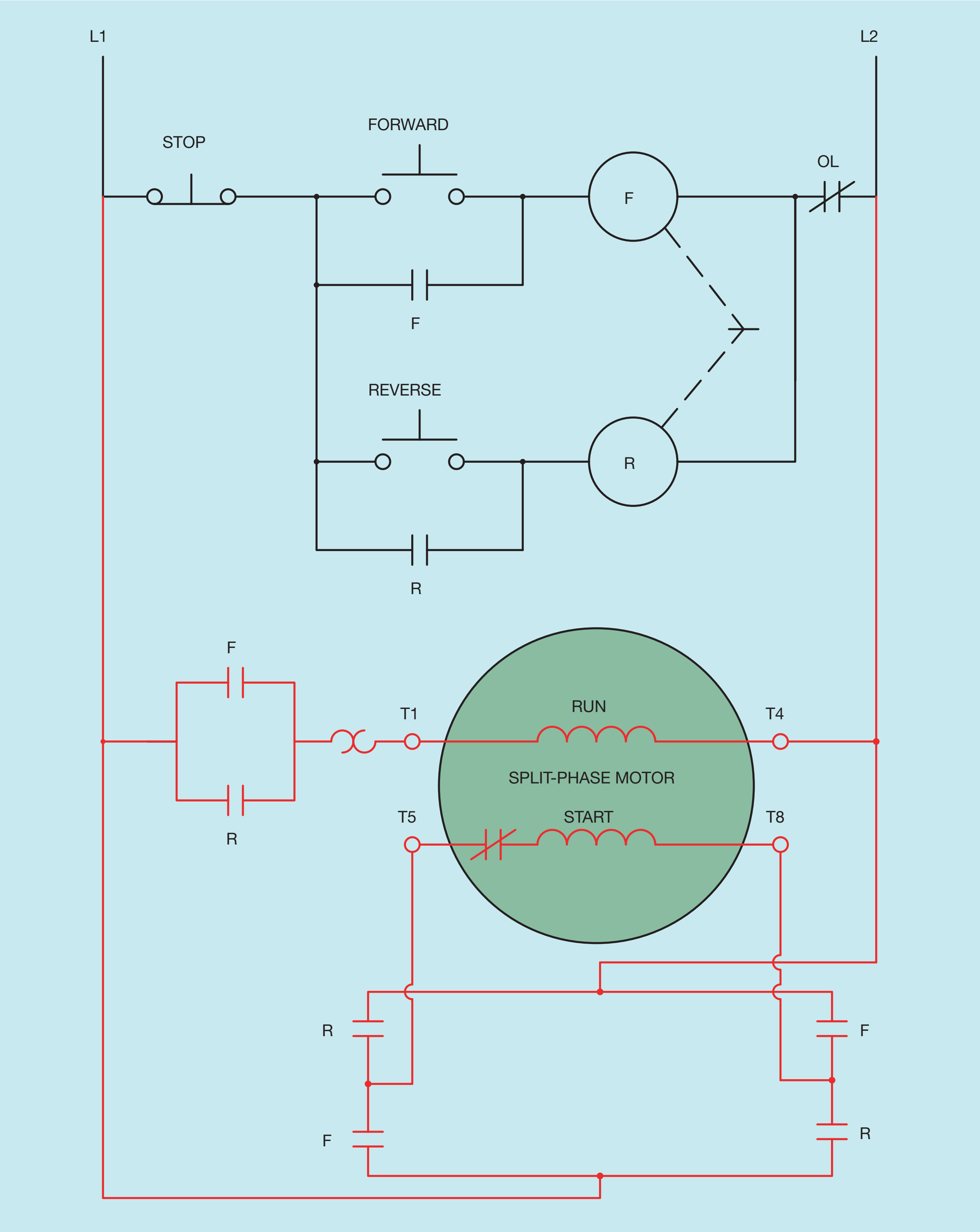


Figure 29–13 Reversing a single-phase split-phase motor. (Source: Delmar/Cengage Learning.)

Review Questions

1. How can the direction of rotation of a three-phase motor be changed?
2. What is interlocking?
3. Referring to the schematic shown in Figure 29–7, how would the circuit operate if the normally closed R contact connected in series with F coil were connected normally open?
4. What would be the danger, if any, if the circuit were wired as stated in question 3?
5. How would the circuit operate if the normally closed auxiliary contacts were connected so that F contact was connected in series with F coil, and R contact was connected in series with R coil, Figure 29–7?
6. Assume that the circuit shown in Figure 29–7 were to be connected as shown in Figure 29–14. In what way would the operation of the circuit be different, if at all?

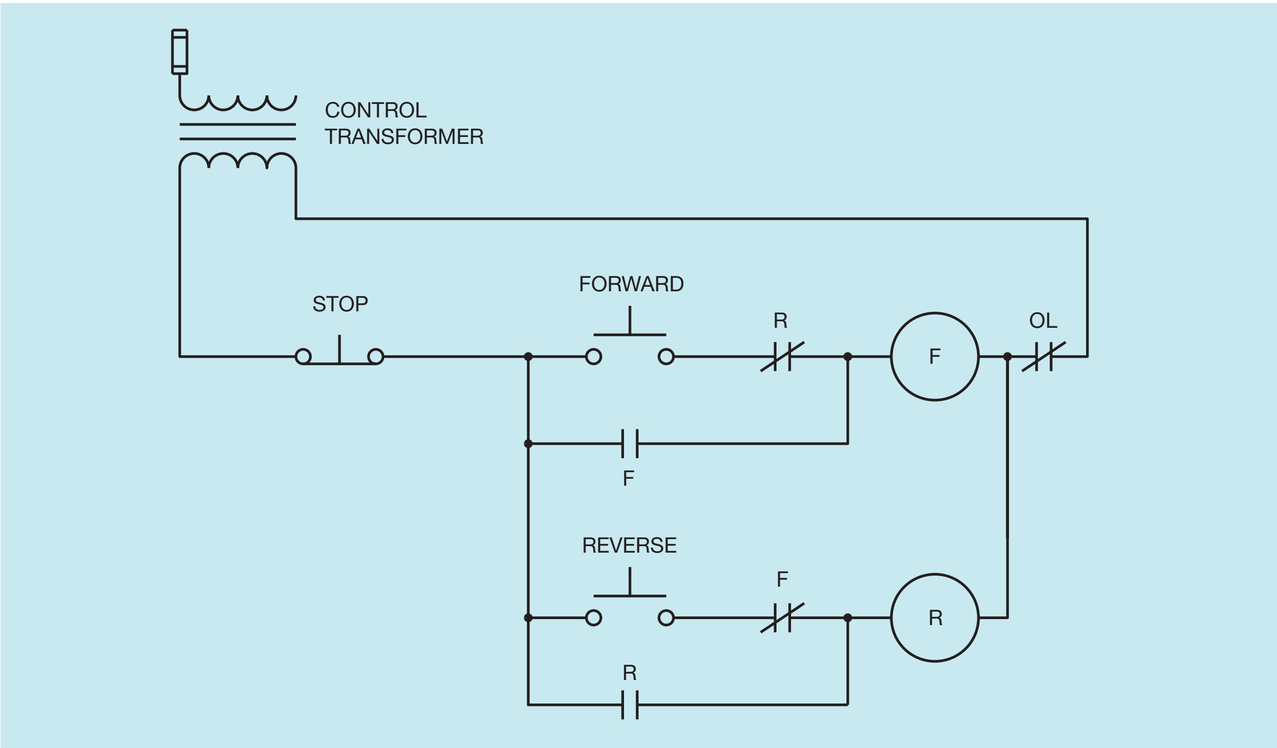


Figure 29–14 The position of the holding contacts has been changed from that in Figure 29–7. (Source: Delmar/Cengage Learning.)

CHAPTER 30
JOGGING AND INCHING

OBJECTIVES

After studying this chapter, the student will be able to:

- Define the term jogging.
- State the purpose of jogging.
- State the difference between jogging and inching.
- Describe the operation of a jogging control circuit using control relays.
- Describe the operation of a jogging control circuit using a selector switch.
- Connect a jogging circuit.

The definition of jogging or inching as described by NEMA is *"the quickly repeated closure of a circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine."* The term *jogging* actually means to start a motor with short jabs of power at full voltage. The term *inching* means to start a motor with short jabs of power at reduced voltage. Although the two terms mean different things, they are often used interchangeably because both are accomplished by preventing the holding contacts from sealing the circuit.

Jogging Circuits

Various jogging circuits are presented in this chapter. As with many other types of control circuits, there are different ways in which jogging can be accomplished, but basically, jogging is accomplished by preventing the holding contact from sealing the circuit around the start push button when the motor starter energizes. It should also be noted that jogging circuits require special motor starters rated for jogging duty.

One of the simplest jogging circuits is shown in Figure 30–1. This circuit is basically a start-stop push-button control circuit that has been reconnected so that the START button is in parallel with both the STOP button and holding contact. To jog the motor, simply hold down the STOP button and jog the circuit by pressing the START button. To run the motor, release the STOP button and press the START button. If the motor is in operation, the STOP button will break the circuit to the holding contact and de-energize M coil.

Double Acting Push Buttons

Jogging can also be accomplished using a double acting push button. Two circuits of that type are shown in Figure 30–2. The normally closed section of the JOG push button is connected in such a manner that

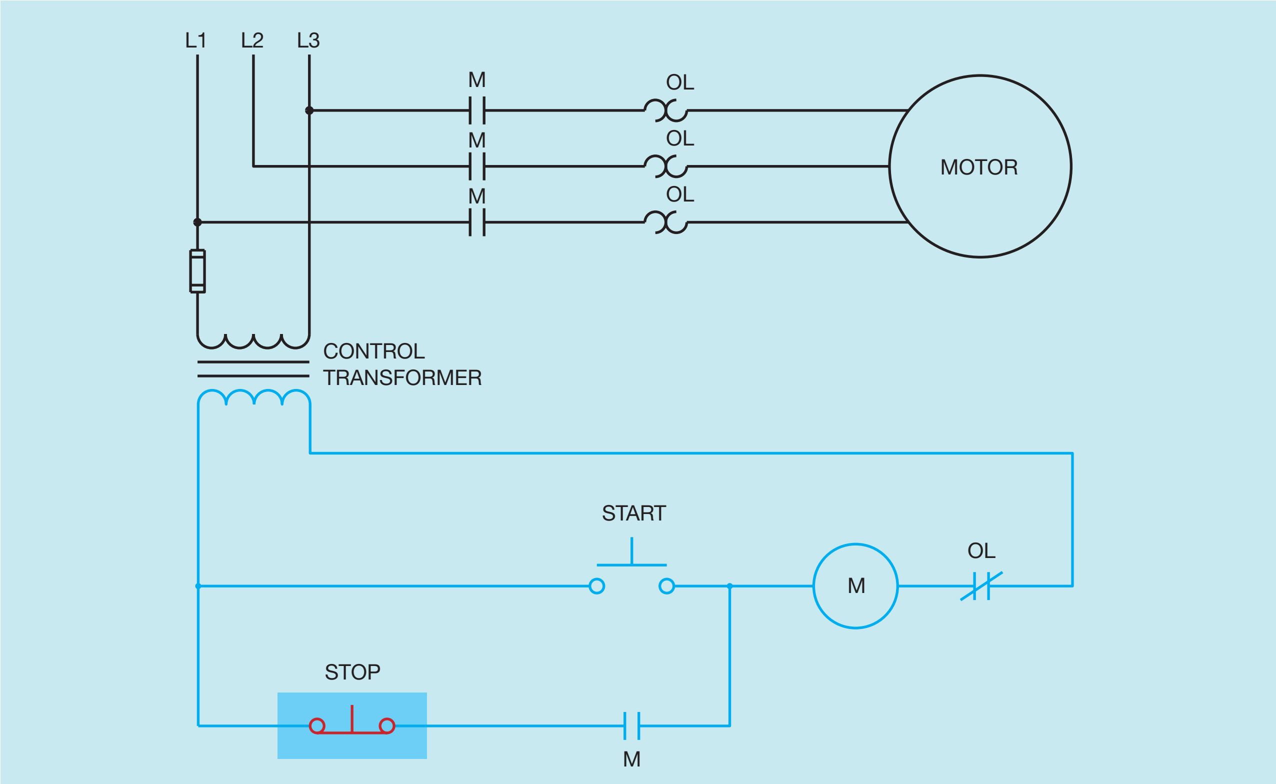


Figure 30–1 The stop button prevents the holding contact from sealing the circuit. (Source: Delmar/Cengage Learning.)

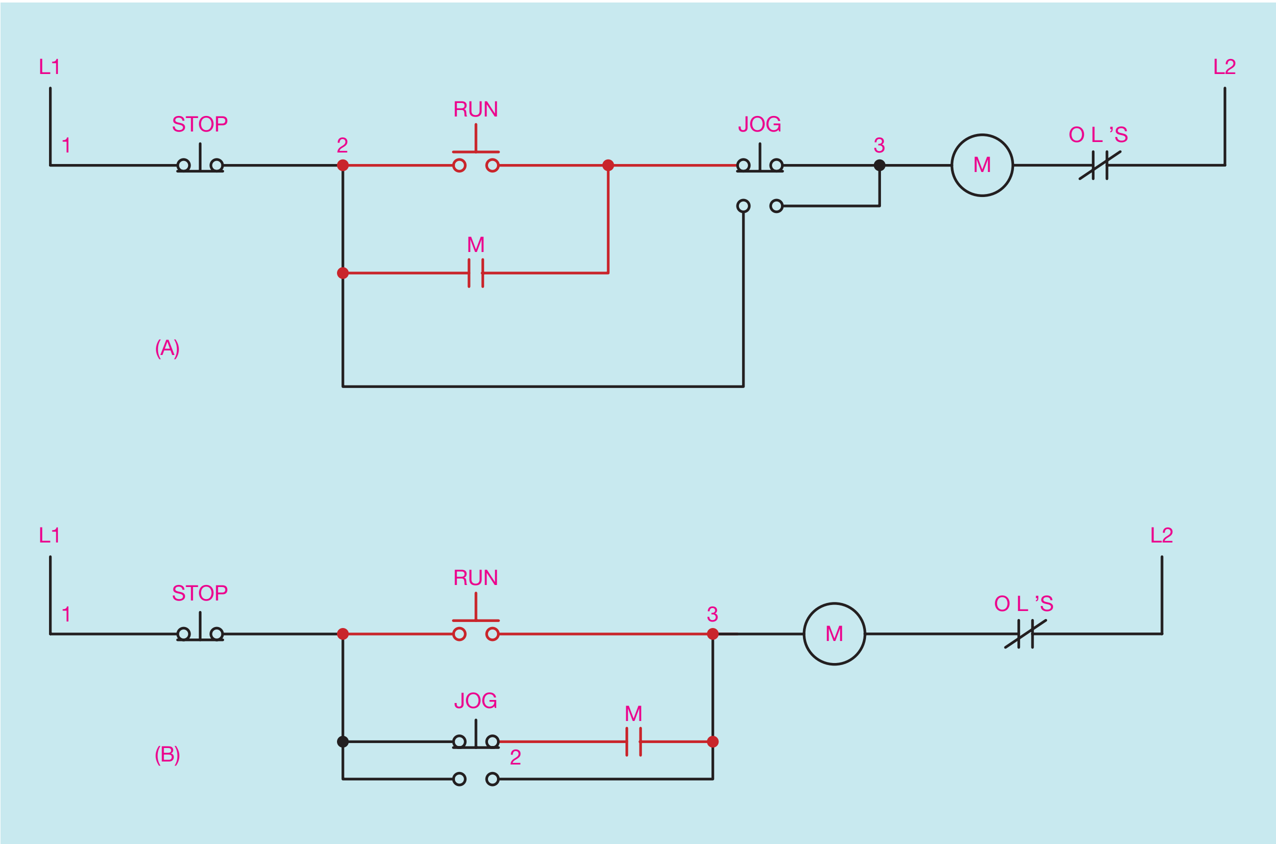


Figure 30–2 Double acting push buttons are used to provide jogging control. (Source: Delmar/Cengage Learning.)

when the button is pushed it will defeat the holding contact and prevent it from sealing the circuit. The normally open section of the JOG button completes a circuit to energize the coil of the motor starter. When the button is released, the normally open section breaks the circuit to M coil before the normally closed section reconnects to the circuit. This permits the starter to reopen the holding contacts before the normally closed section of the JOG button reconnects.

Although this circuit is sometimes used for jogging, it does have a severe problem. The action of either of these two circuits depends on the normally open M auxiliary contact (holding contact), which is used to seal the circuit, being open before the normally closed section of the JOG button makes connection. Since push buttons employ a spring to return the contacts to their normal position, if a person's finger should slip off the JOG button, it is possible for the spring to reestablish connection with the normally closed contacts before the holding contact has time to reopen. This would cause the motor to continue running instead of stopping. In some cases, this could become a significant safety hazard.

Using a Control Relay

The addition of a control relay to the jog circuit eliminates the problem of the holding contacts making connection before the normally closed section of the jog push button reconnects. Two circuits that employ a control relay to provide jogging are shown in Figure 30–3. In both of these circuits, the control relay, not M starter, provides the auxiliary holding contacts. The JOG push button energizes the coil of M motor starter but does not energize the coil of control relay CR. The START push button is used to energize the coil of CR relay. When energized, CR relay contacts provide connection to M coil. The use of control relays in a jogging circuit is very popular because of the simplicity and safety offered.

A jogging circuit for a forward-reverse control is shown in Figure 30–4. Note that a control relay is used to provide jogging in either direction. When the forward jog push button is pressed, the normally open section makes connection and provides power to F coil. This causes F load contacts to close and connect the motor to the power line. The normally open F auxiliary contact closes, also, but the normally closed section of the forward jog button is now open, preventing coil CR from being energized. Since CR contact remains open, the circuit to F coil cannot be sealed by the normally open F auxiliary contact.

If the forward start button is pressed, a circuit is completed to F coil, causing all F contacts to change position. The normally open F auxiliary contact closes and provides a path through the normally closed section of both jog buttons to CR coil. This causes CR auxiliary contact to close and provide a current path through the now closed F auxiliary contact to F coil, sealing the circuit when the forward push button is released. The reverse jog button and reverse start button operate the same way. Note also that normally closed F and R auxiliary contacts are used to provide interlocking for the forward-reverse control.

Jogging Controlled by a Selector Switch

A selector switch can also be employed to provide jogging. The switch is used to break the connection to the holding contacts (Figure 30–5). In this circuit, a single-pole single-throw toggle switch is used. When the switch is in the ON position, connection is made to the holding contacts. If the switch is in the OFF position, the holding contacts cannot seal the circuit when the START button is released. Note that the START button acts as both the start and jog button for this circuit. A selector switch can be used to provide the same basic type of control (Figure 30–6).

Inching Controls

As stated previously, jogging and inching are very similar in that both are accomplished by providing short jabs of power to a motor to help position certain pieces of machinery. Inching, however, is accomplished by providing a reduced amount of power to the motor. Transformers can be used to reduce the amount of voltage applied to the motor during inching, or reactors or resistors can be connected in series with the motor to reduce the current supplied by the power line. In the circuit shown in Figure 30–7, resistors are connected in series with the motor during inching. Notice that inching control requires the use of a separate contactor because the power supplied to the motor must be separate from full line voltage.

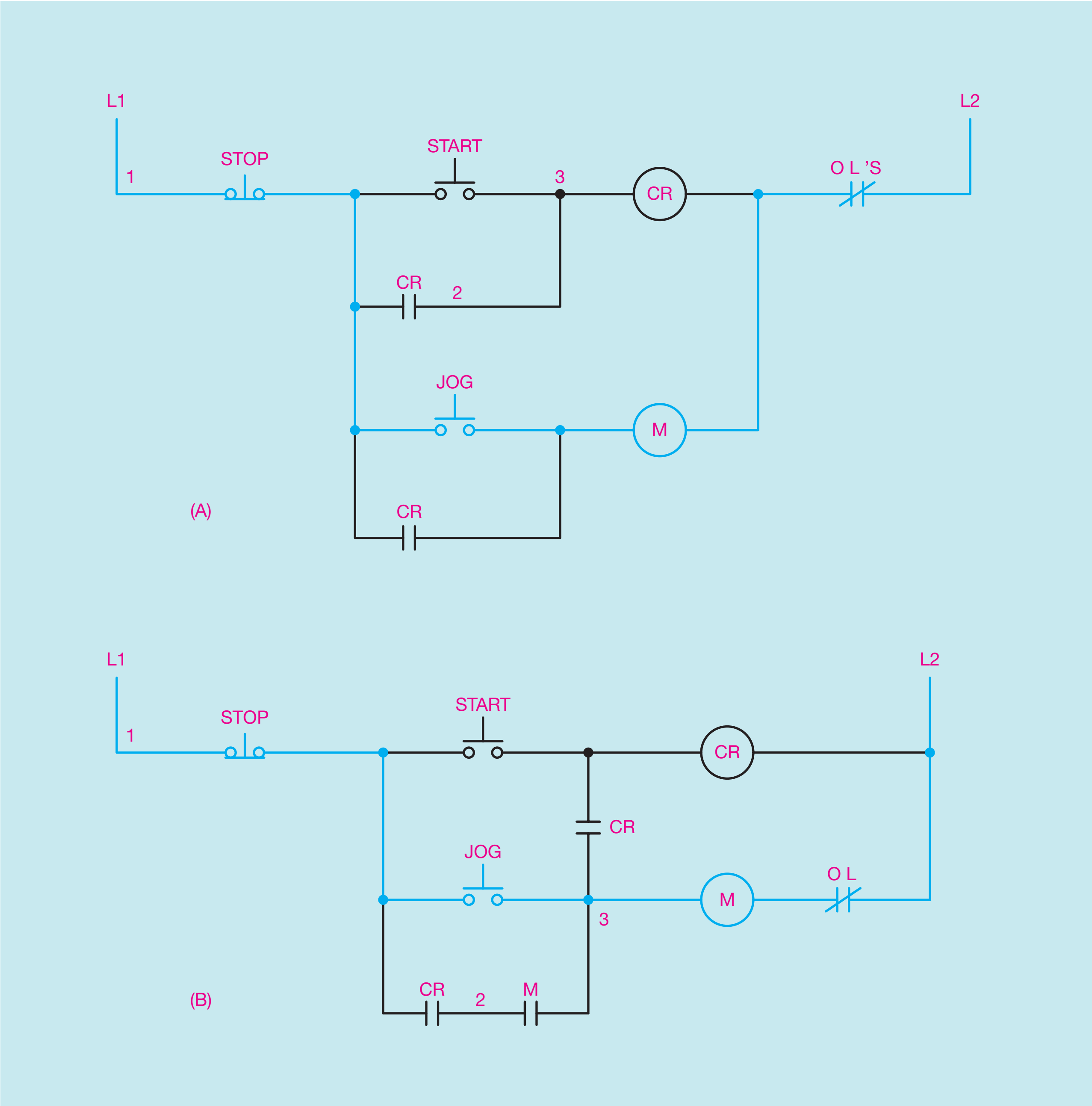


Figure 30–3 Control relays provide jogging control. (Source: Delmar/Cengage Learning.)

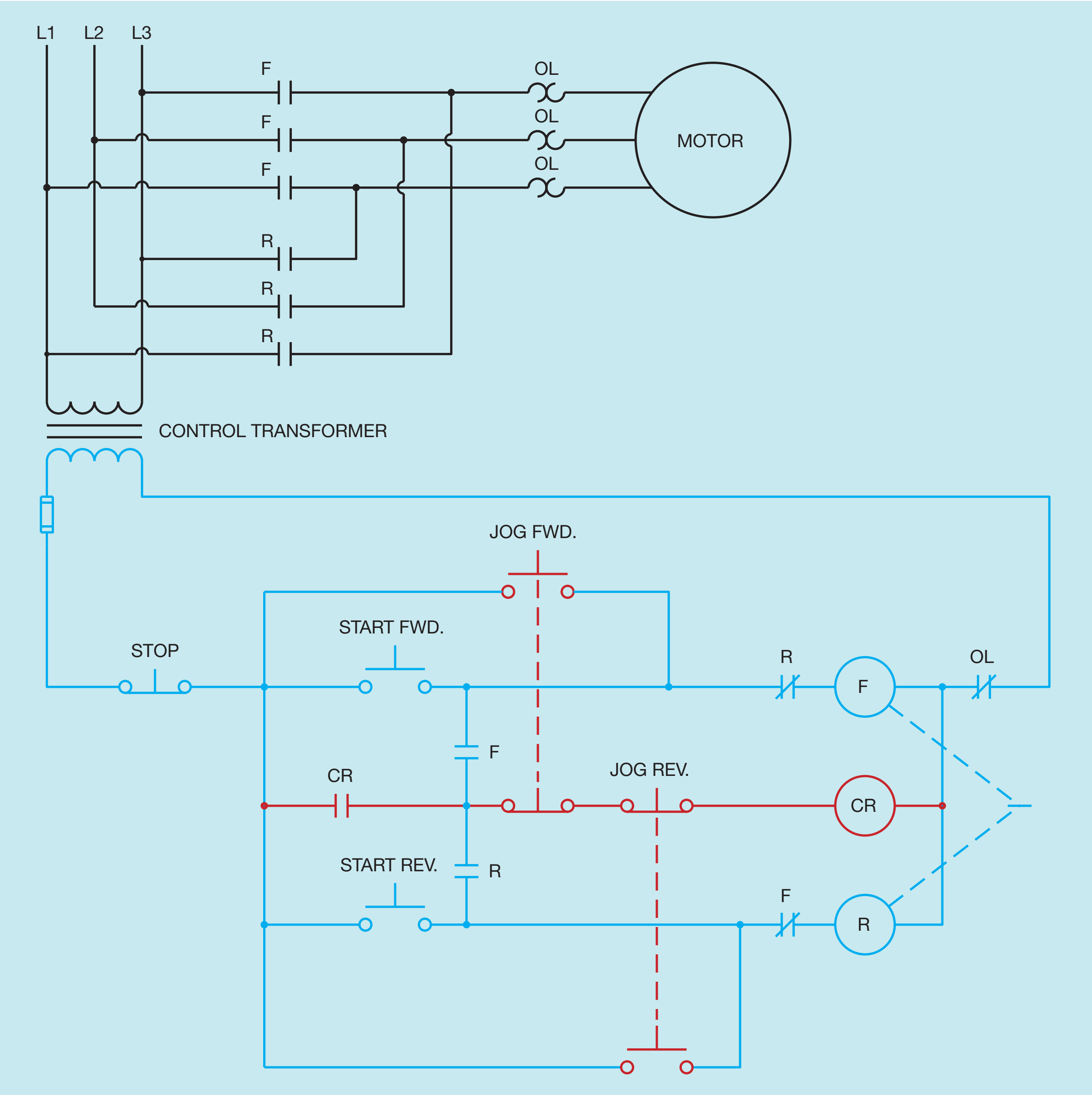


Figure 30–4 Jogging using a control relay on a forward-reverse control. (Source: Delmar/Cengage Learning.)

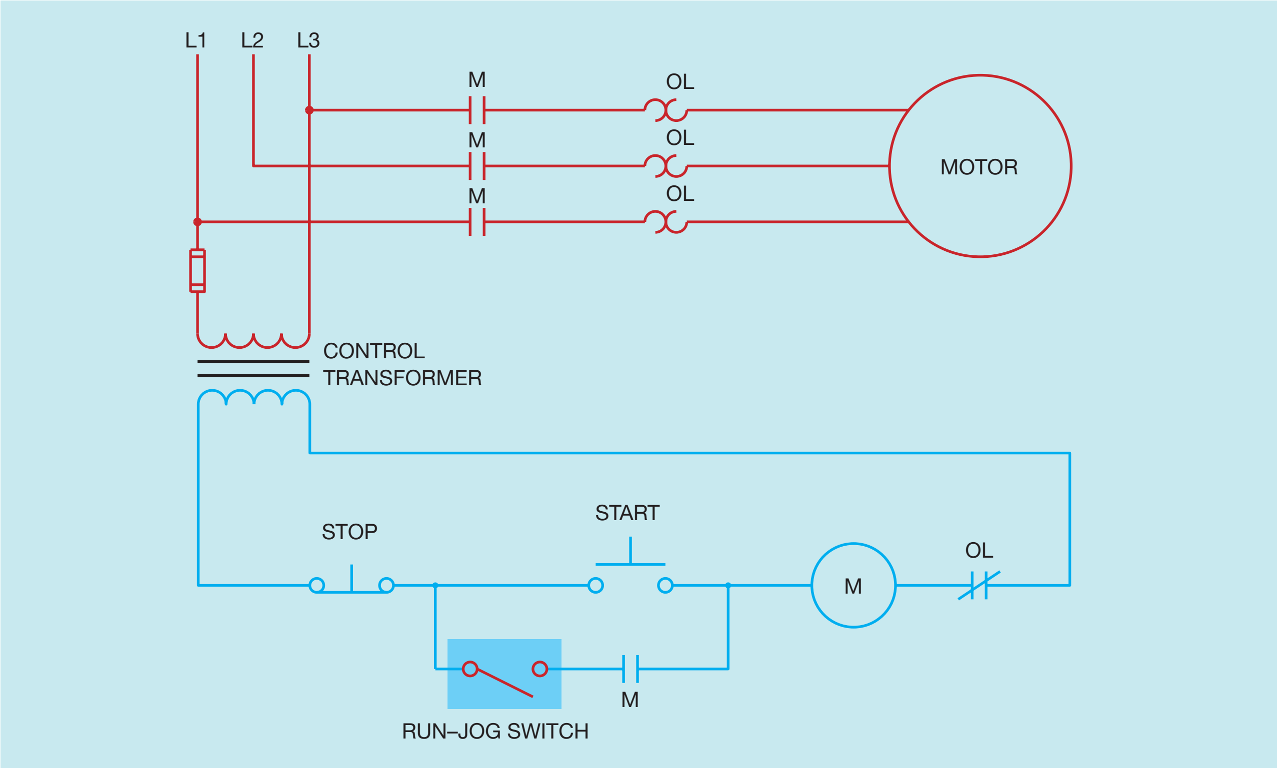


Figure 30–5 A single pole single throw toggle switch provides jog or run control. (Source: Delmar/Cengage Learning.)

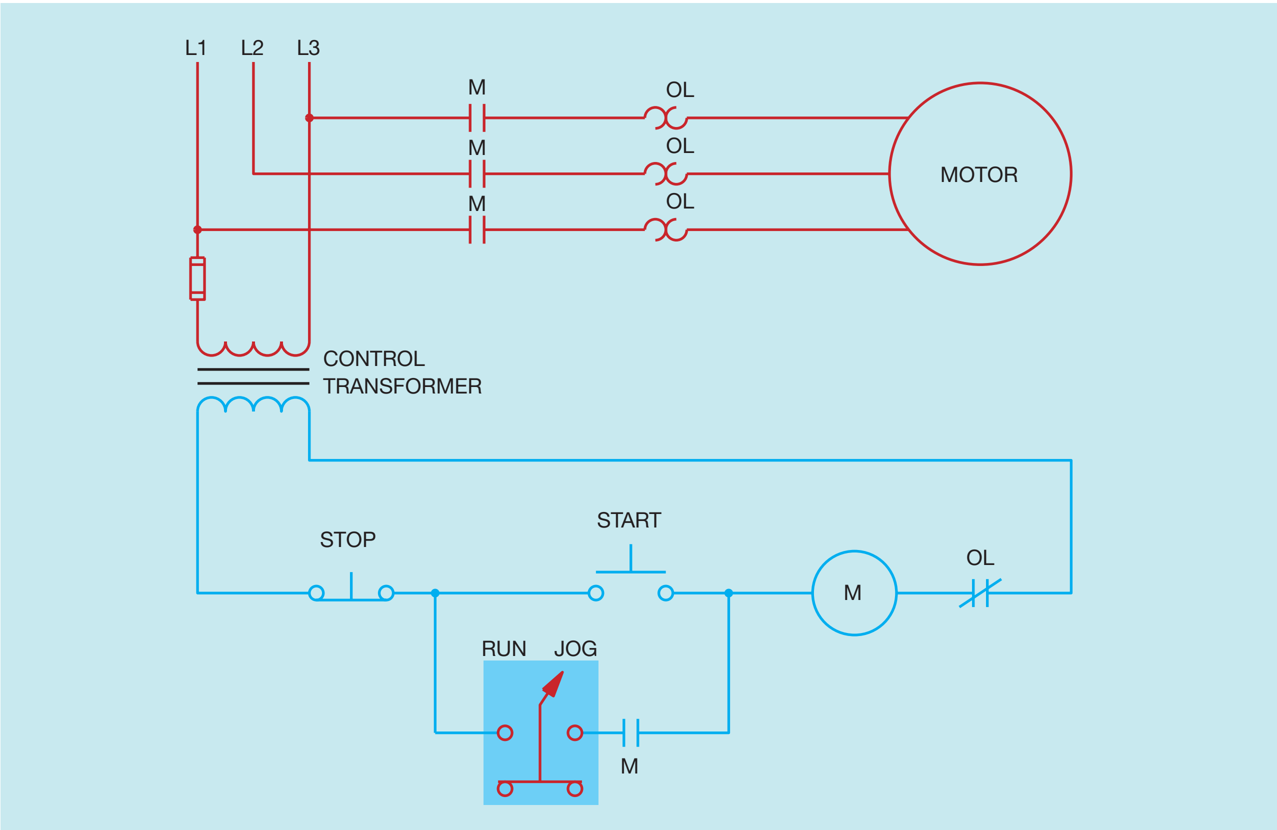


Figure 30–6 A selector switch provides run-jog control. (Source: Delmar/Cengage Learning.)

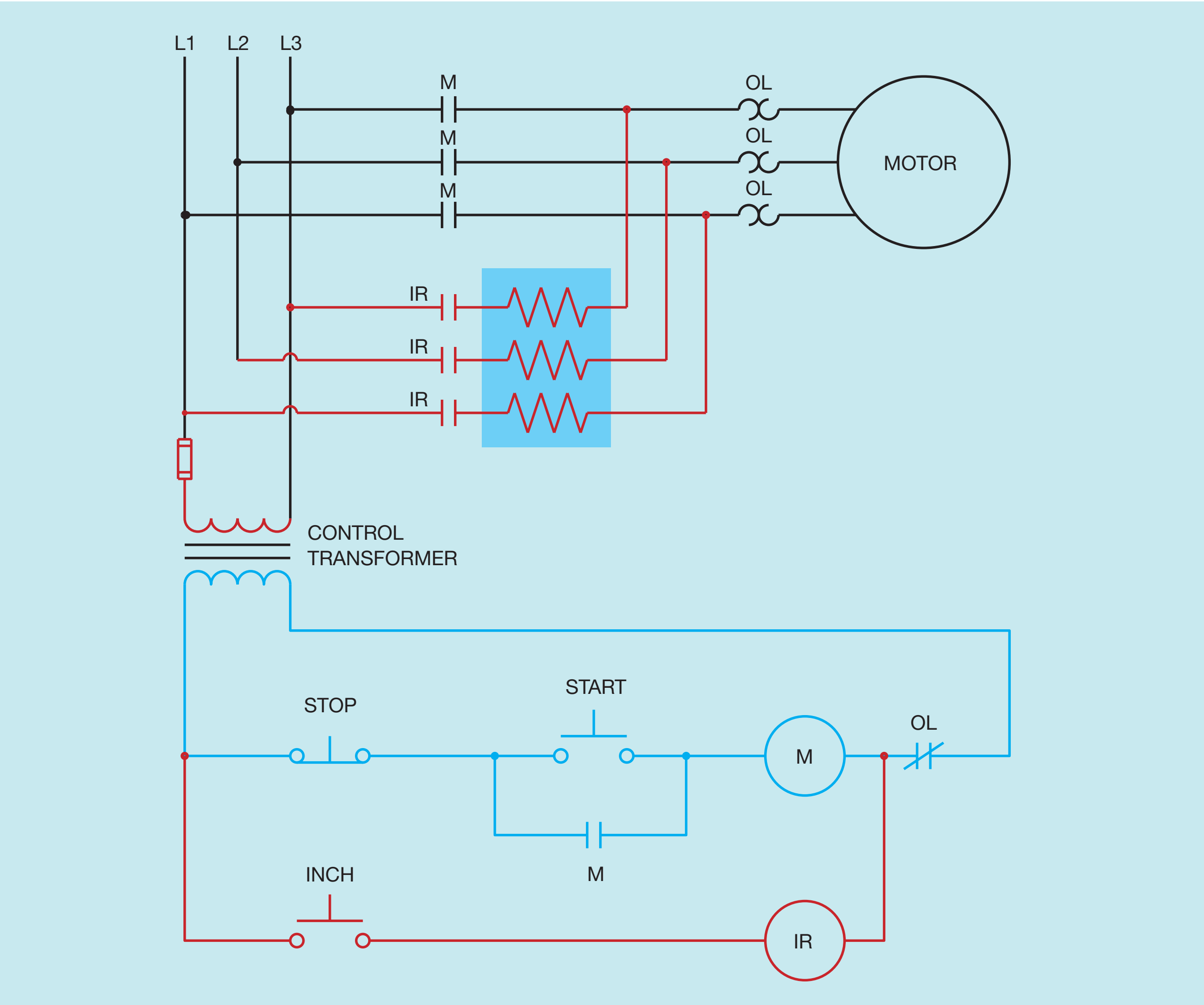


Figure 30–7 Resistors are used to reduce power to the motor. (Source: Delmar/Cengage Learning.)

Review Questions

1. Explain the difference between inching and jogging.
2. What is the main purpose of jogging?
3. Refer to the circuit shown in Figure 30–8. In this circuit, the jog button has been connected incorrectly. The normally closed section has been connected in parallel with the run push button, and the normally open section has been connected in series with the holding contacts. Explain how this circuit operates.
4. Refer to the circuit shown in Figure 30–9. In this circuit, the jog push button has again been connected incorrectly. The normally closed section of the button has been connected in series with the normally open run push button, and the normally open section of the jog button is connecting in parallel with the holding contacts. Explain how this circuit operates.

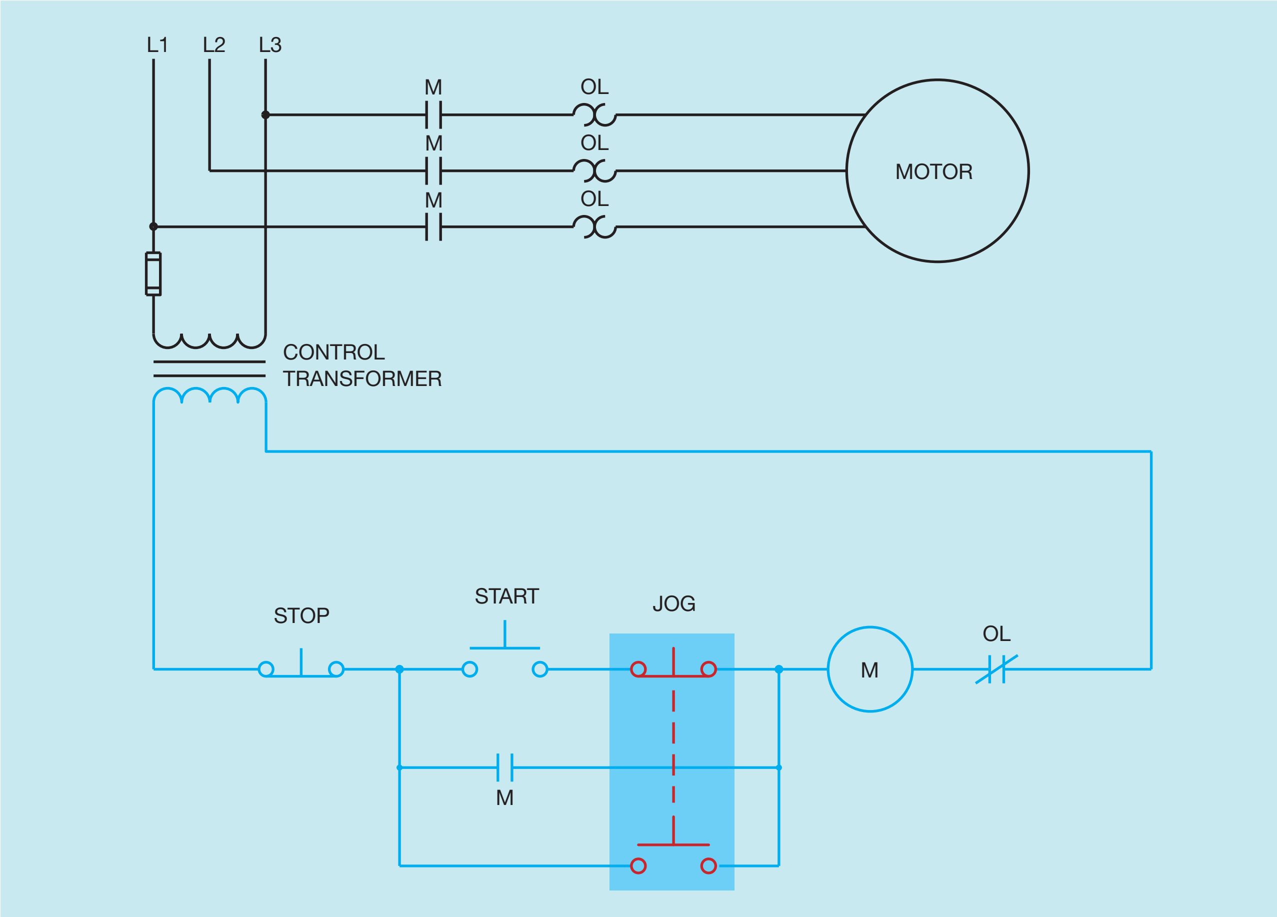


Figure 30–8 The jog button is connected incorrectly. (Source: Delmar/Cengage Learning.)

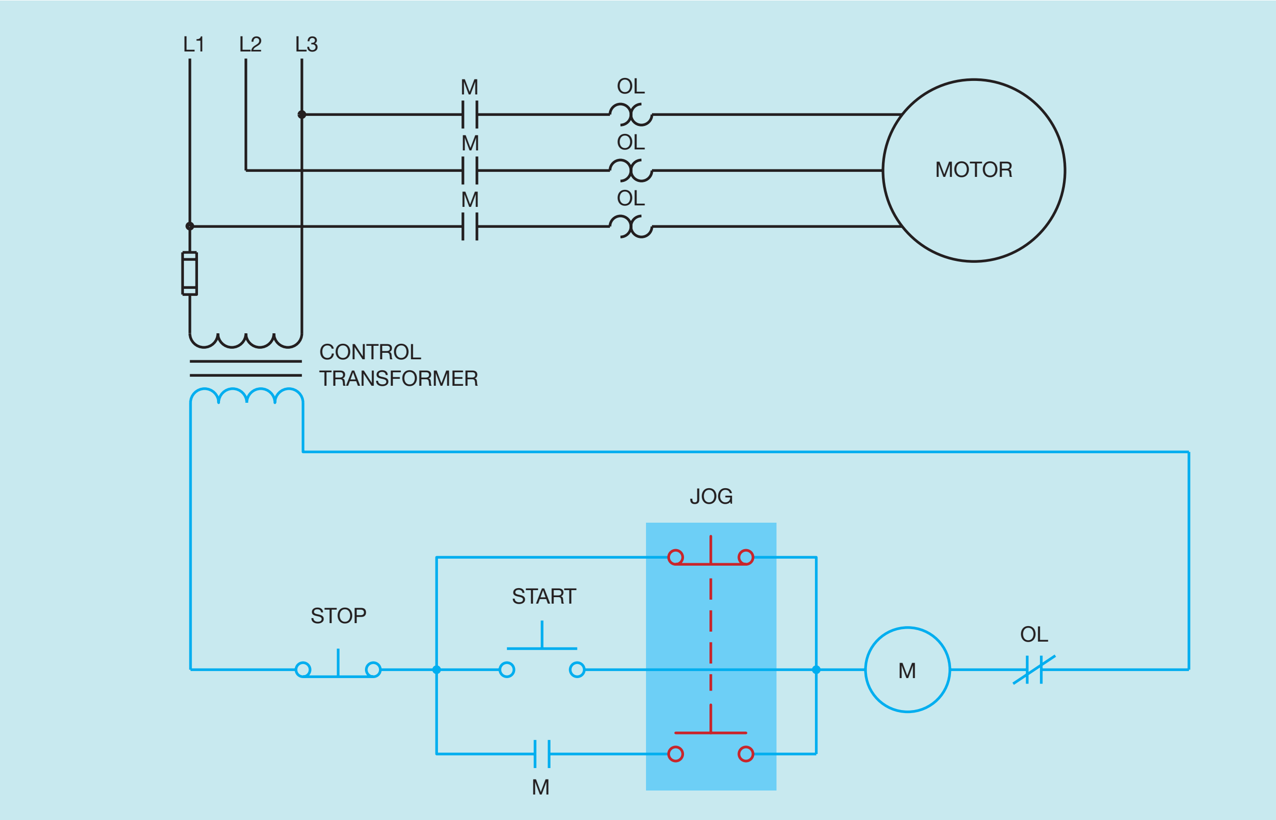


Figure 30–9 Another incorrect connection for the jog button. (Source: Delmar/Cengage Learning.)

CHAPTER 31
SEQUENCE CONTROL

OBJECTIVES

After studying this chapter, the student will be able to:

- State the purpose for starting motors in a predetermined sequence.
- Read and interpret sequence control schematics.
- Convert a sequence control schematic into a wiring diagram.
- Connect a sequence control circuit.

Sequence control forces motors to start or stop in a predetermined order. One motor cannot start until some other motor is in operation. Sequence control is used by such machines as hydraulic presses that must have a high pressure pump operating before it can be used, or by some air conditioning systems that require that the blower be in operation before the compressor starts. There are several methods by which sequence control can be achieved.

Sequence Control Circuit #1

One design that will meet the requirements is shown in Figure 31–1. In this circuit, push button #1 must be pressed before power can be provided to push button #2. When motor starter #1 energizes, the normally open auxiliary contact 1M closes, providing power to coil 1M and to push button #2. Motor starter #2 can now be started by pressing push button #2. Once motor starter #2 is energized, auxiliary contact 2M closes, providing power to coil 2M and push button #3. If the stop button should be pressed or if any overload contact opens, power will be interrupted to all starters.

Sequence Control Circuit #2

A second method of providing sequence control is shown in Figure 31–2. Since the motor connections are the same as the previous circuit, only the control part of the schematic is shown. In this circuit, normally open auxiliary contacts located on motor starters 1M and 2M are used to ensure that the three motors start in the proper sequence. A normally open 1M auxiliary contact connected in series with starter coil 2M prevents motor #2 from starting before motor #1, and a normally open 2M auxiliary contact connected in series with coil 3M prevents motor #3 from starting before motor #2. If the stop button should be pressed or if

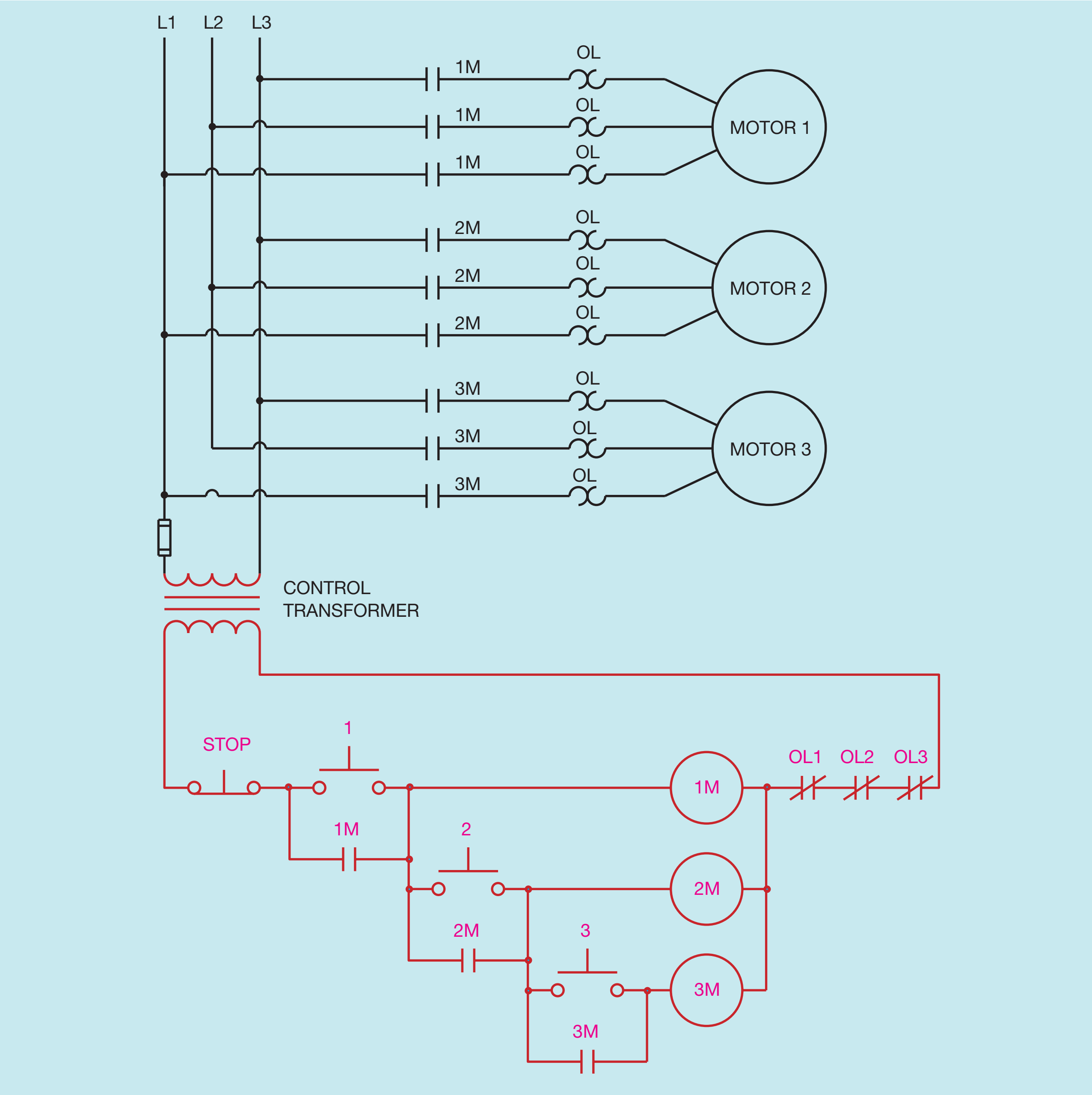


Figure 31–1 One example of a circuit that provides sequence control. (Source: Delmar/Cengage Learning.)

any overload contact should open, power will be interrupted to all starters.

Sequence Control Circuit #3

A third circuit that is almost identical to the previous circuit is shown in Figure 31–3. This circuit also employs the use of normally open auxiliary contacts to prevent motor #2 from starting before motor #1, and motor #3 cannot start before motor #2. These normally open auxiliary contacts that control the starting sequence are often called *permissive* contacts because they permit some action to take place. The main difference between the two circuits is that in the circuit shown in Figure 31–2, the stop push button interrupts the power to all the motor starters. The circuit in Figure 31–3 depends on the normally open auxiliary contacts reopening to stop motors #2 and #3.

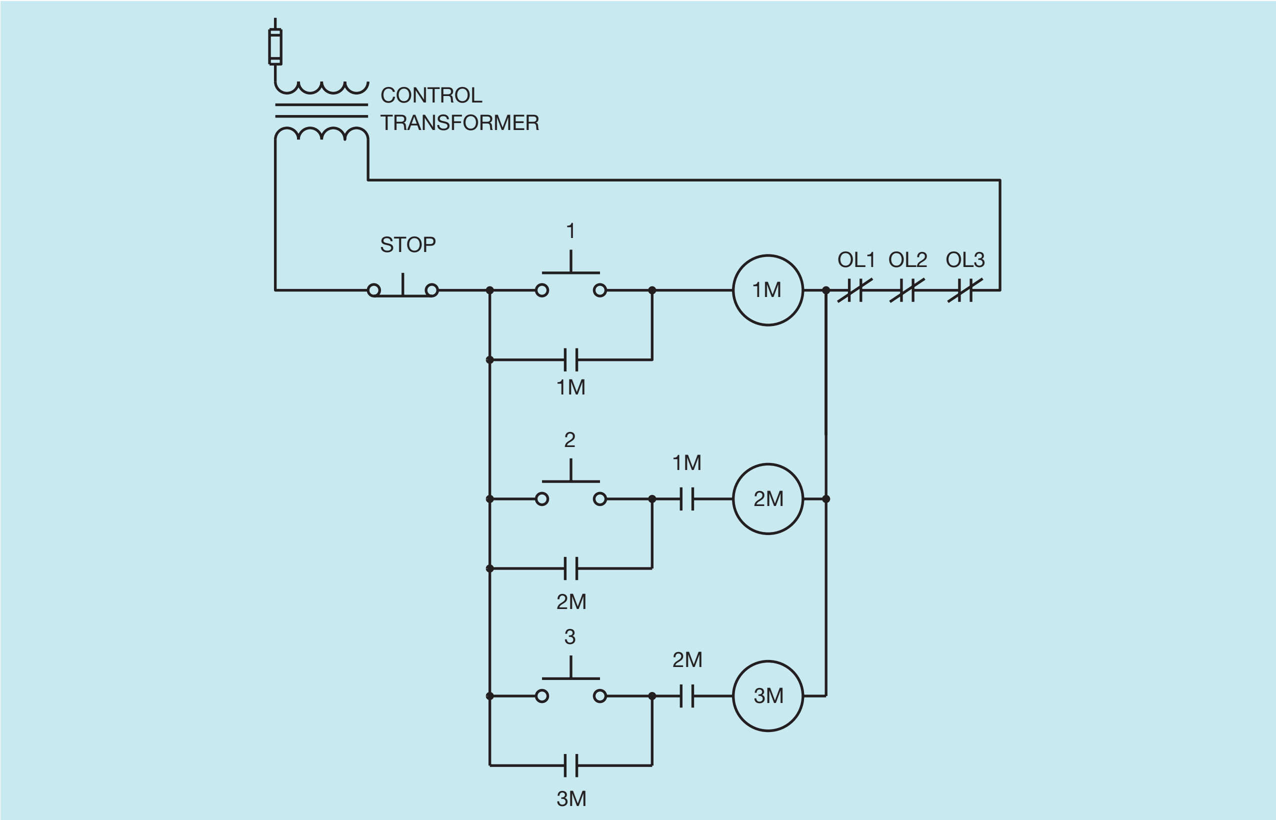


Figure 31–2 A second circuit for sequence control. (Source: Delmar/Cengage Learning.)

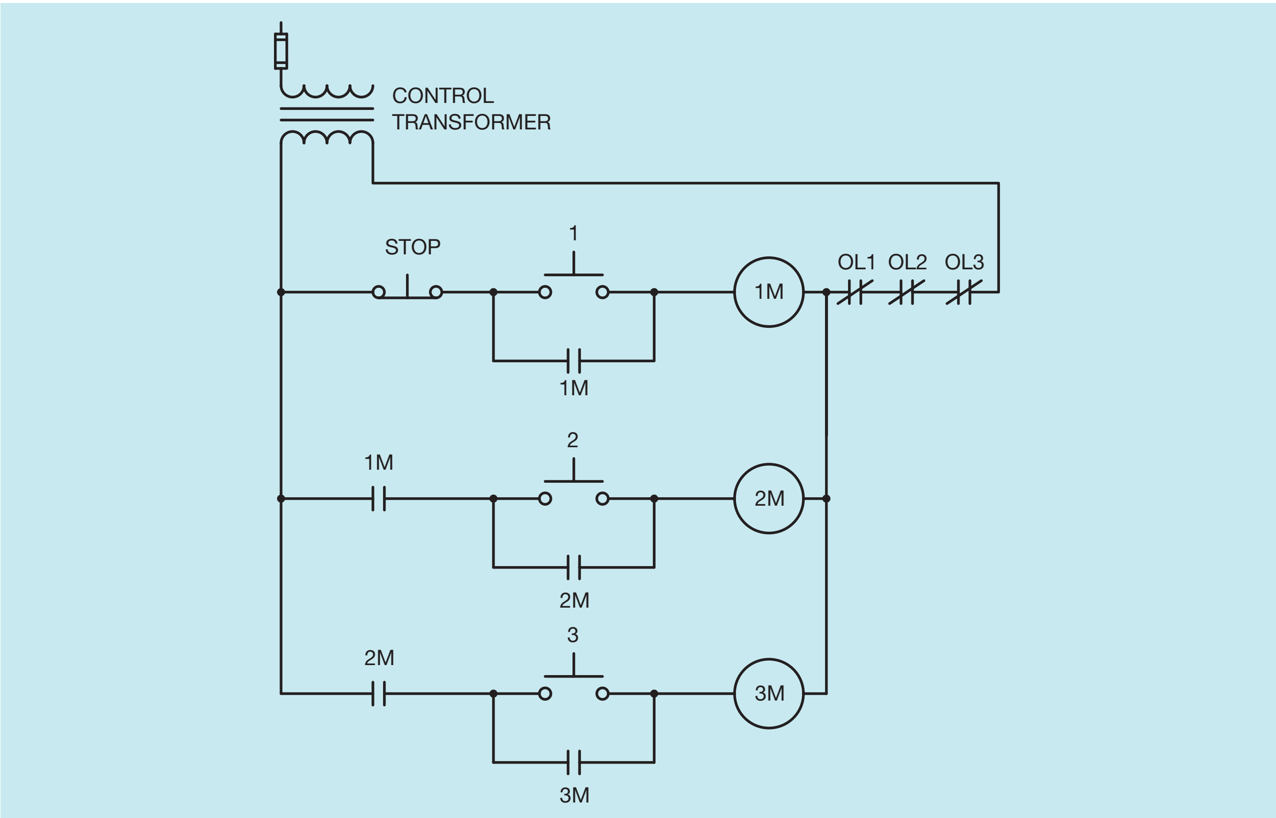


Figure 31–3 A third circuit for sequence control. (Source: Delmar/Cengage Learning.)

Automatic Sequence Control

Circuits that permit the automatic starting of motors in sequence are common. There are a number of methods that can be employed to determine when the next motor should start. Some circuits sense motor current. When the current of a motor drops to a predetermined level, it will permit the next motor to start. Other circuits sense the speed of one motor before permitting the next one to start. One of the most common methods is time delay. The circuit shown in Figure 31–4 will permit three motors to start in sequence. Motor #1 will start immediately when the start button is pressed. Motor #2 will start five seconds after motor #1 starts, and motor #3 will start five seconds after motor #2 starts. Timer coil TR1 is connected in parallel with 1M starter coil. Since they are connected in parallel, they will energize at the same time. After a delay of 5 seconds, TR1 contact will close and energize coils 2M and TR2. Motor #2 will start immediately, but timed contact TR2 will delay closing for 5 seconds. After the delay period, starter coil 3M will energize and start motor #3. When the STOP button is pushed, all motors will stop at virtually the same time.

Although the circuit logic in Figure 31–4 is correct, most ladder diagrams do not show coils connected in parallel. A modification of the circuit is shown in Figure 31–5. In this circuit, auxiliary contacts on the motor starters are used to control the action of the timed relays. Note that the logic of the circuit is identical to that of the circuit in Figure 31–4.

Stopping the Motors in Sequence

Some circuit requirements may demand that the motors turn off in sequence instead of turning on in sequence. This circuit will require the use of off-delay timers. Also, a control relay with four contacts will be needed. The circuit shown in Figure 31–6 will permit the motors to start in sequence from one to three when the START button is pressed. Although they start in sequence, the action will be so fast that it will appear they all start at approximately the same time. When the STOP button is pressed, however, they will stop in sequence from three to one with a time delay of 5 seconds between each motor. Motor #3 will stop immediately. Five seconds later motor #2 will

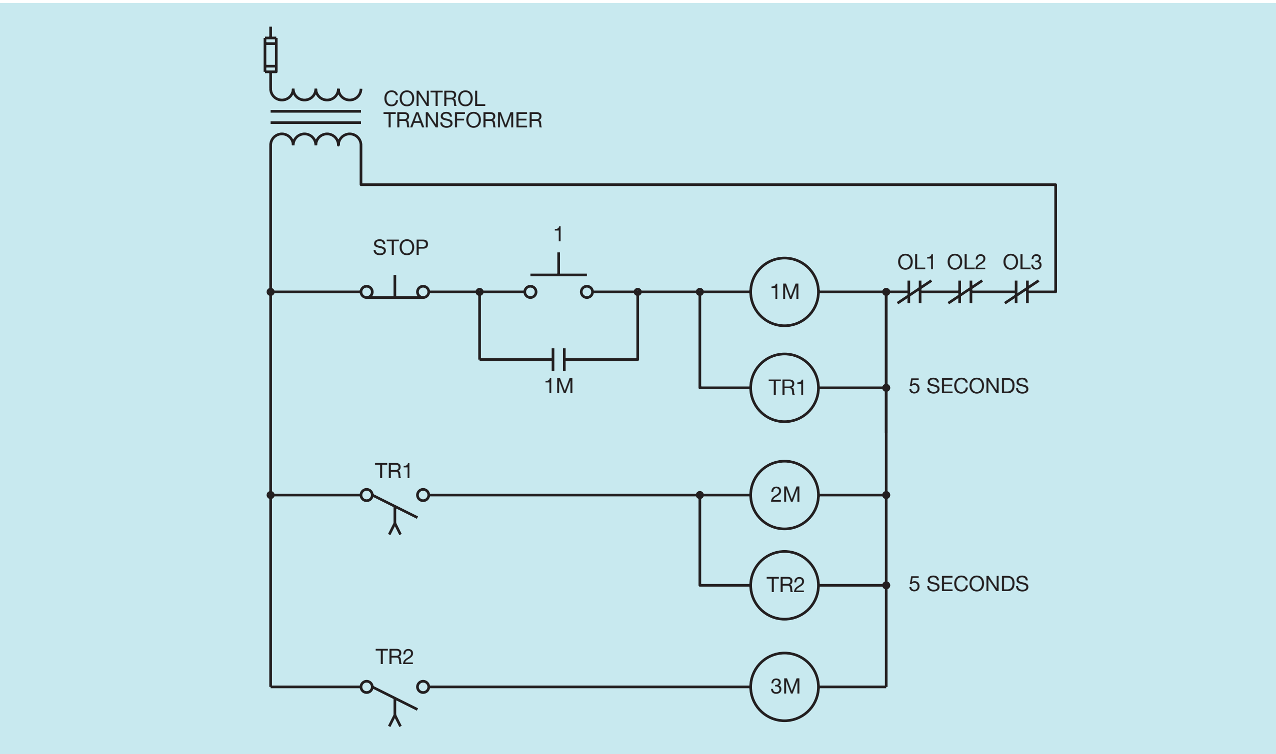


Figure 31–4 Timed starting for three motors. (Source: Delmar/Cengage Learning.)

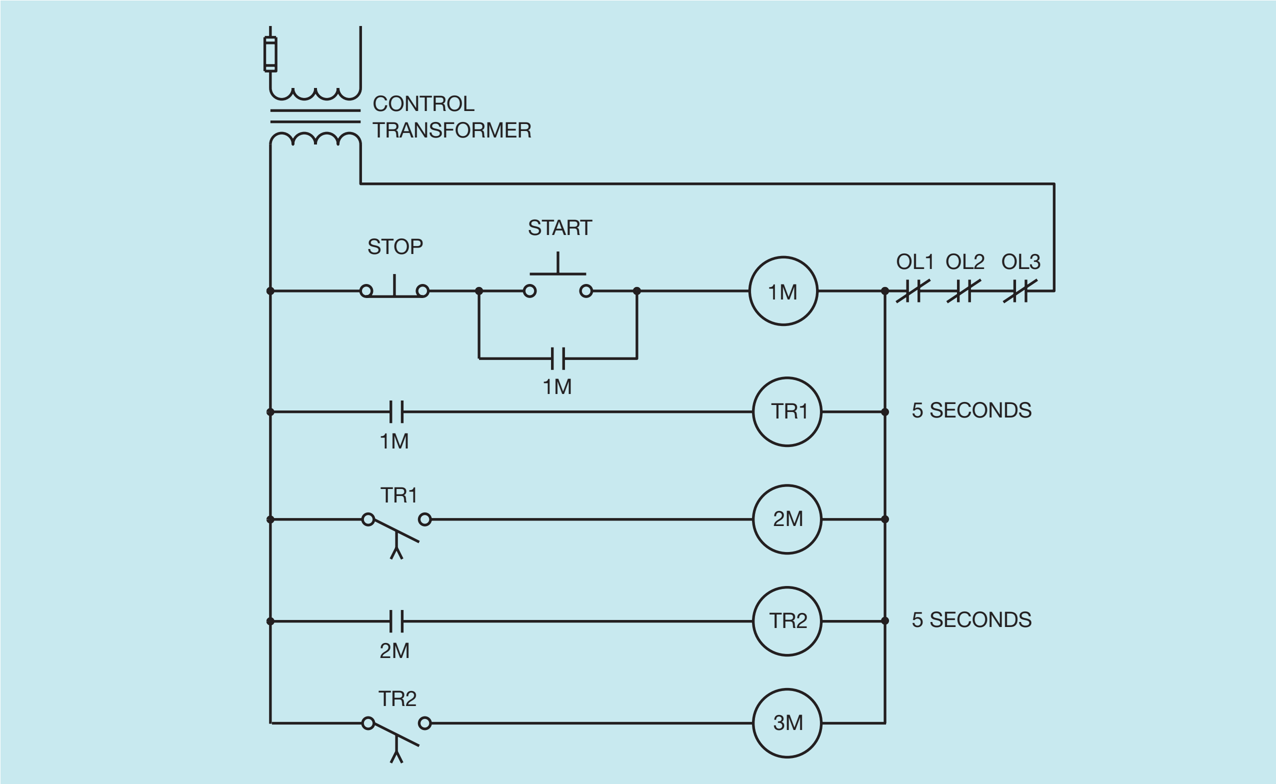


Figure 31–5 Circuit is modified to eliminate parallel coils. (Source: Delmar/Cengage Learning.)

stop, and five seconds after motor #2 stops, motor #1 will stop. An overload on any motor will stop all motors immediately.

Circuit Operation

When the START push button is pressed, control relay CR energizes and causes all CR contacts to close, Figure 31–7. Motor starter 2M cannot energize because of the normally open 1M contact connected in series with coil 2M, and motor starter 3M cannot energize because of the normally open 2M contact connected in series with coil 3M. Motor starter 1M does energize, starting motor #1 and closing all 1M contacts, Figure 31–8.

The 1M contact connected in series with coil 2M closes and energizes coil 2M, Figure 31–9. This causes motor #2 to start and all 2M contacts to close. Off-delay timer TR1 energizes and immediately closes the TR1 contact connected in parallel with the CR contact that is connected in series with coil 1M.

When the 2M contact connected in series with coil 3M closes, starter coil 3M energizes and starts motor #3. The 3M auxiliary contact connected in series with off-delay timer coil TR2 closes and energizes the timer, causing timed contacts TR2 to close immediately, Figure 31–10. Although this process seems long when discussed in step-by-step order, it actually takes place almost instantly.

When the STOP button is pressed, all CR contacts open immediately, Figure 31–11. Motor #1 continues to run because the now closed TR1 contact maintains a circuit to the coil of 1M starter. Motor #2 continues to run because of the now closed TR2 contact. Motor #3, however stops immediately when the CR contact connected in series with coil 3M opens. This causes the 3M auxiliary contact connected in series with TR2 coil to open and de-energize the timer. Since TR2 is an off-delay timer, the timing process starts when the coil is de-energized. TR2 contact will remain closed for a period of 5 seconds before it opens.

When TR2 contact opens, coil 2M de-energizes and stops motor #2. When the 2M auxiliary contacts open, TR1 coil de-energizes and starts the time delay for contact TR1, Figure 31–12. After a delay of 5 seconds, timed contact TR1 opens and de-energizes coil

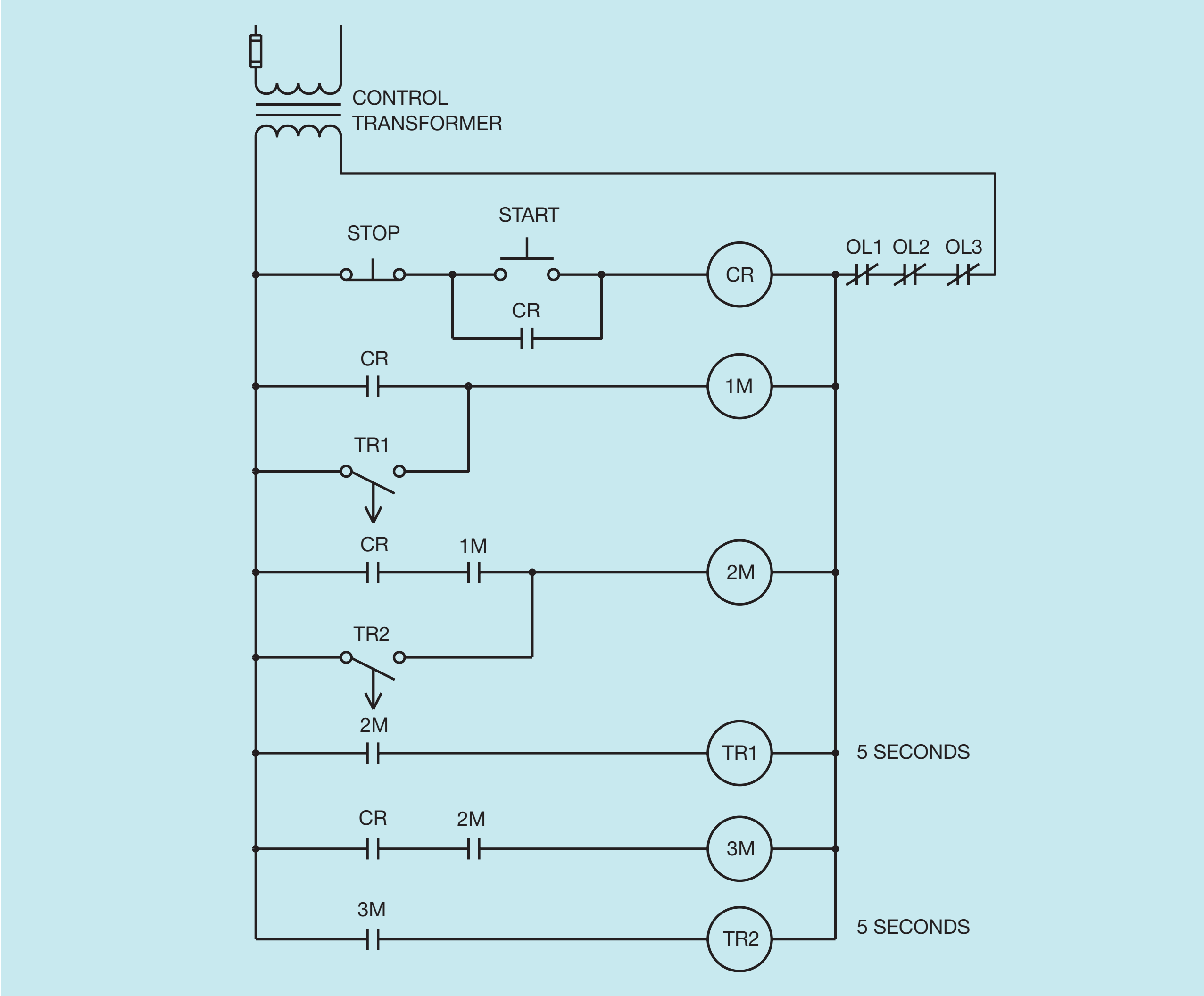


Figure 31–6 Motors start in sequence from 1 to 3 and stop in sequence from 3 to 1 with a delay of 5 seconds between the stopping of each motor. (Source: Delmar/Cengage Learning.)

1M, stopping motor #1 and opening the 1M auxiliary contact connected in series with coil 2M. The circuit is now back in its normal de-energized state, as shown in Figure 31–6.

Timed Starting and Stopping of Three Motors

The addition of two timers make it possible to start the motors in sequence from 1 to 3 with a time delay between the starting of each motor, as well as stopping the motors in sequence from 3 to 1 with a time delay between the stopping of each motor. The circuit shown in Figure 31–13 makes this amendment. When the START button is pressed, all CR contacts close. Motor #1 starts immediately when starter 1M energizes. The 1M auxiliary contact closes and energizes on-delay timer TR3. After 5 seconds, starter 2M energizes and starts motor #2. The 2M auxiliary contact connected in series with off-delay timer TR1 closes, causing timed contact TR1 to close immediately. The second 2M auxiliary contact connected in series with on-delay timer TR4 closes and starts the timing process. After 5 seconds, timed contact TR4 closes and energizes starter coil 3M, starting motor #3. The 3M auxiliary

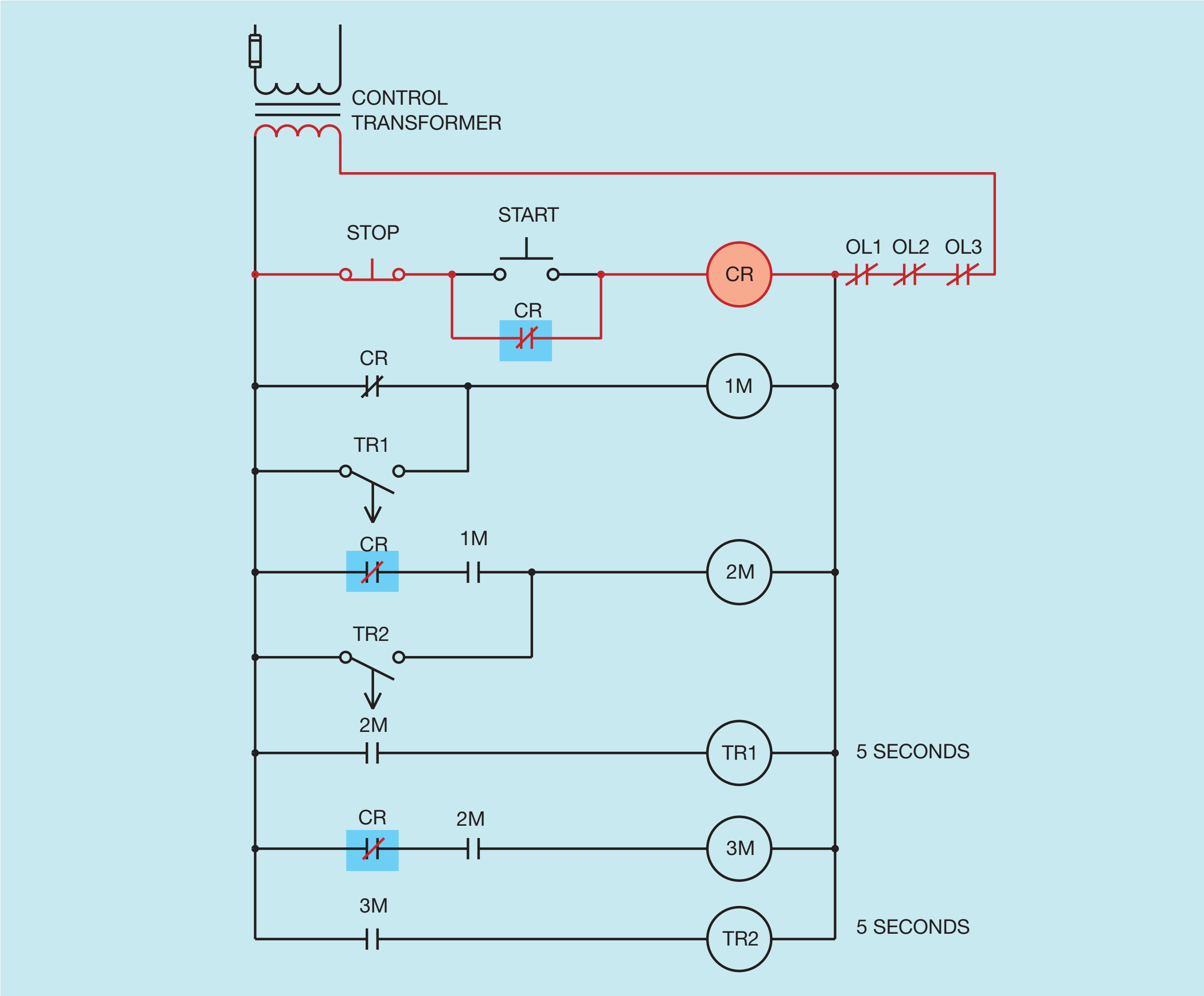


Figure 31–7 Control relay CR energizes and closes all CR contacts. (Source: Delmar/Cengage Learning.)

contact connected in series with off-delay timer TR2 closes and energizes the timer. Timed contact TR2 closes immediately. All motors are now running.

When the STOP button is pressed, all CR contacts open immediately. This de-energizes starter 3M, stopping motor #3 and de-energizing off-delay timer coil TR2. After a delay of 5 seconds, timed contact TR2 opens and de-energizes starter 2M. This causes motor #2 to stop, off-delay timer TR1 to de-energize, and on-delay timer TR4 to de-energize. TR4 contact reopens immediately. After a delay of 5 seconds, timed contact TR1 opens and de-energizes starter coil 1M. This causes motor #1 to stop and on-delay timer TR3 to de-energize. Contact TR3 reopens immediately and the circuit is back in its original de-energized state.

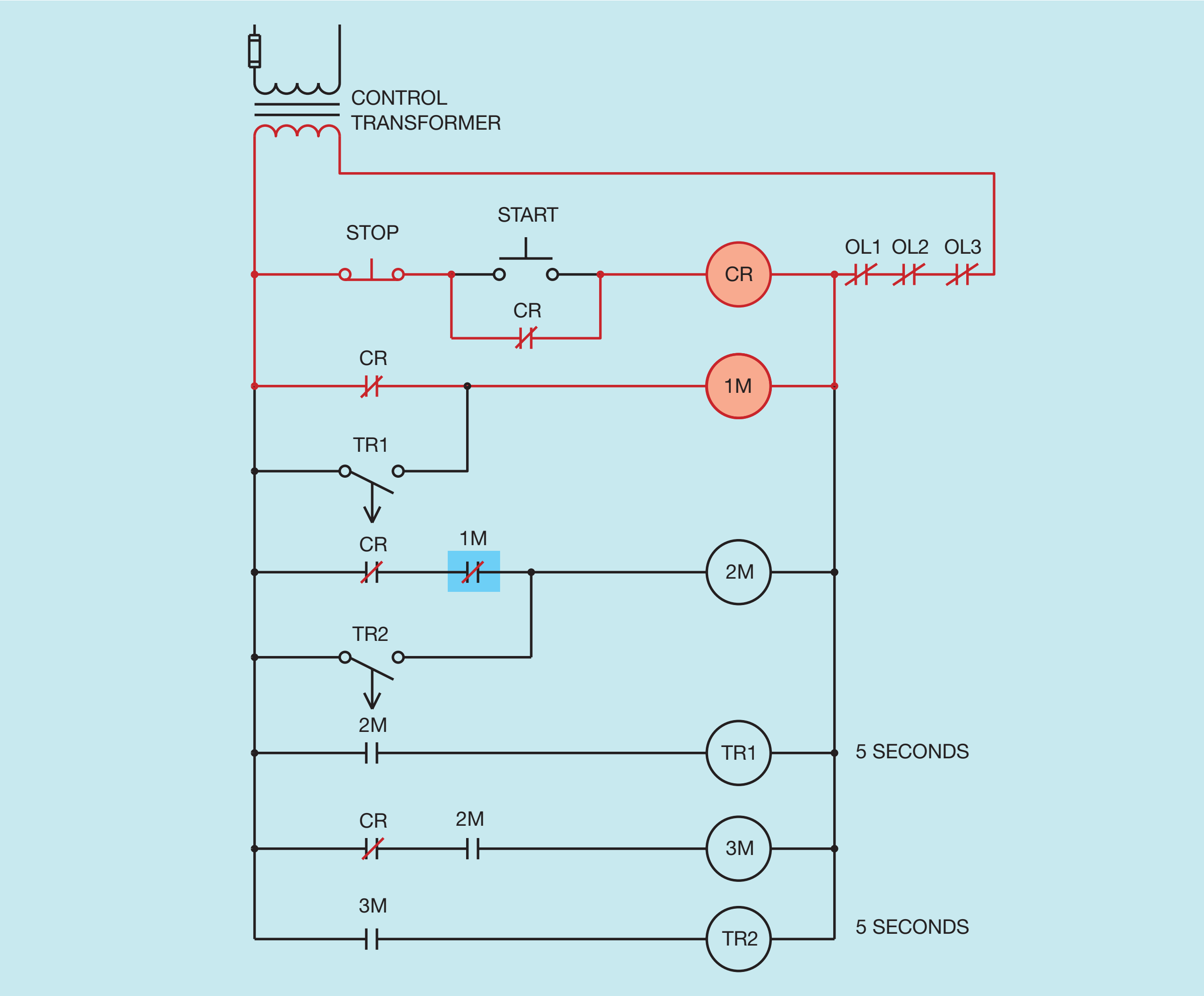


Figure 31–8 Motor #1 starts. (Source: Delmar/Cengage Learning.)

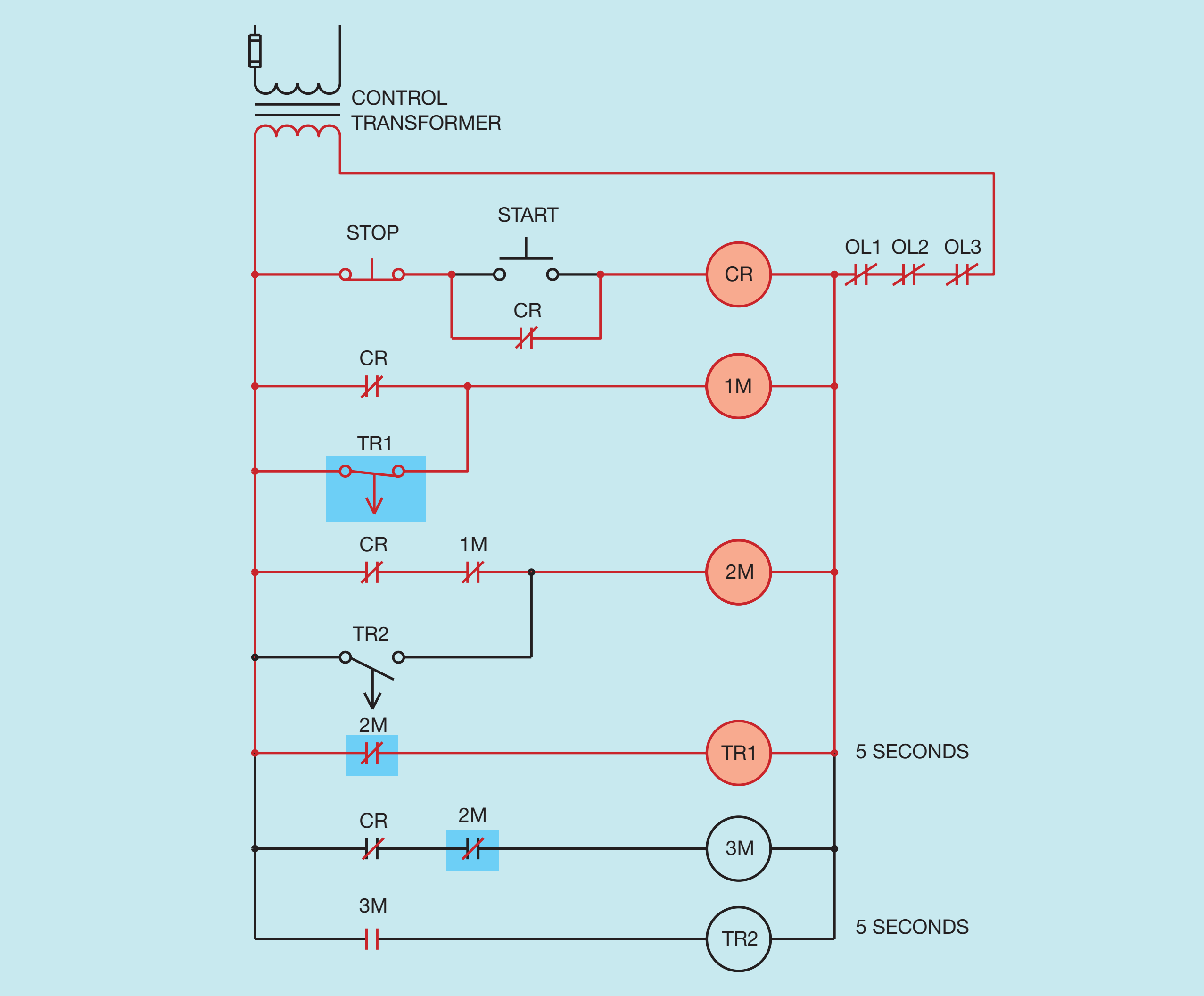


Figure 31–9 Motor #2 starts. (Source: Delmar/Cengage Learning.)

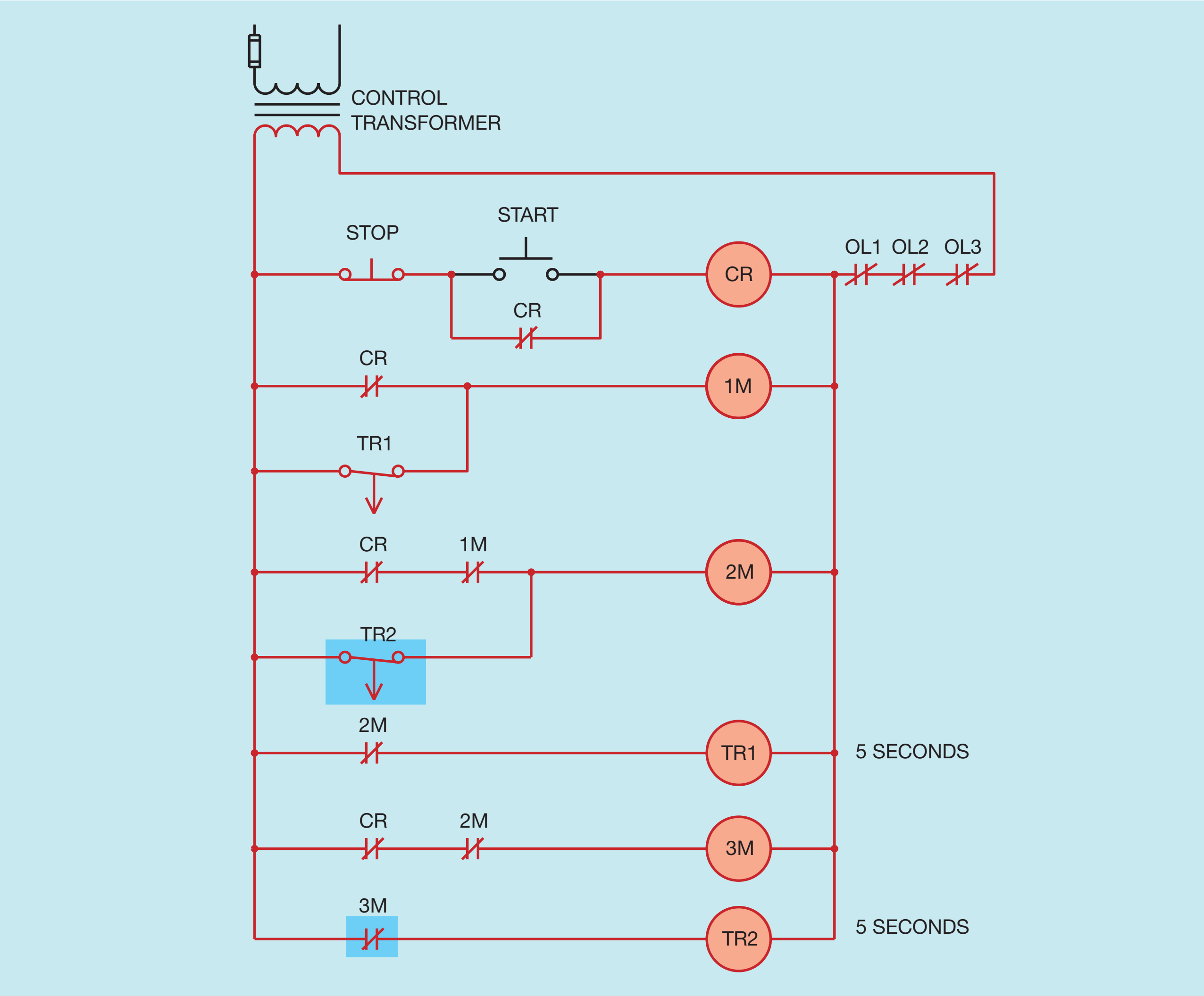


Figure 31–10 Motor #3 starts. (Source: Delmar/Cengage Learning.)

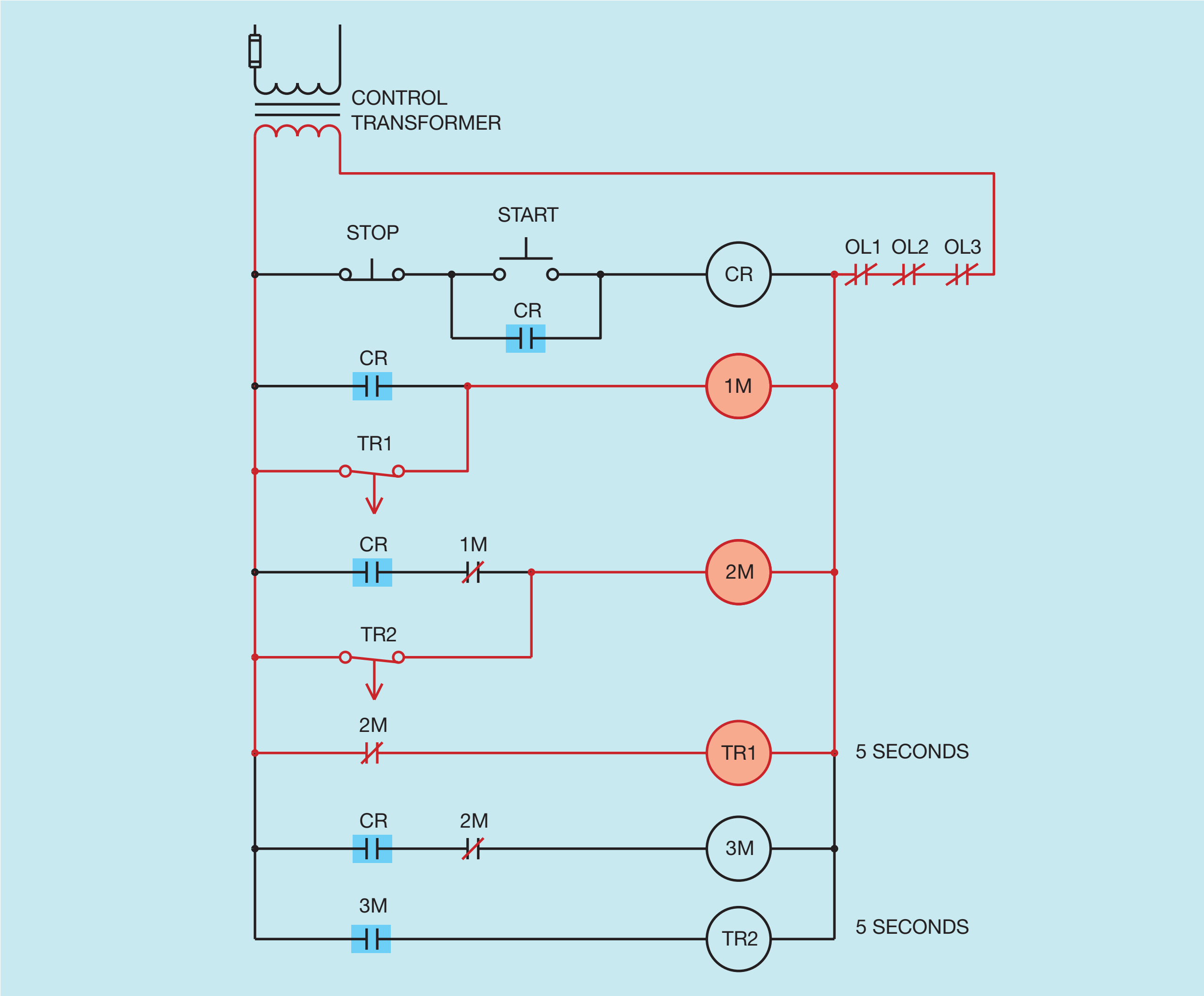


Figure 31–11 Motor #3 stops. (Source: Delmar/Cengage Learning.)

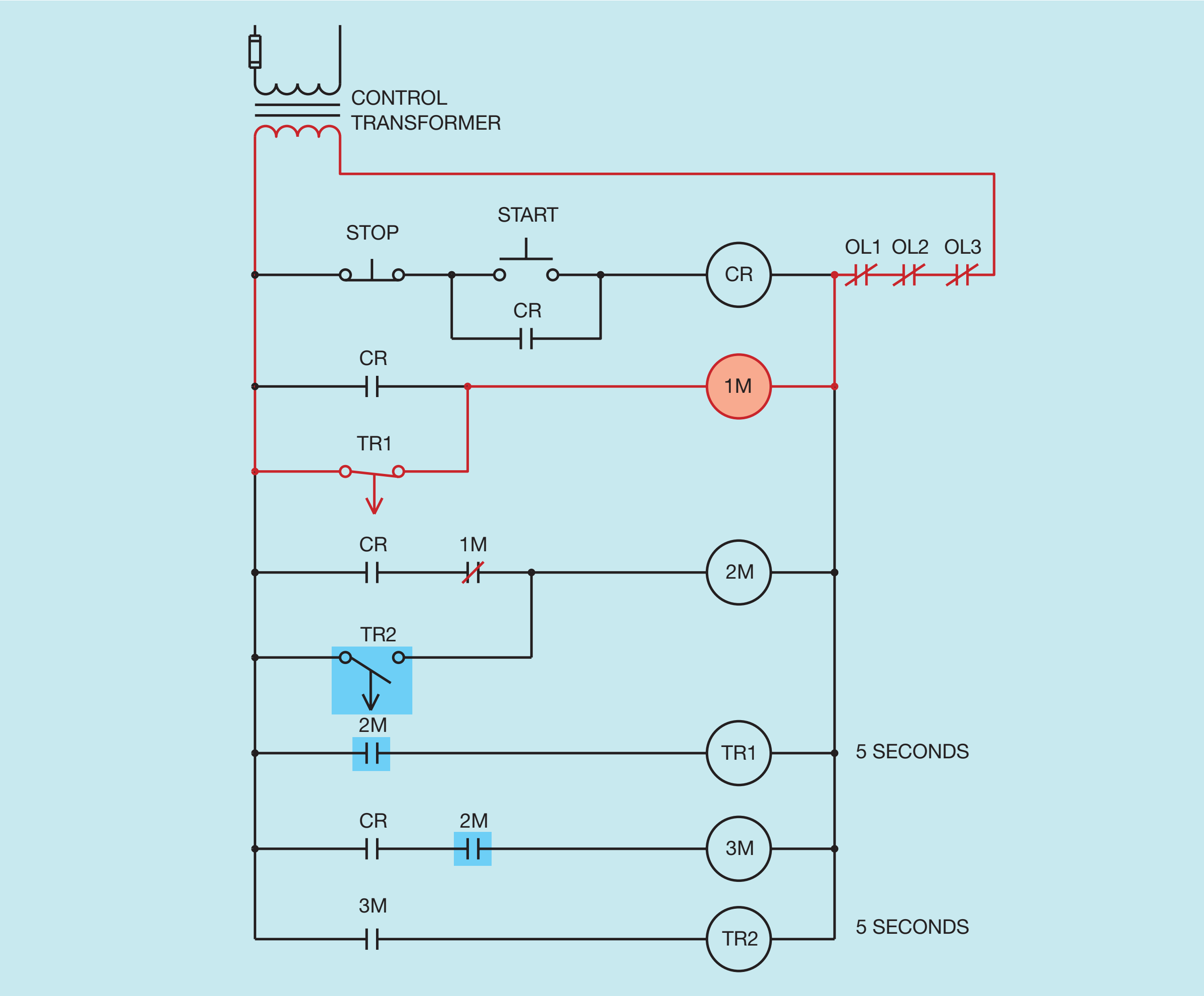


Figure 31–12 Motor #2 stops. (Source: Delmar/Cengage Learning.)

Review Questions

1. What is the purpose of sequence control?

2. Refer to the schematic diagram in Figure 31–14. Assume that the 1M contact located between wire numbers 29 and 30 had been connected normally closed instead of normally open. How would this circuit operate?

3. Assume that all three motors shown in Figure 31–14 are running. Now assume that the stop button is pressed and motors #1 and #2 stop running, but motor #3 continues to operate. Which of the following could cause this problem?
   a. Stop button is shorted.
   b. 2M contact between wire numbers 31 and 32 is hung closed.
   c. The 3M load contacts are welded shut.
   d. The normally open 3M contact between wire numbers 23 and 31 is hung closed.

4. Referring to Figure 31–14, assume that the normally open 2M contact located between wire

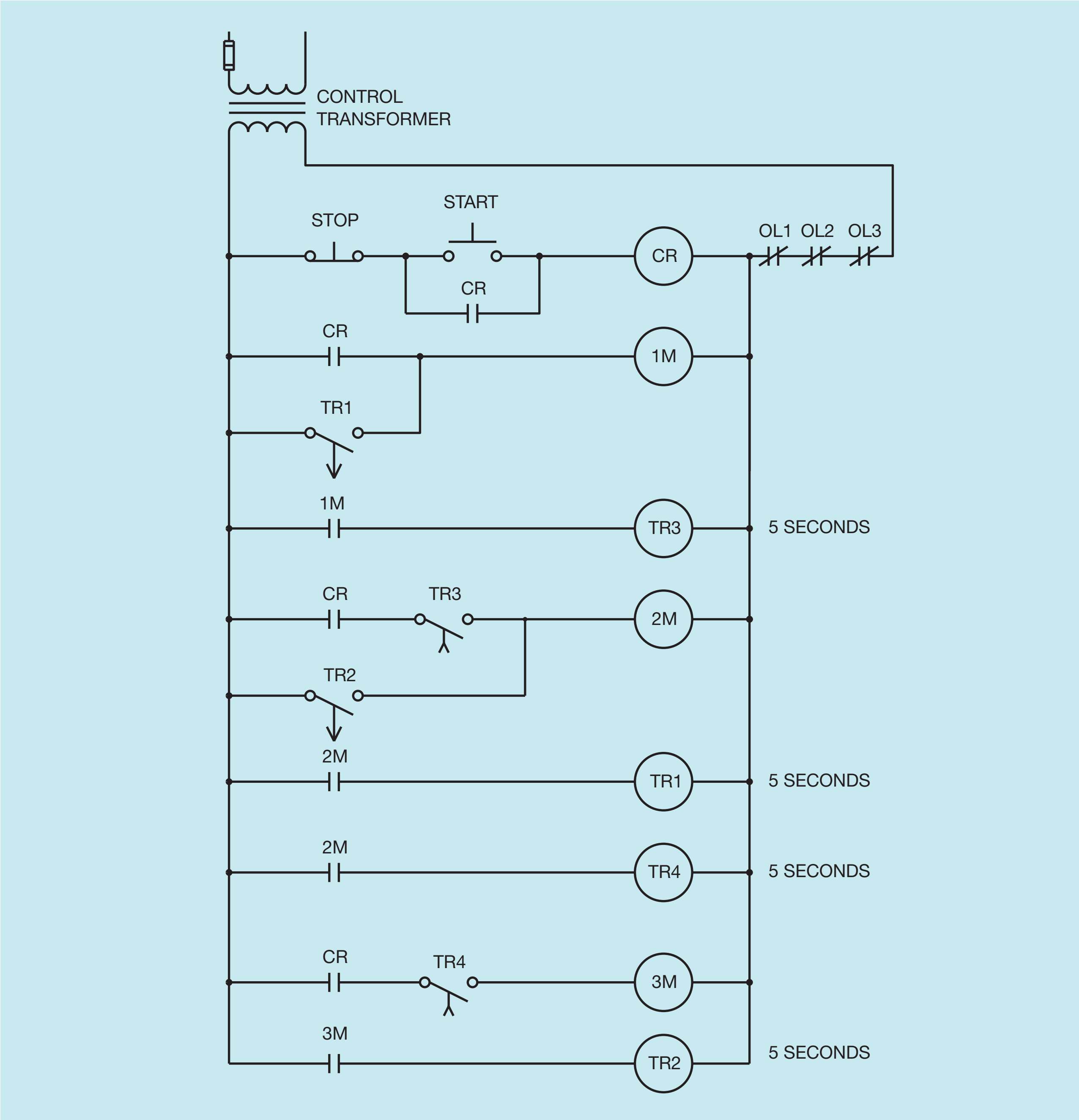


Figure 31–13 Motors start and stop in sequence with a time delay between starting and stopping. (Source: Delmar/Cengage Learning.)

numbers 23 and 29 is welded closed. Also assume that none of the motors are running. What would happen if:

a. The number 2 push button were pressed before the number 1 push-button?
b. The number 1 push button were pressed first?

5. In the control circuit shown in Figure 31–2, if an overload occurs on any motor, all three motors will stop running. Using a separate sheet of paper, redesign the circuit so that the motors must still start in sequence from 1 to 3, but an overload on any motor will stop only that motor. If an overload should occur on motor #1, for example, motors #2 and #3 would continue to operate.

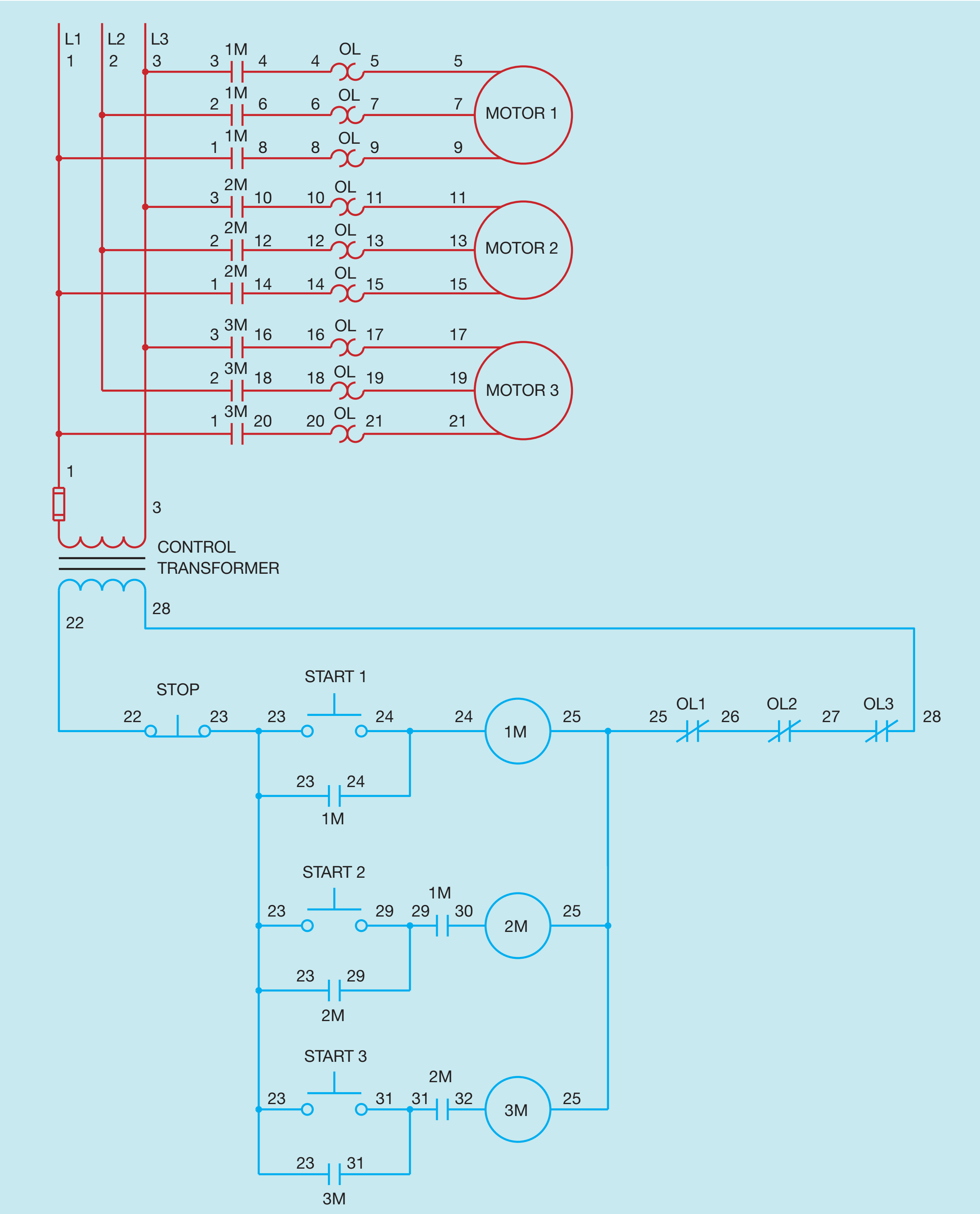


Figure 31–14 Sequence control schematic with wire numbers. (Source: Delmar/Cengage Learning.)

CHAPTER 32
DC MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- List applications of DC motors.
- Describe the electrical characteristics of DC motors.
- Describe the field structure of a DC motor.
- Change the direction of rotation of a DC motor.
- Identify the series and shunt fields and the armature winding with an ohmmeter.
- Connect motor leads to form a series, shunt, or compound motor.
- Describe the difference between a differential and a cumulative compound motor.

Application

DC motors are used in applications where variable speed and strong torque are required. They are used for cranes and hoists when loads must be started slowly and accelerated quickly. DC motors are also used in printing presses, steel mills, pipe forming mills, and many other industrial applications where speed control is important.

Speed Control

The speed of a DC motor can be controlled by applying variable voltage to the armature or field. When full voltage is applied to both the armature and the field, the motor operates at its base or normal speed. When full voltage is applied to the field and reduced voltage is applied to the armature, the motor operates below normal speed. When full voltage is applied to the armature and reduced voltage is applied to the field, the motor operates above normal speed.

Motor Construction

The essential parts of a DC motor are the armature, field windings, brushes, and frame (Figure 32–1).

The Armature

The armature is the rotating part of the motor. It is constructed from an iron cylinder that has slots cut into it. Wire is wound through the slots to form the

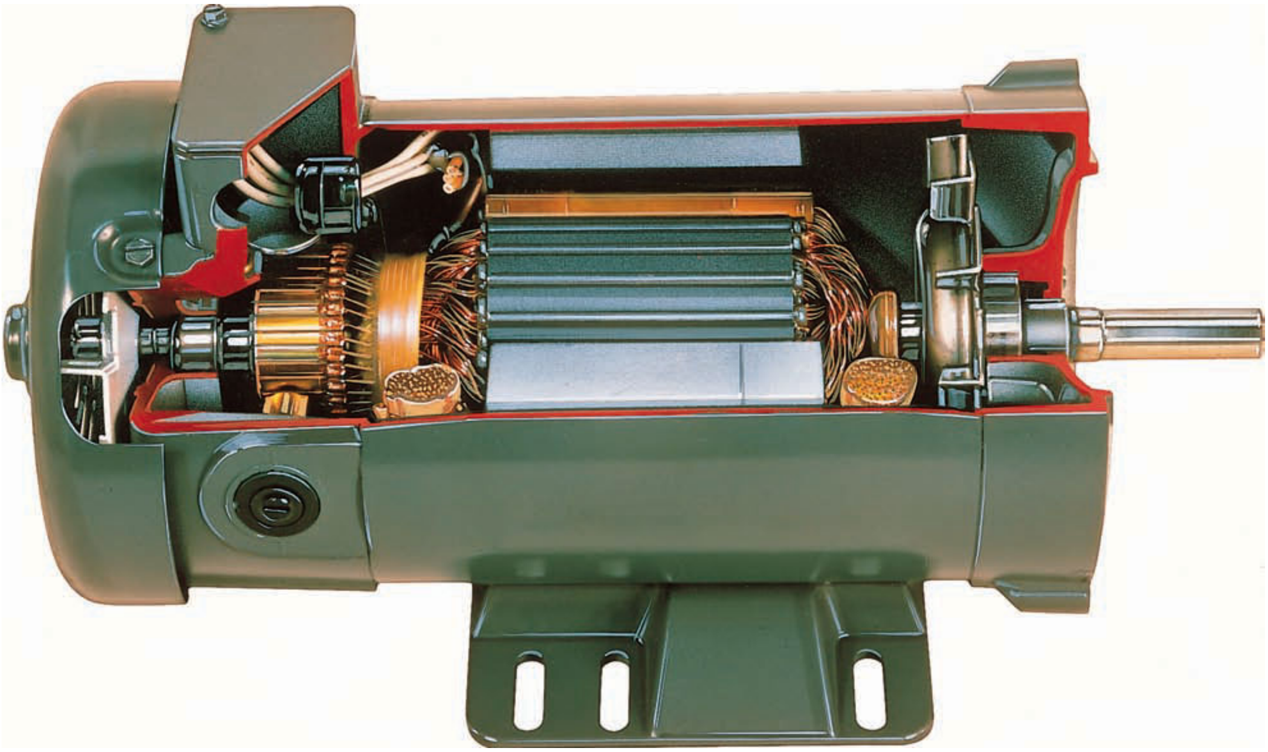


Figure 32–1 DC motor, field structure, and armature assembly. (Courtesy Reliance Electric Co.)

windings. The ends of the windings are connected to the commutator, which consists of insulated copper bars and is mounted on the same shaft as the windings. The windings and commutator together form the armature.

Carbon brushes, which press against the commutator segment, supply power to the armature from the DC power line. The commutator is a mechanical switch that forces current to flow through the armature windings in the same direction. This enables the polarity of the magnetic field produced in the armature to remain constant as it turns.

Armature resistance is kept low, generally less than 1 ohm. This is because the speed regulation of the motor is proportional to the armature resistance. The lower the armature resistance, the better the speed regulation will be. Where the brush leads extend out of the motor at the terminal box, they are labeled A1 and A2.

Field Windings

There are two types of field windings used in DC motors: series and shunt. The series field is made with a few turns of large wire. It has a low resistance and is designed to be connected in series with the armature. The terminal markings, S1 and S2, identify the series field windings.

The shunt field winding is made with many turns of small wire. It has a high resistance and is designed to be connected in parallel with the armature. Since the shunt field is connected in parallel with the armature, line voltage is connected across it. The current through the shunt field is, therefore, limited by its resistance. The terminal markings for the shunt field are F1 and F2.

Identifying Windings

The windings of a DC motor can be identified with an ohmmeter. The shunt field winding can be identified by the fact that it has a high resistance as compared to the other two windings. The series field and armature windings have a very low resistance. They can be identified, however, by turning the motor shaft. When the ohmmeter is connected to the series field and the motor shaft is turned, the ohmmeter reading will not be affected. When the ohmmeter is connected to the armature winding and the motor shaft is turned, the reading will become erratic as the brushes make and break contact with different commutator segments.

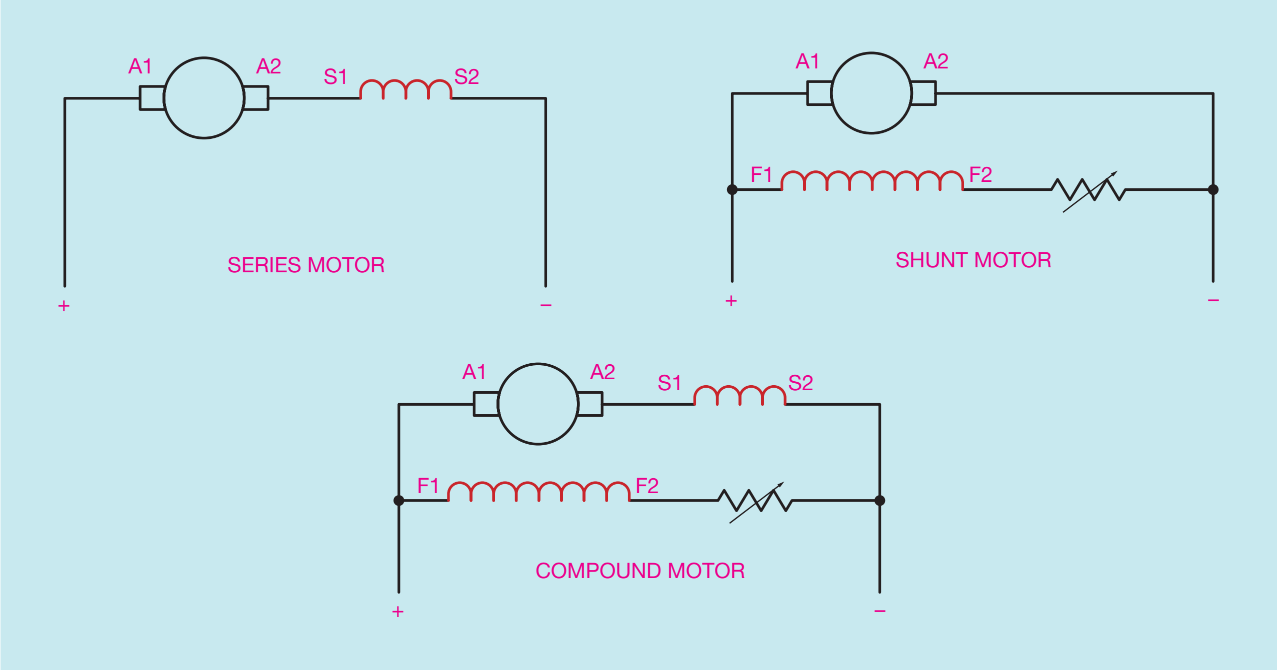


Figure 32–2 DC motor connections. (Source: Delmar/Cengage Learning.)

Types of DC Motors

There are three basic types of DC motors: the series, the shunt, and the compound. The type of motor used is determined by the requirements of the load. The series motor, for example, can produce very high starting torque, but its speed regulation is poor. The only thing that limits the speed of a series motor is the amount of load connected to it. A very common application of a series motor is the starter motor used on automobiles. Shunt and compound motors are used in applications where speed control is essential.

Figure 32–2 shows the basic connections for series, shunt, and compound motors. Notice that the series motor contains only the series field connected in series with the armature. The shunt motor contains only the shunt field connected parallel to the armature. A rheostat is shown connected in series with the shunt field to provide above normal speed control.

The compound motor has both series and shunt field windings. Each pole piece in the motor will have both windings wound on it (Figure 32–3). There are different ways of connecting compound motors. For instance, a motor can be connected as a long shunt compound or as a short shunt compound (Figure 32–4). When a long shunt connection is made, the shunt field is connected parallel to both the armature and the series field. When a short shunt connection is made, the shunt field is connected parallel to the armature, but in series with the series field.

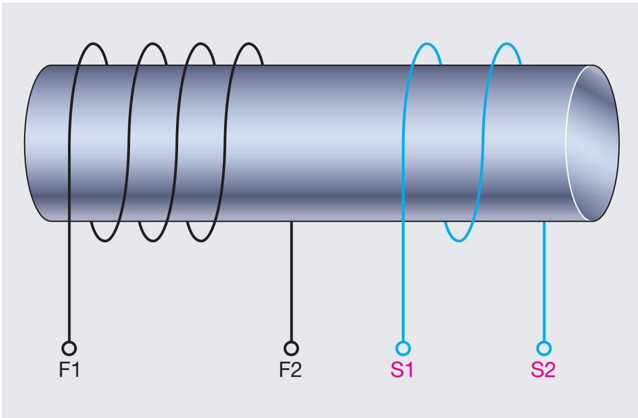


Figure 32–3 Series and shunt field windings are wound. (Source: Delmar/Cengage Learning.)

Compound motors can also be connected as cumulative or differential. When a motor is connected as a cumulative compound, the shunt and series fields are connected in such a manner that as current flows through the windings they aid each other in the production of magnetism (Figure 32–5). When the motor

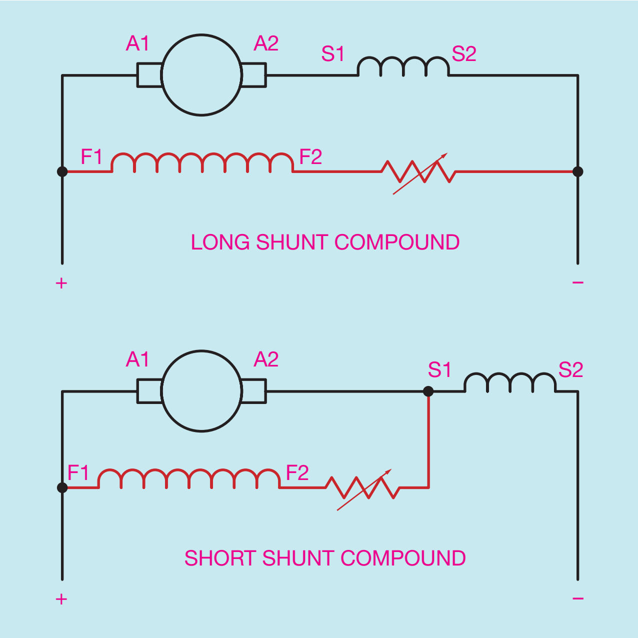


Figure 32–4 Compound motor connections. (Source: Delmar/Cengage Learning.)

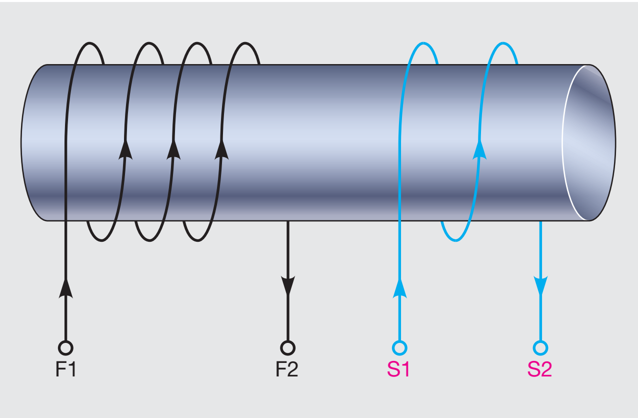


Figure 32–5 Cumulative compound connection. (Source: Delmar/Cengage Learning.)

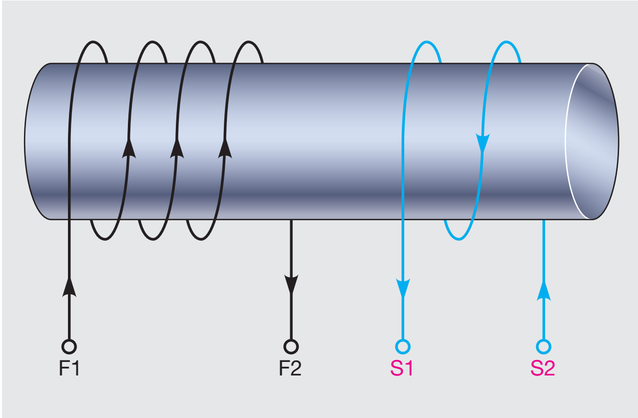


Figure 32–6 Differential compound connection. (Source: Delmar/Cengage Learning.)

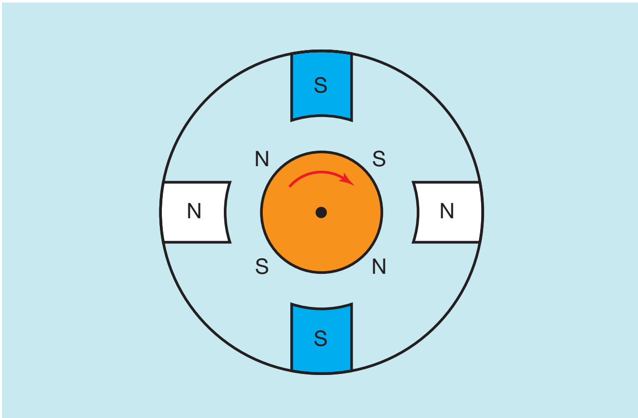


Figure 32–7 Armature rotates in a clockwise direction. (Source: Delmar/Cengage Learning.)

is connected as a differential compound, the shunt and series field windings are connected in such a manner that as current flows through them they oppose each other in the production of magnetism (Figure 32–6).

Direction of Rotation

The direction of rotation of the armature is determined by the relationship of the polarity of the magnetic field of the armature to the polarity of the magnetic field of the pole pieces. Figure 32–7 shows a motor connected in such a manner that the armature will rotate in a clockwise direction due to the attraction and repulsion of magnetic fields. If the input lines to the motor are reversed, the magnetic polarity of both the pole pieces and the armature will be reversed and the motor will continue to operate in the same direction (Figure 32–8).

To reverse the direction of rotation of the armature, the magnetic polarity of the armature and the field must be changed in relation to each other. In Figure 32–9, the armature leads have been changed, but the field leads have not. Notice that the attraction and repulsion of the magnetic fields now cause the armature to turn in a counterclockwise direction.

When the direction of rotation of a series or shunt motor is to be changed, either the field or the armature

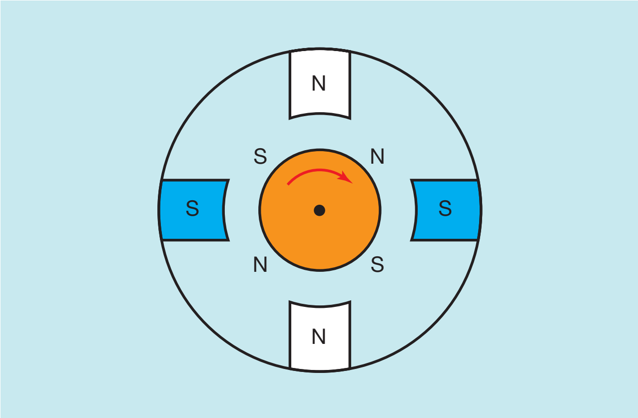


Figure 32–8 Changing input lines will not reverse the direction of rotation. (Source: Delmar/Cengage Learning.)

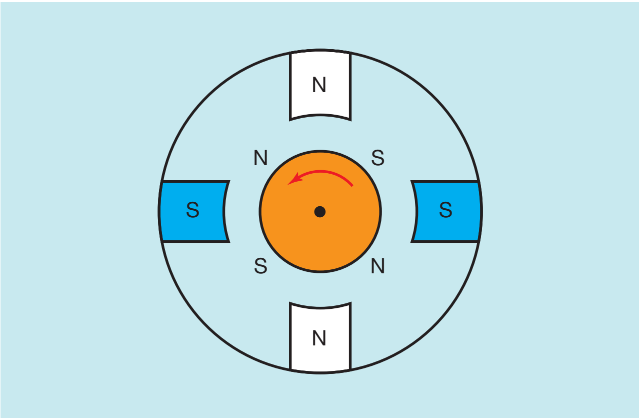


Figure 32–9 When the armature leads are reversed, the direction of rotation is changed. (Source: Delmar/Cengage Learning.)

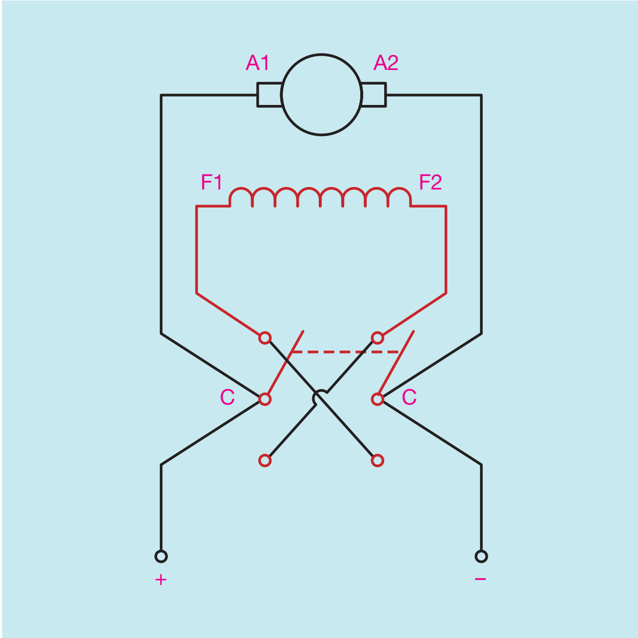


Figure 32–10 Double-pole, double-throw switch used to reverse the direction of rotation of a shunt motor. (Source: Delmar/Cengage Learning.)

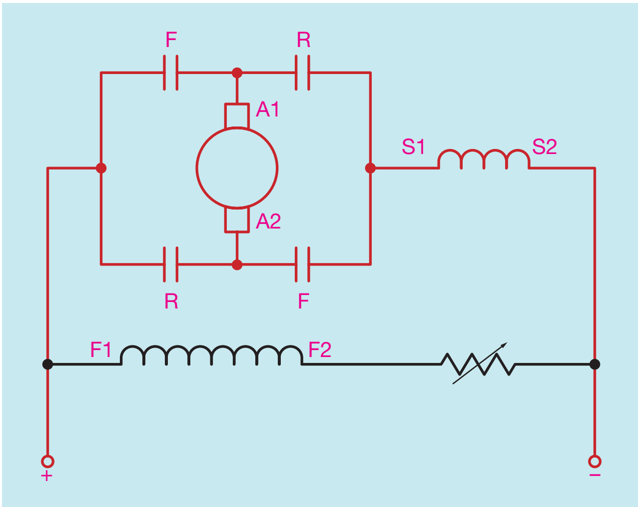


Figure 32–11 Contactors reverse the direction of current flow through the armature. (Source: Delmar/Cengage Learning.)

leads can be reversed. Many small DC shunt motors are reversed by reversing the connection of the shunt field leads. This is done because the current flow through the shunt field is much lower than the current flow through the armature. This permits a small switch, instead of a large solenoid switch, to be used as a reversing switch. Figure 32–10 shows a double-pole, double-throw (DPDT) switch used as a reversing switch. Power is connected to the common terminals of the switch and the stationary terminals are cross connected.

When a compound motor is to be reversed, only the armature leads are changed. If the motor is reversed by changing the shunt field leads, the motor will be changed from a cumulative compound motor to a differential compound motor. If this happens, the motor speed will drop sharply when load is added to the motor. Figure 32–11 shows a reversing circuit using magnetic contactors to change the direction of current flow through the armature. Notice that the direction of current flow through the series and shunt fields remains the same whether the F contacts or the R contacts are closed.

Standard Connections

When DC motors are wound, the terminal leads are marked in a standard manner. This permits the direction of rotation to be determined when the motor windings are connected. The direction of rotation is determined by facing the commutator end of the motor, which is generally located on the rear of the motor, but not always. Figure 32–12 shows the standard connections for a series motor, Figure 32–13 shows the standard connections for a shunt motor, and Figure 32–14 shows the standard connections for a cumulative compound motor.

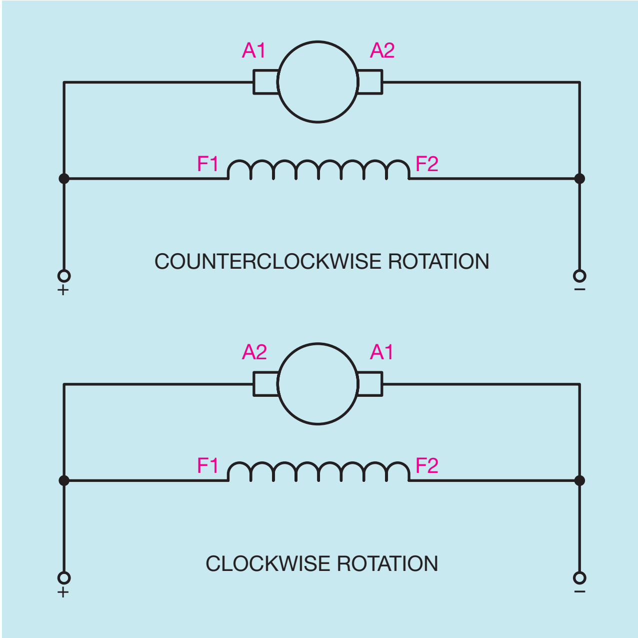


Figure 32–13 Standard connections for shunt motors. (Source: Delmar/Cengage Learning.)

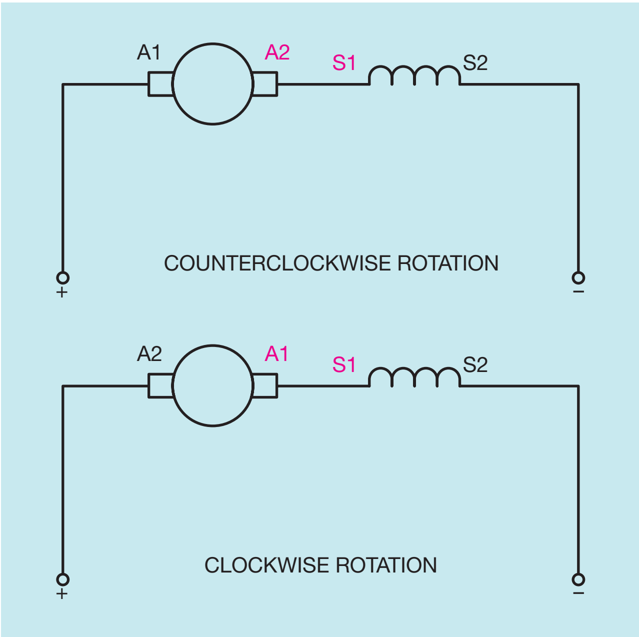


Figure 32–12 Standard connections for series motors. (Source: Delmar/Cengage Learning.)

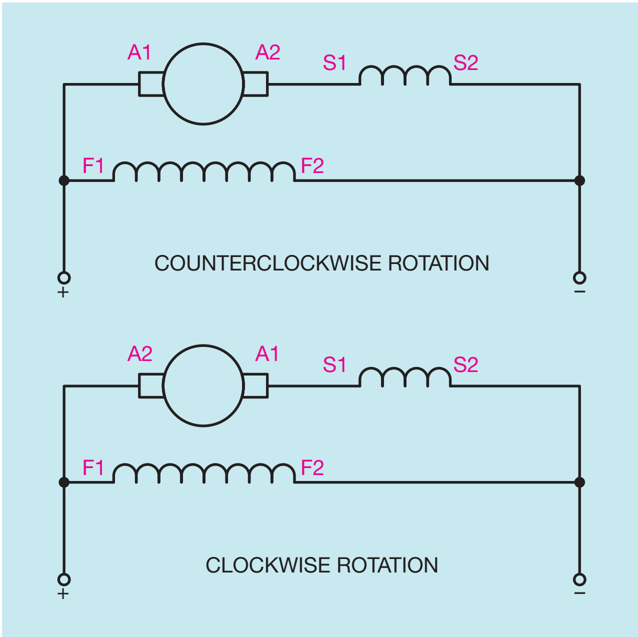


Figure 32–14 Standard connections for compound motors. (Source: Delmar/Cengage Learning.)

Review Questions

1. How can a DC motor be made to operate below its normal speed?
2. Name the three basic types of DC motors.
3. Explain the physical difference between series field windings and shunt field windings.
4. The speed regulation of a DC motor is proportional to what?
5. What connection is made to form a long shunt compound motor?
6. Explain the difference between the connection of a cumulative compound and a differential compound motor.
7. How is the direction of rotation of a DC motor changed?
8. Why is it important to reverse only the armature leads when changing the rotation of a compound motor?

CHAPTER 33

STARTING METHODS FOR DC MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe across-the-line starting for small DC motors.
- Explain why a current-limiting resistor may be used when starting a DC motor.
- Connect an across-the-line starter for a DC motor.
- Recommend troubleshooting solutions for across-the-line starters.
- Draw diagrams of motor starter control circuits.
- Describe field current protection for DC motors.
- Describe the use of series resistance for limiting armature current when starting a DC motor.
- Connect a timed starting control for a DC motor.

Small DC motors are often started directly across-the-line because they have low inertia, which permits them to gain speed quickly, causing a rapid increase of counter-EMF to limit in-rush current. Fractional horsepower manual starters and magnetic starters that are generally used to control small AC motors are often employed to start small DC motors. Although only one load contact would be required to break the circuit and stop the motor, load contacts are often connected in series (Figure 33–1). Direct current is more difficult to interrupt than alternating current because it does not fall to zero at periodic intervals. Connecting the load contacts in series increases the total air gap between contacts and aids in interrupting an electric arc.

Contactors that are designed to control direct current devices are generally of the clapper type because those exhibit a greater air gap between the movable and stationary load contacts. Because of the distance the armature must travel, these contactors often contain two coils connected in parallel. One coil is called the pick-up coil and the other is called the holding coil. The pick-up coil is designed for momentary duty only and

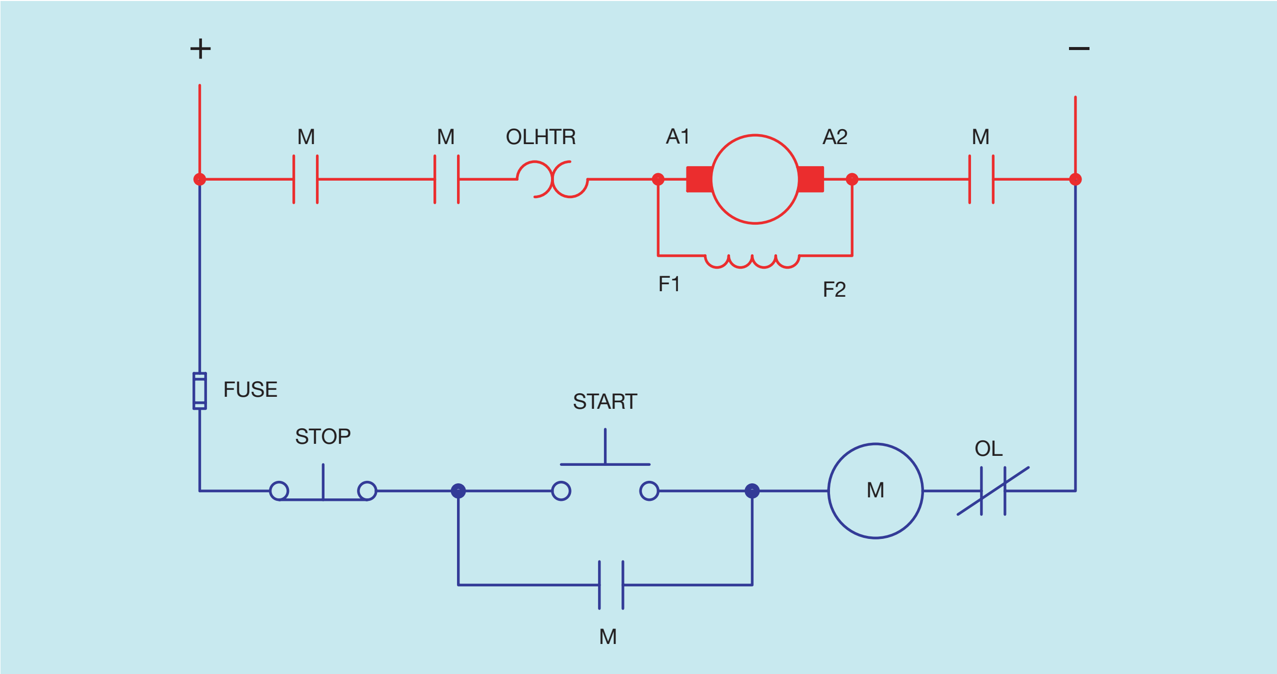


Figure 33–1 Load contacts are connected in series to provide a greater air gap, which helps interrupt an arc. (Source: Delmar/Cengage Learning.)

the holding coil is designed for continuous duty. When the contactor is energized, both coils operate to create a strong electromagnetic field. When the armature closes, the pick-up coil is disconnected and the armature is held in place by the holding coil. Some of these contactors are equipped with a small limit switch that opens the circuit when the armature closes, Figure 33–2. Other dual coil contactors depend on a normally closed contact to disconnect the pick-up coil when the contactor is energized (Figure 33–3). When the Start button is pressed, a circuit is complete through the normally closed M contact to provide power to both the Holding coil and Pick-up coil. When the contactor energizes, the normally closed contact opens and disconnects the Pick-up coil. The Holding coil provides a magnetic field of sufficient strength to keep the armature closed.

Another common method of momentarily providing a strong magnetic field during pick-up and then reducing the current flow to the coil is to insert a current limiting resistor in series with the contactor coil (Figure 33–4). When the Start button is pressed, the normally closed contact provides a path around the current limiting resistor, permitting full voltage to be applied to the coil. When the contactor energizes, the normally closed contact opens, inserting the current limiting resistor in series with the coil.

When large DC motors are to be started, current inrush to the armature must be limited. One method of limiting this current is to connect resistors in series with the armature. When the armature begins to turn, counter-EMF is developed in the armature. As counter-EMF increases, resistance can be shunted out of the armature circuit, permitting the armature to turn at a higher speed. When armature speed increases, counter-EMF also increases. Resistance can be shunted out of the circuit in steps until the armature is connected directly to the power line.

Limiting the starting current of the armature is not the only factor that should be considered in a DC control circuit. Most DC motor control circuits use a *field current relay (FCR)* connected in series with the shunt field of the motor. The FCR insures that current is flowing through the shunt field before voltage can be connected to the armature.

If the motor is running and the shunt field opens, the motor will become a series motor and begin to increase rapidly in speed. If this happens, both the motor and the equipment it is operating can be destroyed. For this reason, the shunt field relay must disconnect the armature from the line if shunt field current stops flowing.

The circuit shown in Figure 33–5 is a DC motor control with two steps of resistance connected in series with the armature. When the motor is started, both

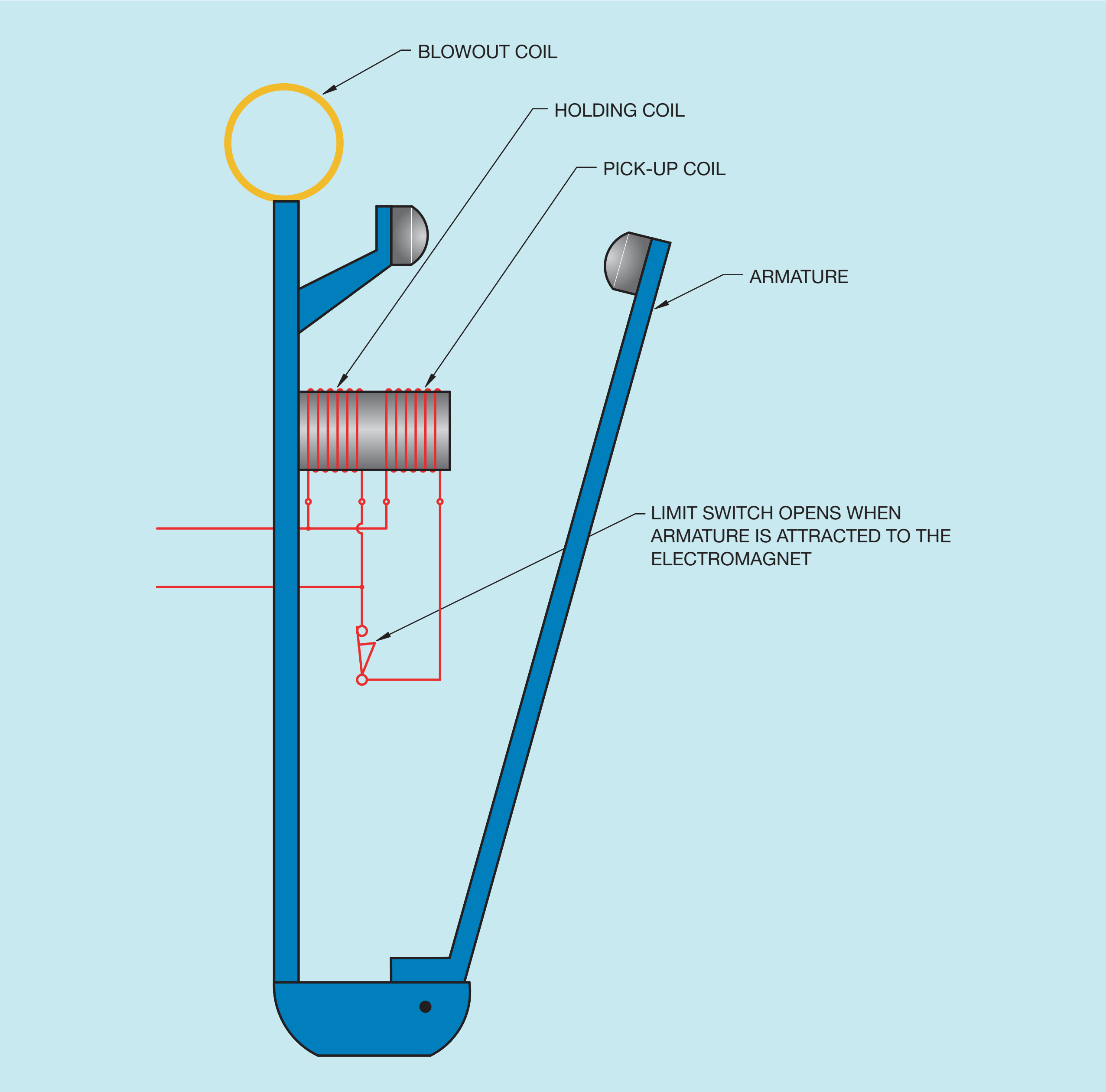


Figure 33–2 The Pick-up coil is disconnected by the limit switch when the armature closes. (Source: Delmar/Cengage Learning.)

resistors limit current flow to the armature. Time-delay relays are used to shunt the starting resistors out of the circuit in time intervals of five seconds each until the armature is connected directly to the line.

The circuit operates as follows: When the START button is pushed, current is supplied to relay coil F and all F contacts change position. One F contact is connected parallel to the START button and acts as a holding contact. Another F contact connects the FCR and the shunt field to the line.

When shunt field current begins to flow, contact FCR closes. When contact FCR closes, a circuit is completed to motor starter coil M and coil TR1. When starter M energizes, contact M closes and connects the armature circuit to the DC line. Five seconds after coil TR1 energizes, contact TR1 closes. This permits current to flow to relay coils S1 and TR2. When contact S1 closes, resistor R1 is shunted out of the circuit. Five seconds after relay coil TR2 energizes, contact TR2 closes. When contact TR2 closes, current can flow to coil S2.

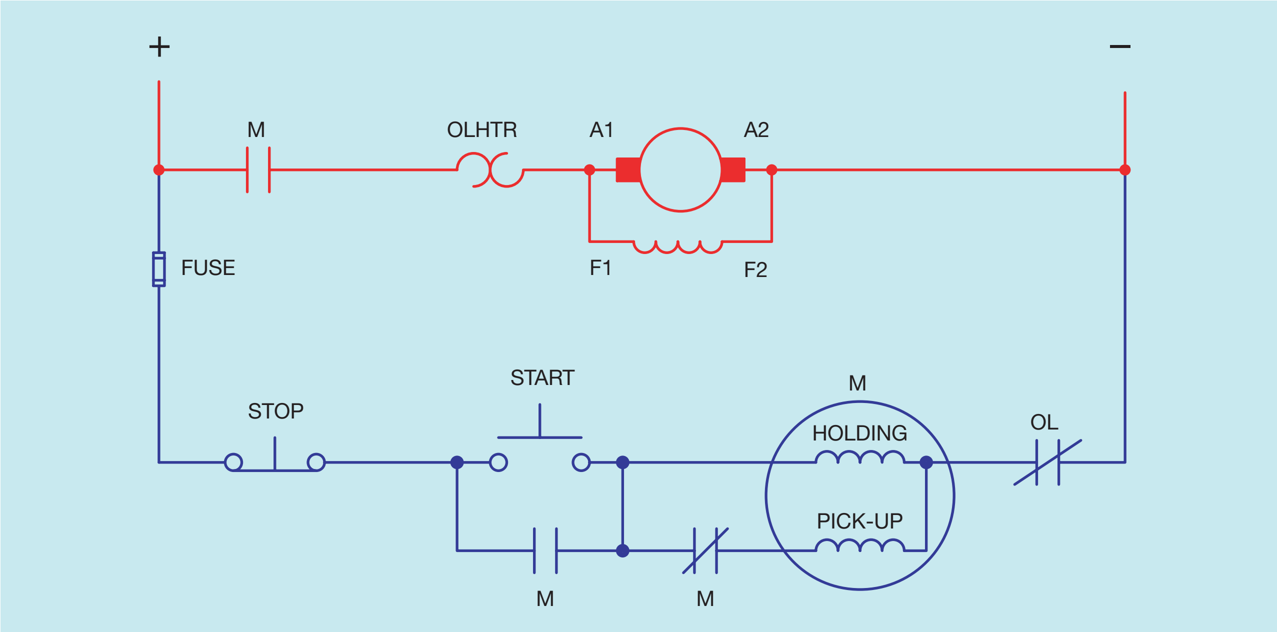


Figure 33–3 The Pick-up coil is disconnected by the normally closed M contact when the contactor energizes. (Source: Delmar/Cengage Learning.)

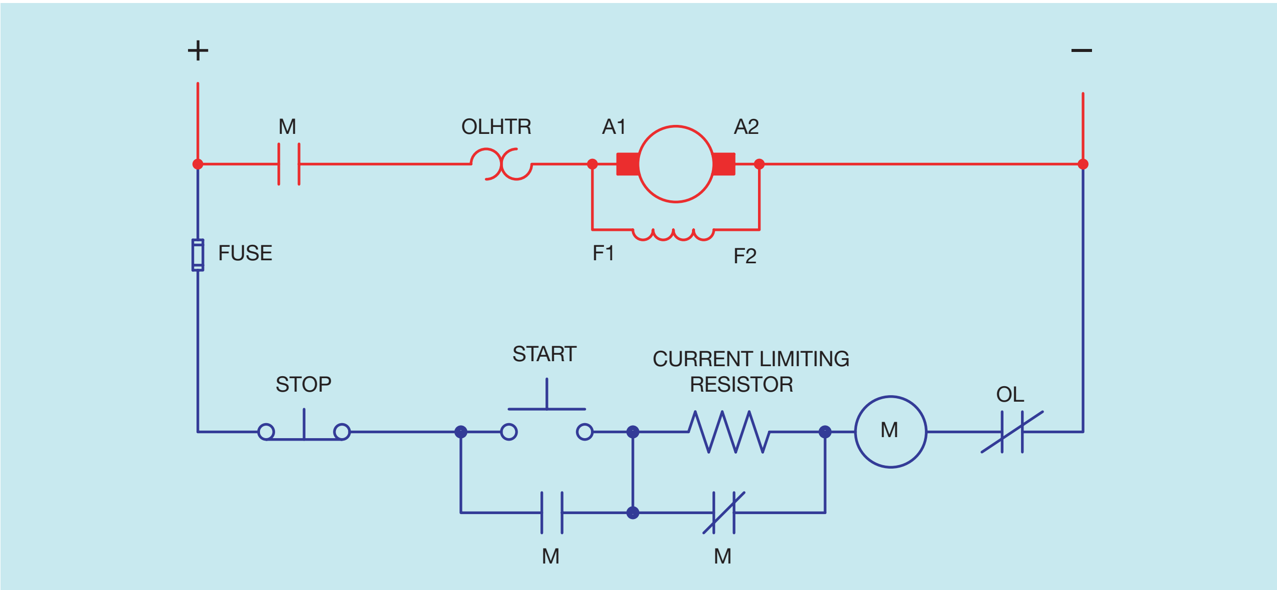


Figure 33–4 A current limiting resistor reduces current to the coil after the contactor is energized. (Source: Delmar/Cengage Learning.)

When contact S2 closes, resistor R2 is shunted out of the circuit and the armature is connected directly to the DC power line.

When the STOP button is pushed, relay F de-energizes and opens all F contacts. This breaks the circuit to starter coil M, which causes contact M to open and disconnect the armature from the line. When coil TR1 de-energizes, contact TR1 opens immediately and de-energizes coils S1 and TR2. When coil TR2 de-energizes, contact TR2 opens immediately and de-energizes coil S2. All contacts in the circuit are back in their original positions, and the circuit is ready to be started again.

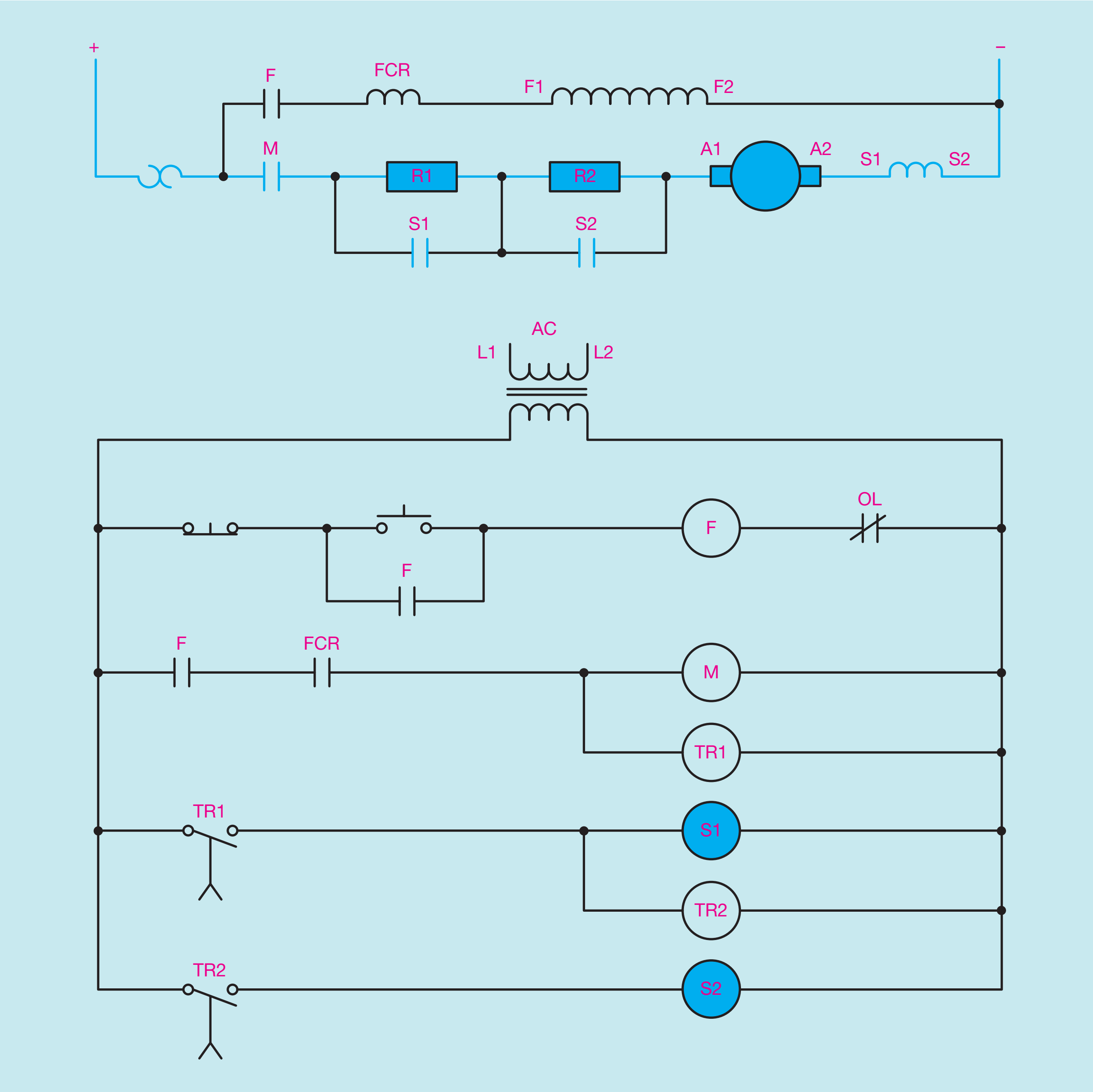


Figure 33–5 Time-delay starter for a DC motor. (Source: Delmar/Cengage Learning.)

Review Questions

1. Why are contacts often connected in series when controlling small DC motors?
2. Why is direct current more difficult to interrupt than alternating current?
3. Why are clapper type contactors generally used to control DC devices?
4. When a contactor employs the use of dual coils, how are the holding and pick-up coils connected in relationship to each other?
5. How is the in-rush current to large DC motors often limited?
6. What is the purpose of the FCR?
7. How is the FCR connected in relationship to the shunt field?
8. Is the FCR a current relay or a voltage relay?
9. Refer to Figure 33–5. What would be the action of the circuit if timers TR1 and TR2 were to be replaced with off-delay timers?

CHAPTER 34
SOLID-STATE DC DRIVES

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe armature control.
- Discuss DC voltage control with a three-phase bridge rectifier.
- Describe methods of current limit control.
- Discuss feedback for constant speed control.

Direct current motors are used throughout much of industry because of their ability to produce high torque at low speed, and because of their variable speed characteristics. DC motors are generally operated at or below *normal speed.* Normal speed for a DC motor is obtained by operating the motor with full rated voltage applied to the field and armature. The motor can be operated at below normal speed by applying rated voltage to the field and reduced voltage to the armature.

In Chapter 33, resistance was connected in series with the armature to limit current and, therefore, speed. Although this method does work and was used in industry for many years, it is seldom used today. When resistance is used for speed control, much of the power applied to the circuit is wasted in heating the resistors, and the speed control of the motor is not smooth because resistance is taken out of the circuit in steps.

Speed control of a DC motor is much smoother if two separate *power supplies,* which convert the AC voltage to DC voltage, are used to control the motor instead of resistors connected in series with the armature (Figure 34–1). Notice that one power supply is used to supply a constant voltage to the shunt field of the motor, and the other power supply is variable and supplies voltage to the armature only.

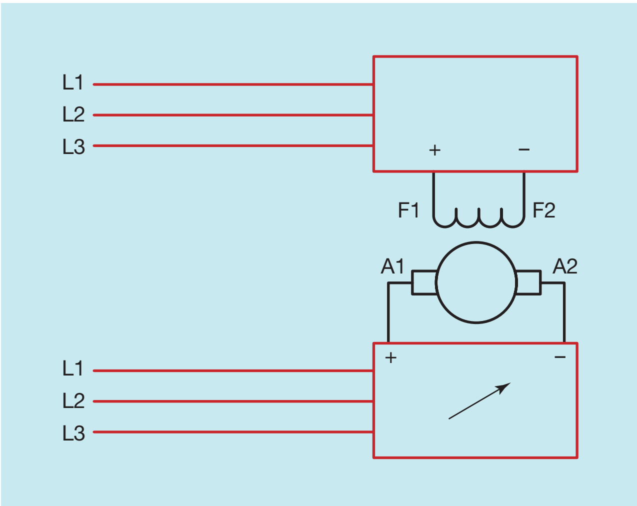


Figure 34–1 Separate power supplies used to control armature and field. (Source: Delmar/Cengage Learning.)

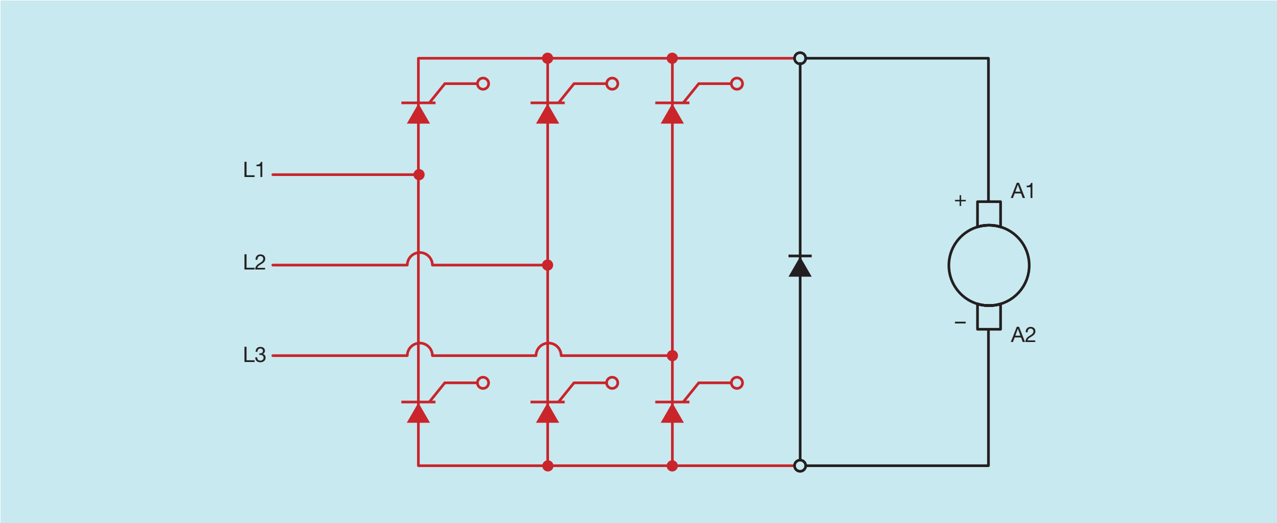


Figure 34–2 Three-phase bridge rectifier. (Source: Delmar/Cengage Learning.)

The Shunt Field Power Supply

Most solid-state DC motor controllers provide a separate DC power supply, which is used to furnish excitation current to the shunt field. The shunt field of most industrial motors requires a current of only a few amperes to excite the field magnets; therefore, a small power supply can be used to fulfill this need. The shunt field power supply is generally designed to remain turned on even when the main (armature) power supply is turned off. If power is connected to the shunt field even when the motor is not operating, the shunt field will act as a small resistance heater for the motor. This heat helps prevent moisture from forming in the motor due to condensation.

The Armature Power Supply

The armature power supply is used to provide variable DC voltage to the armature of the motor. This power supply is the heart of the solid-state motor controller. Depending on the size and power rating of the controller, armature power supplies can be designed to produce from a few amperes to hundreds of amperes. Most of the solid-state motor controllers intended to provide the DC power needed to operate large DC motors convert three-phase AC voltage directly into DC voltage with a three-phase bridge rectifier.

The diodes of the rectifier, however, are replaced with SCRs to provide control of the output voltage (Figure 34–2). Figure 34–3 shows SCRs used for this type of DC motor controller. A large diode is often connected across the output of the bridge. This diode is known as a *freewheeling,* or *kickback,* diode and is used to kill inductive spike voltages produced in the armature. If armature power is suddenly interrupted, the collapsing magnetic field induces a high voltage into the armature windings. The diode is reverse biased

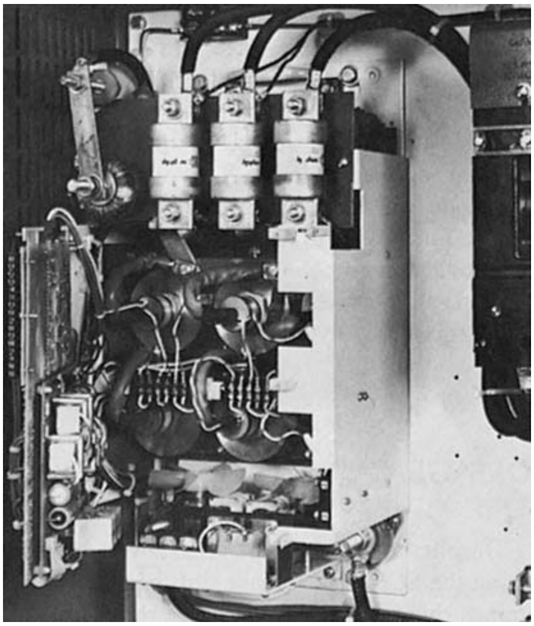


Figure 34–3 SCR controller for providing power to large DC motors. (Courtesy Eaton Corp., Cutler-Hammer Products.)

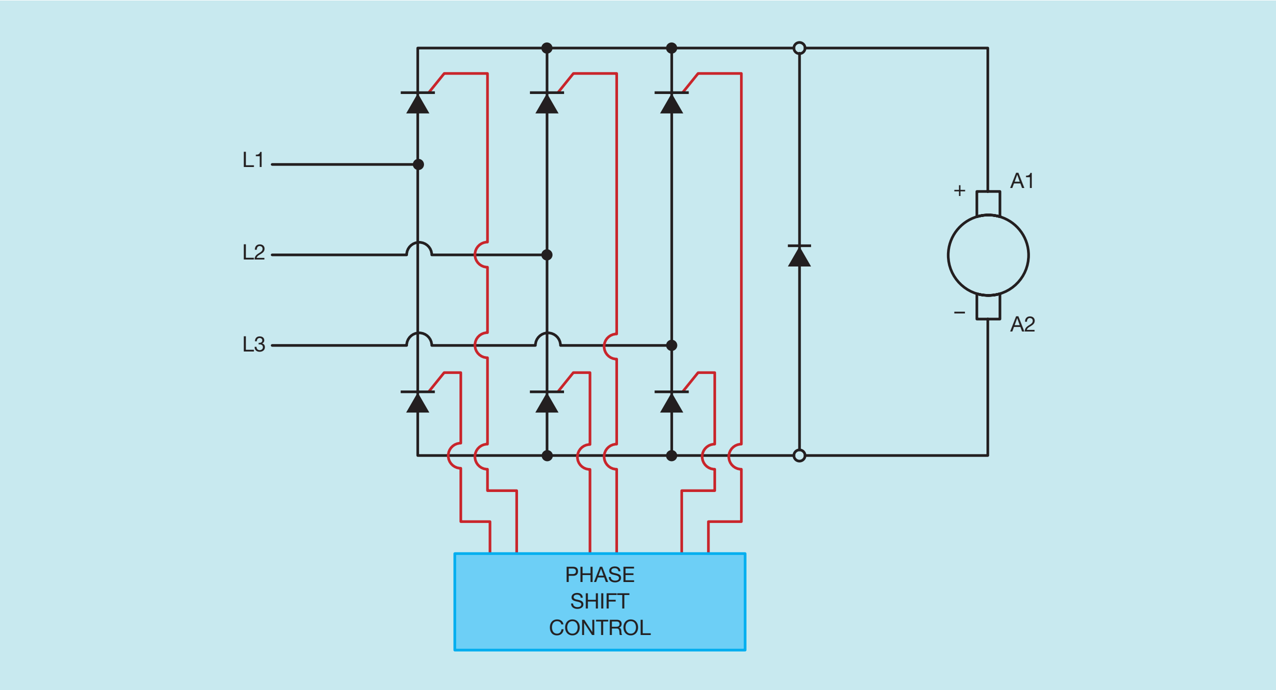


Figure 34–4 Phase shift controls output voltage. (Source: Delmar/Cengage Learning.)

when the power supply is operating under normal conditions, but an induced voltage is opposite in polarity to the applied voltage. This means the kickback diode will be forward biased to any voltage induced into the armature. Since a silicon diode has a voltage drop of 0.6 to 0.7 volts in the forward direction, a high voltage spike cannot be produced in the armature.

Voltage Control

Output voltage control is achieved by phase shifting the SCRs. The phase shift control unit determines the output voltage of the rectifier (Figure 34–4). Since the phase shift unit is the real controller of the circuit, other sections of the circuit provide information to the phase shift control unit. Figure 34–5 shows a typical phase shift control unit.

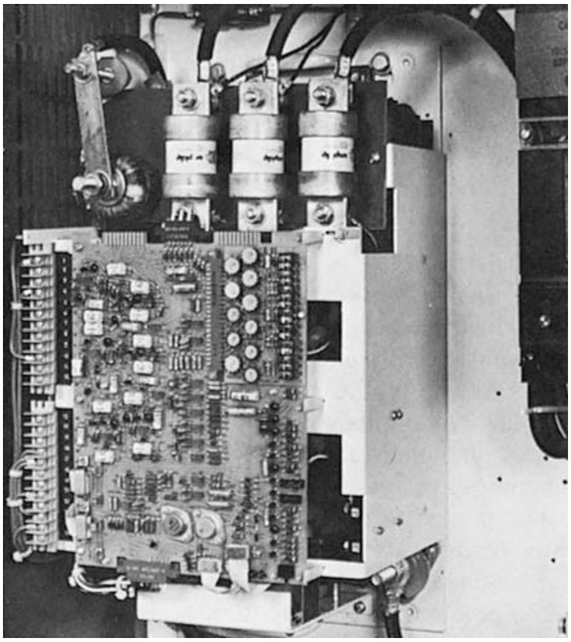


Figure 34–5 Phase shift control board for controlling SCRs. (Courtesy Eaton Corp., Cutler-Hammer Products.)

Field Failure Control

As stated previously, if current flow through the shunt field is interrupted, a compound wound, DC motor will become a series motor and race to high speeds. Some method must be provided to disconnect the armature from the circuit in case current flow through the shunt field stops. Several methods can be used to sense

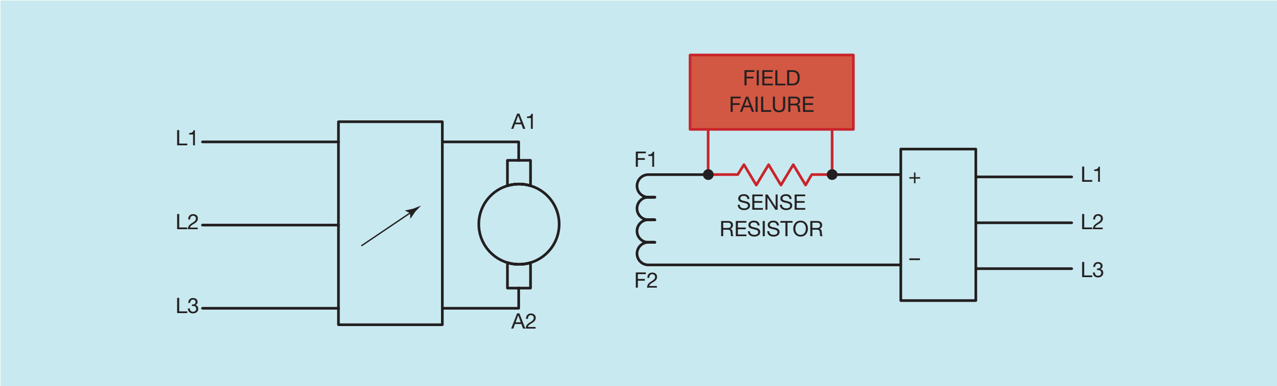


Figure 34–6 Resistor used to sense current flow through field. (Source: Delmar/Cengage Learning.)

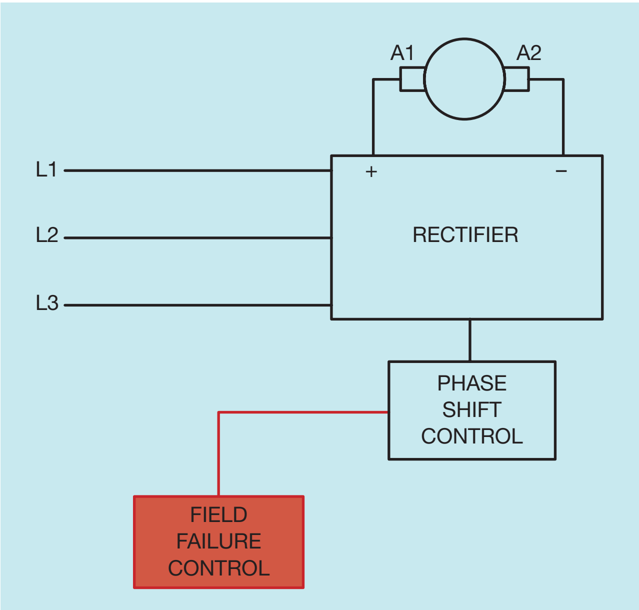


Figure 34–7 Field failure control signals the phase shift control. (Source: Delmar/Cengage Learning.)

current flow through the shunt field. In Chapter 33, a current relay was connected in series with the shunt field. A contact of the current relay was connected in series with the coil of a motor starter used to connect the armature to the power line. If current flow were stopped, the contact of the current relay would open, causing the circuit of the motor starter coil to open.

Another method used to sense current flow is to connect a low value of resistance in series with the shunt field (Figure 34–6). The voltage drop across the sense resistor is proportional to the current flowing through the resistor ($E = I \times R$). Since the sense resistor is connected in series with the shunt field, the current flow through the sense resistor must be the same as the current flow through the shunt field. A circuit can be designed to measure the voltage drop across the sense resistor. If this voltage falls below a certain level, a signal is sent to the phase shift control unit and the SCRs are turned off (Figure 34–7).

Current Limit Control

The armature of a large DC motor has a very low resistance, typically less than 1 ohm. If the controller is turned on with full voltage applied to the armature, or if the motor stalls while full voltage is applied to the armature, a very large current will flow. This current can damage the armature of the motor or the electronic components of the controller. For this reason, most solid-state, DC motor controls use some method to limit the current to a safe value.

One method of sensing the current is to insert a low value of resistance in series with the armature circuit. The amount of voltage dropped across the sense resistor is proportional to the current flow through the resistor. When the voltage drop reaches a certain level, a signal is sent to the phase shift control telling it not to permit any more voltage to be applied to the armature.

When DC motors of about 25 horsepower or larger are to be controlled, resistance connected in series with the armature can cause problems. Therefore, another method of sensing armature current can be used (Figure 34–8). In this circuit, current transformers are connected to the AC input lines. The current supplied to the rectifier will be proportional to the current supplied to the armature. When a predetermined

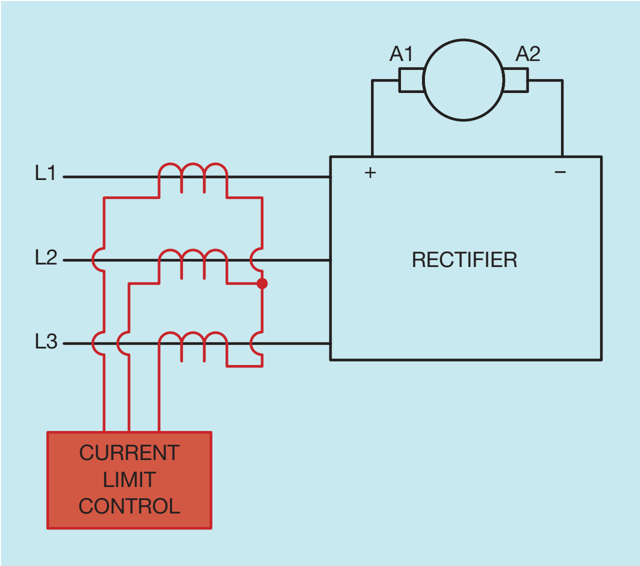


Figure 34–8 Current transformers measure ac line current. (Source: Delmar/Cengage Learning.)

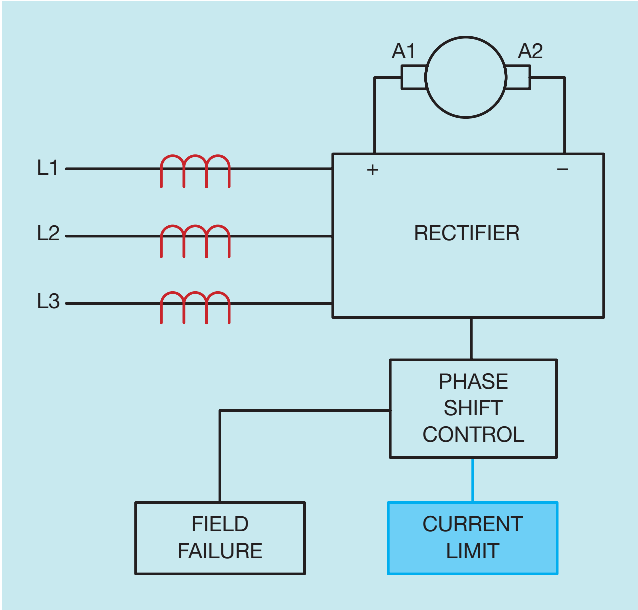


Figure 34–9 Current flow to armature is limited. (Source: Delmar/Cengage Learning.)

amount of current is detected by the current transformers, a signal is sent to the phase shift control telling it not to permit the voltage applied to the armature to increase (Figure 34–9). This method of sensing the armature current has the advantage of not adding resistance to the armature circuit. Regardless of the method used, the current limit control signals the phase shift control, and the phase shift control limits the voltage applied to the armature.

Speed Control

The greatest advantage of using direct current motors is their variable speed characteristic. Although the ability to change motor speed is often desirable, it is generally necessary that the motor maintain a constant speed once it has been set. For example, assume that a DC motor can be adjusted to operate at any speed from 0 to 1800 rpm. Now assume that the operator has adjusted the motor to operate at 1200 rpm. The operator controls are connected to the phase shift control unit (Figure 34–10). If the operator desires to change speed, a signal is sent to the phase shift control unit and the phase shift control permits the voltage applied to the armature to increase or decrease.

DC motors, like many other motors, will change speed if the load is changed. If the voltage connected to the armature remains constant, an increase in load will cause the motor speed to decrease, or a decrease in load will cause the motor speed to increase. Since the phase shift unit controls the voltage applied to the armature, it can be used to control motor speed. If the motor speed is to be held constant, some means must be used to detect the speed of the motor. A very common method of detecting motor speed is with the use of an *electrotachometer* (Figure 34–11). An electrotachometer is a small, permanent, magnet generator connected to the motor shaft. The output voltage of the generator is proportional to its speed. The output voltage of the generator is connected to the phase shift control unit (Figure 34–12). If load is added to the motor, the motor speed will decrease. When the motor speed decreases, the output voltage of the electrotachometer drops. The phase shift unit detects the voltage drop of the tachometer and increases the armature voltage until the tachometer voltage returns to the proper value.

If the load is removed, the motor speed will increase. An increase in motor speed causes an increase in the output voltage of the tachometer. The phase shift unit detects the increase of tachometer voltage and causes a decrease in the voltage applied to the armature. Electronic components respond so fast that there is almost no noticeable change in motor speed when load is added or removed. An SCR motor control unit is shown in Figure 34–13.

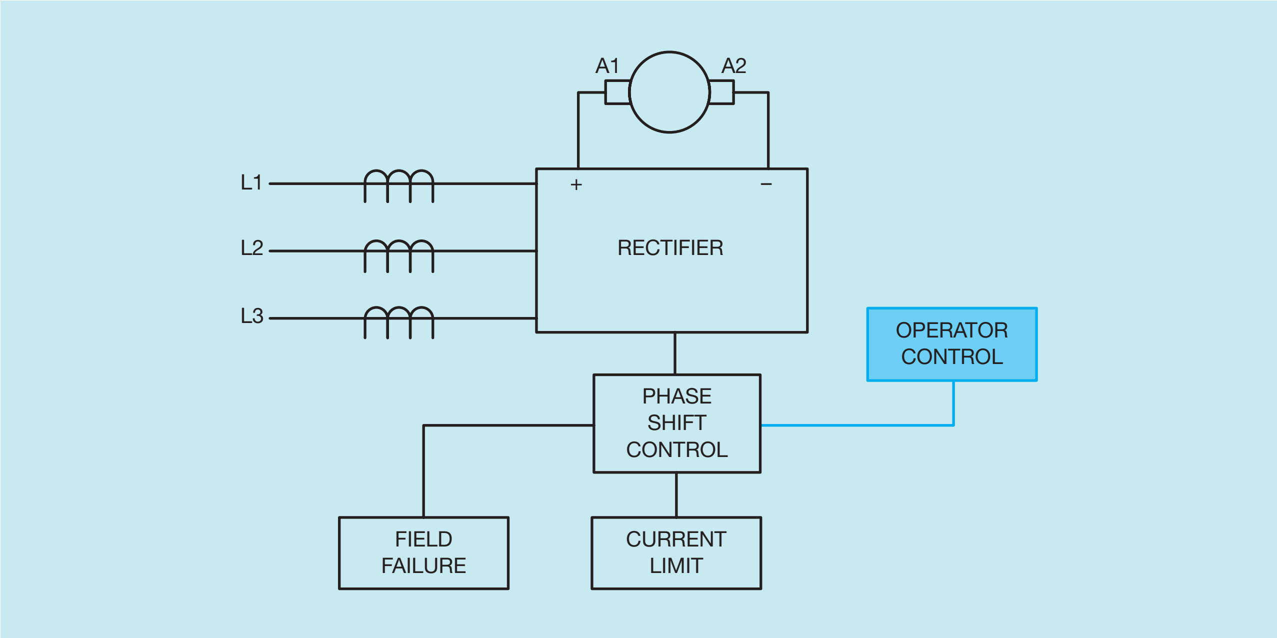


Figure 34–10 Operator control is connected to the phase shift control unit. (Source: Delmar/Cengage Learning.)

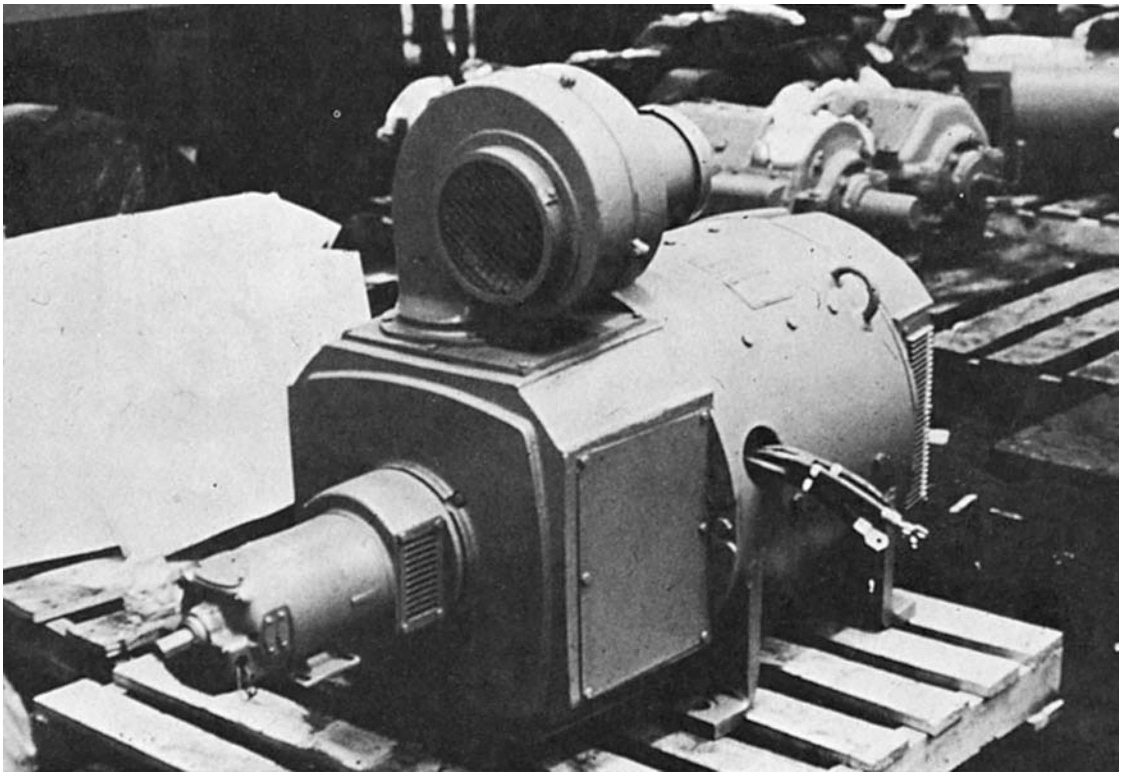


Figure 34–11 Direct current motor with tachometer attached for measuring motor speed. (Courtesy Allen-Bradley Co., Drives Division.)

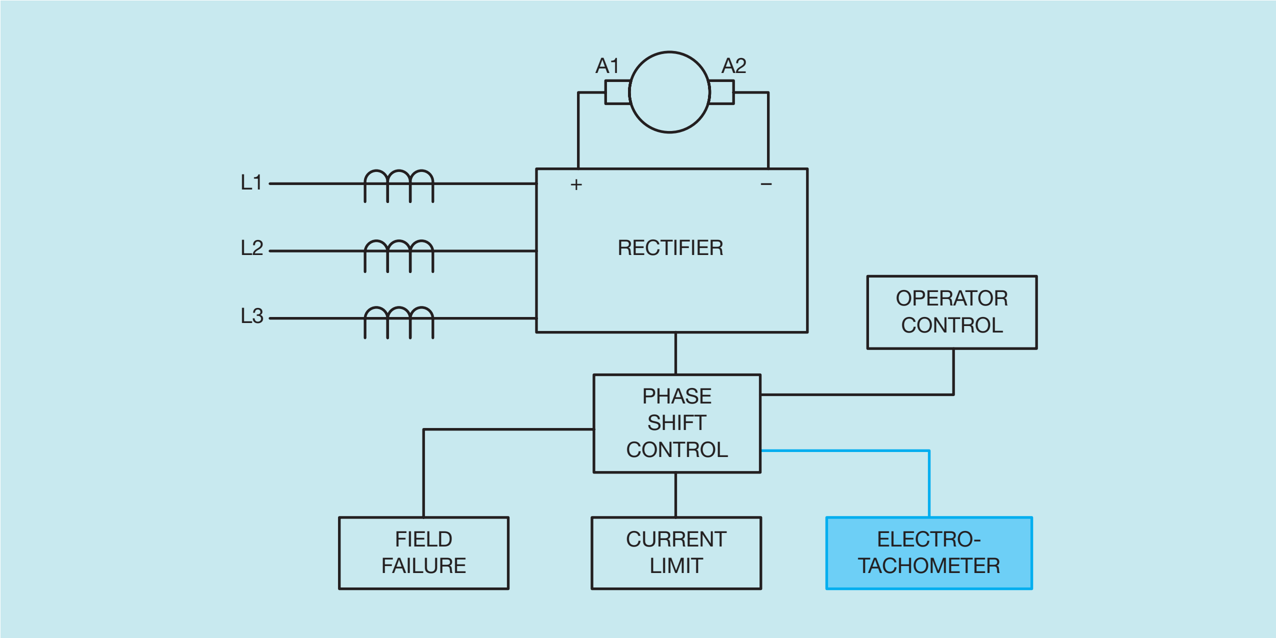


Figure 34–12 Electrotachometer measures motor speed. (Source: Delmar/Cengage Learning.)

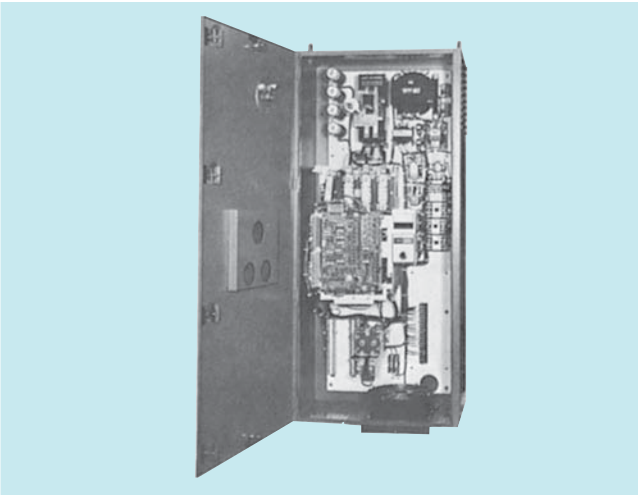


Figure 34–13 SCR motor control unit mounted in a cabinet. (Courtesy Eaton Corp., Cutler-Hammer Products.)

Review Questions

1. What electronic component is generally used to change the AC voltage into DC voltage in large DC motor controllers?
2. Why is this component used instead of a diode?
3. What is a "freewheeling" or "kickback" diode?
4. Name two methods of sensing the current flow through the shunt field.
5. Name two methods of sensing armature current.
6. What unit controls the voltage applied to the armature?
7. What device is often used to sense motor speed?
8. If the motor speed decreases, does the output voltage of the electrotachometer increase or decrease?

CHAPTER 35
STEPPING MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of a DC stepping motor.
- Describe the operation of a stepping motor when connected to AC power.
- Discuss the differences between stepping motors and other types of motors.
- Discuss the differences between four-step and eight-step switching.

Stepping motors are devices that convert electrical impulses into mechanical movement. Stepping motors differ from other types of DC or AC motors in that their output shaft moves through a specific angular rotation each time the motor receives a pulse. Each time a pulse is received, the motor shaft moves a precise amount. The stepping motor allows a load to be controlled with regard to speed, distance, or position. These motors are very accurate in their control performance. Generally, less than 5% error per angle of rotation exists, and this error is not cumulative, regardless of the number of rotations. Stepping motors are operated on DC power, but can be used as a two-phase synchronous motor when connected to AC power.

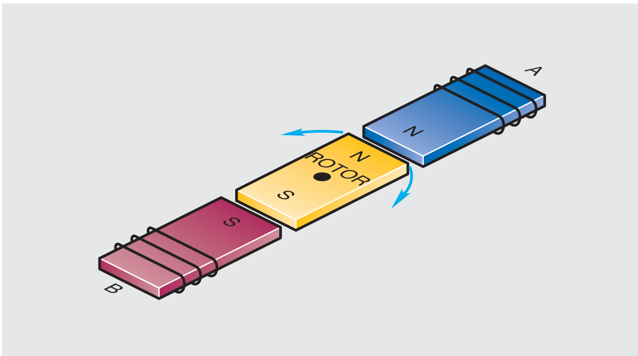


Figure 35–1 The rotor could turn in either direction. (Source: Delmar/Cengage Learning.)

Theory of Operation

Stepping motors operate on the theory that like magnetic poles repel and unlike magnetic poles attract. Consider the circuit shown in Figure 35–1. In this illustration, the rotor is a permanent magnet and the stator winding consists of two electromagnetics. If current flows through the winding of stator pole A in such a direction that it creates a north magnetic pole, and through B in such a direction that it creates a south magnetic pole, it is impossible to determine the direction of rotation. In this condition, the rotor could turn in either direction.

Now consider the circuit shown in Figure 35–2. In this circuit, the motor contains four stator poles instead of two. The direction of current flow through stator

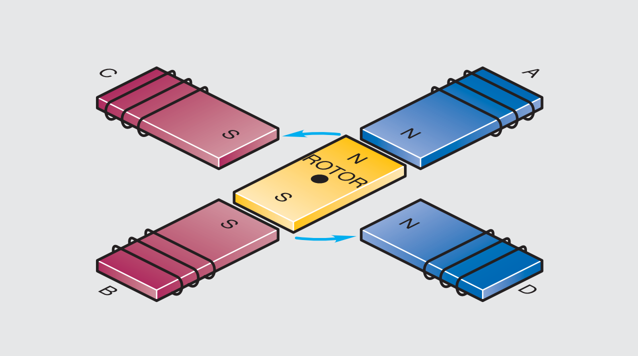


Figure 35–2 Direction of rotation is known. (Source: Delmar/Cengage Learning.)

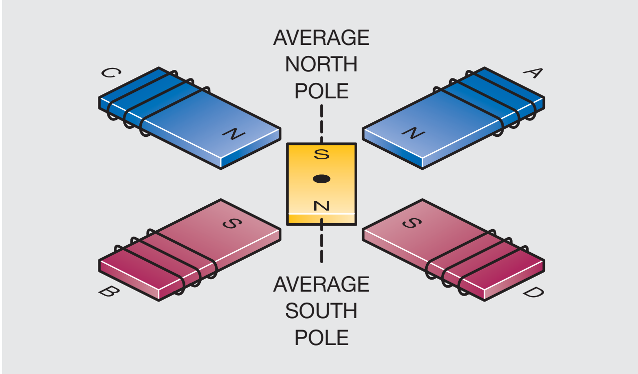


Figure 35–3 Rotor is positioned between the pole pieces. (Source: Delmar/Cengage Learning.)

pole A is still in such a direction as to produce a north magnetic field; the current flow through pole B produces a south magnetic field. The current flow through stator pole C, however, produces a south magnetic field, and the current flow through pole D produces a north magnetic field. As illustrated, there is no doubt regarding the direction or angle of rotation. In this example, the rotor shaft will turn 90 degrees in a counterclockwise direction.

Figure 35–3 shows yet another condition. In this example, the current flow through poles A and C is in such a direction as to form a north magnetic pole, and the direction of current flow through poles B and D forms a south magnetic pole. In this illustration, the permanent magnetic rotor has rotated to a position between the actual pole pieces.

To allow for better stepping resolution, most stepping motors have eight stator poles, and the pole pieces and rotor have teeth machined into them as shown in Figure 35–4. In practice, the number of teeth machined in the stator and rotor determines the angular

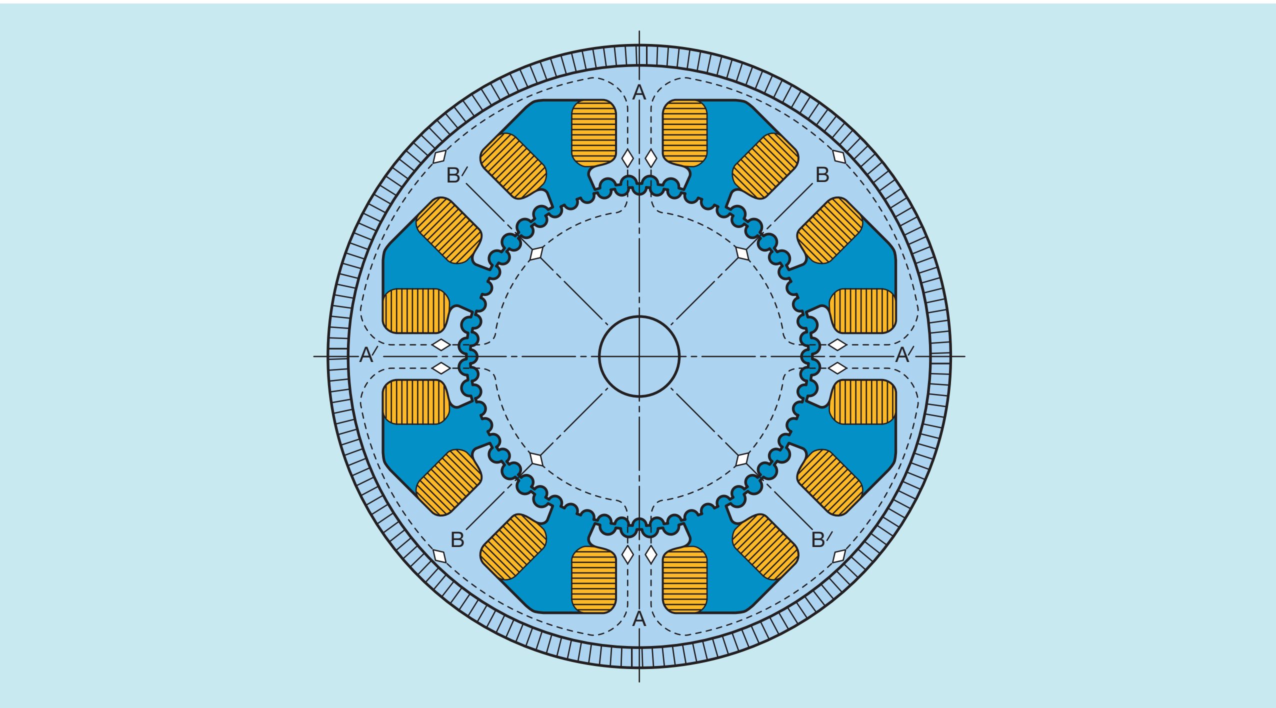


Figure 35–4 Construction of a DC stepping motor. (Courtesy The Superior Electric Company.)

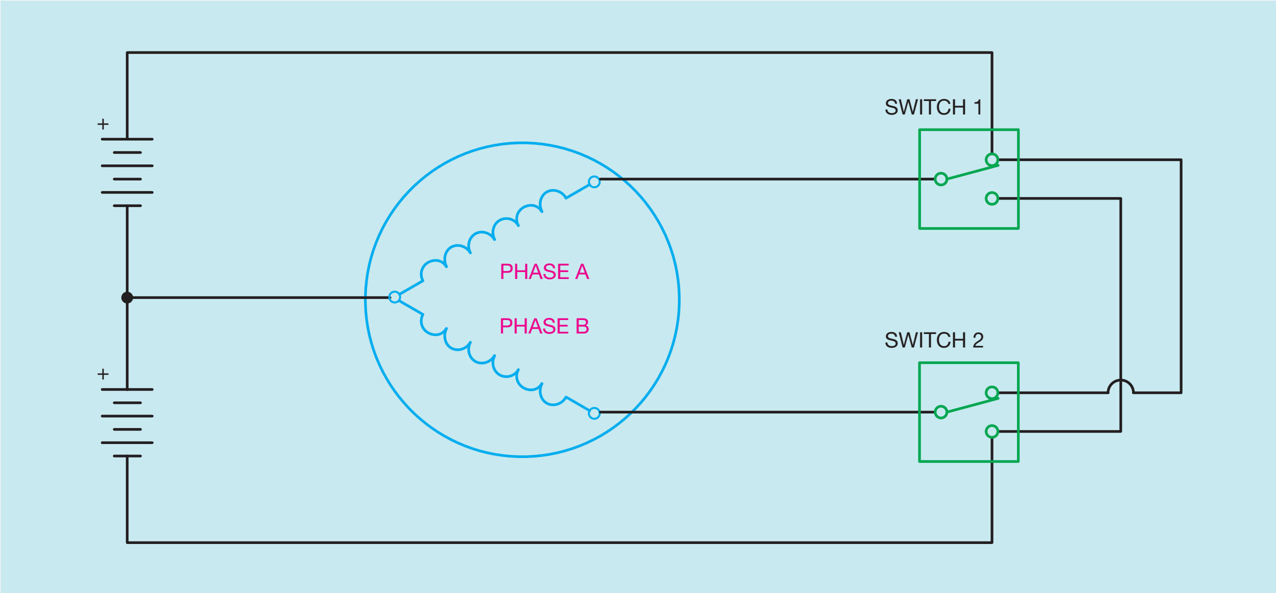


Figure 35–5 Standard three-lead motor. (Source: Delmar/Cengage Learning.)

rotation achieved each time the motor is stepped. The stator-rotor tooth configuration shown in Figure 35–4 produces an angular rotation of 1.8 degrees per step.

Windings

There are different methods for winding stepper motors. A standard three-lead motor is shown in Figure 35–5. The common terminal of the two windings is connected to ground of an above- and below-ground power supply. Terminal 1 is connected to the common of a single-pole double-throw switch (switch #1) and terminal 3 is connected to the common of another single-pole double-throw switch (switch #2). One of the stationary contacts of each switch is connected to the positive or above-ground voltage, and the other stationary contact is connected to the negative or below-ground voltage. The polarity of each winding is determined by the position setting of its control switch.

Stepping motors can also be wound *bifilar* as shown in Figure 35–6. The term *bifilar* means that there are two windings wound together. This is similar to a transformer winding with a center tap lead. Bifilar stepping motors have twice as many windings as the three-lead type, which makes it necessary to use smaller wire in the windings. This results in higher wire resistance in the winding, producing a better inductive-resistive (L/R) time constant for the bifilar wound motor. The increased L/R time constant results in better motor performance. The use of a bifilar stepper motor also simplifies the drive circuitry requirements. Notice that the bifilar motor does not require an above- and below-ground power supply. As a general rule, the power supply voltage should be about five times greater than the motor voltage. A current-limiting resistance is used in the common lead of the motor. This current-limiting resistor also helps to improve the L/R time constant.

Four-Step Switching (Full Stepping)

The switching arrangement shown in Figure 35–6 can be used for a four-step sequence. Each time one of the switches changes position, the rotor will advance one-fourth of a tooth. After four steps, the rotor has turned the angular rotation of one “full” tooth. If the rotor and stator have fifty teeth, it will require 200 steps for the motor to rotate one full revolution. This corresponds to an angular rotation of 1.8 degree per step. (360°/200 steps = 1.8° per step.) Figure 35–7 illustrates the switch positions for each step.

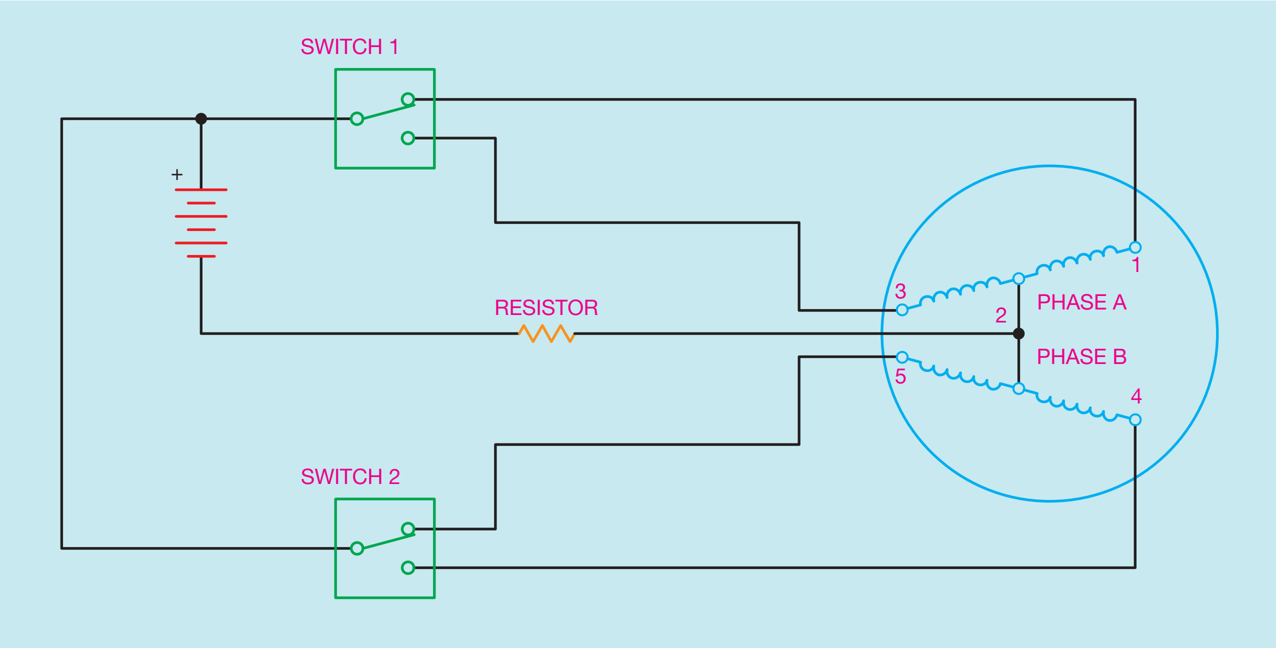


Figure 35–6 Bifilar wound stepping motor. (Source: Delmar/Cengage Learning.)

STEP	SWITCH #1	SWITCH #2
1	1	5
2	1	4
3	3	4
4	3	5
1	1	5

Figure 35–7 Four-step switching sequence. (Source: Delmar/Cengage Learning.)

Eight-Step Switching (Half Stepping)

Figure 35–8 illustrates the connections for an eight-stepping sequence. In this arrangement, the center tap leads for phases A and B are connected through their own separate current limiting resistors back to the negative of the power supply. This circuit contains four separate single pole switches instead of two switches. The advantage of this arrangement is that each step causes the motor to rotate one-eighth of a tooth instead of one-fourth of a tooth. The motor now requires 400 steps to produce one revolution, which produces an angular rotation of 0.9 degree per step. This results in better stepping resolution, and greater speed capability. The chart in Figure 35–9 illustrates the switch position for each step. Figure 35–10 depicts a solid-state switching circuit for an eight-step switching arrangement. A stepping motor is shown in Figure 35–11.

AC Operation

Stepping motors can be operated on AC voltage. In this mode of operation, they become two-phase AC synchronous constant speed motors and are classified as a *permanent magnet induction motor.* Refer to the exploded diagram of a stepping motor in Figure 35–12. Notice that this motor has no brushes, slip rings, commutator, gears, or belts. Bearings maintain a constant air gap between the permanent magnet rotor and the stator windings. A typical eight-stator pole stepping motor will have a synchronous speed of 72 rpm when connected to a 60 hertz two-phase AC power line.

A resistive-capacitive network can be used to provide the 90 degree phase shift needed to change single-phase AC into two-phase AC. A simple forward-off-reverse switch can be added to provide directional

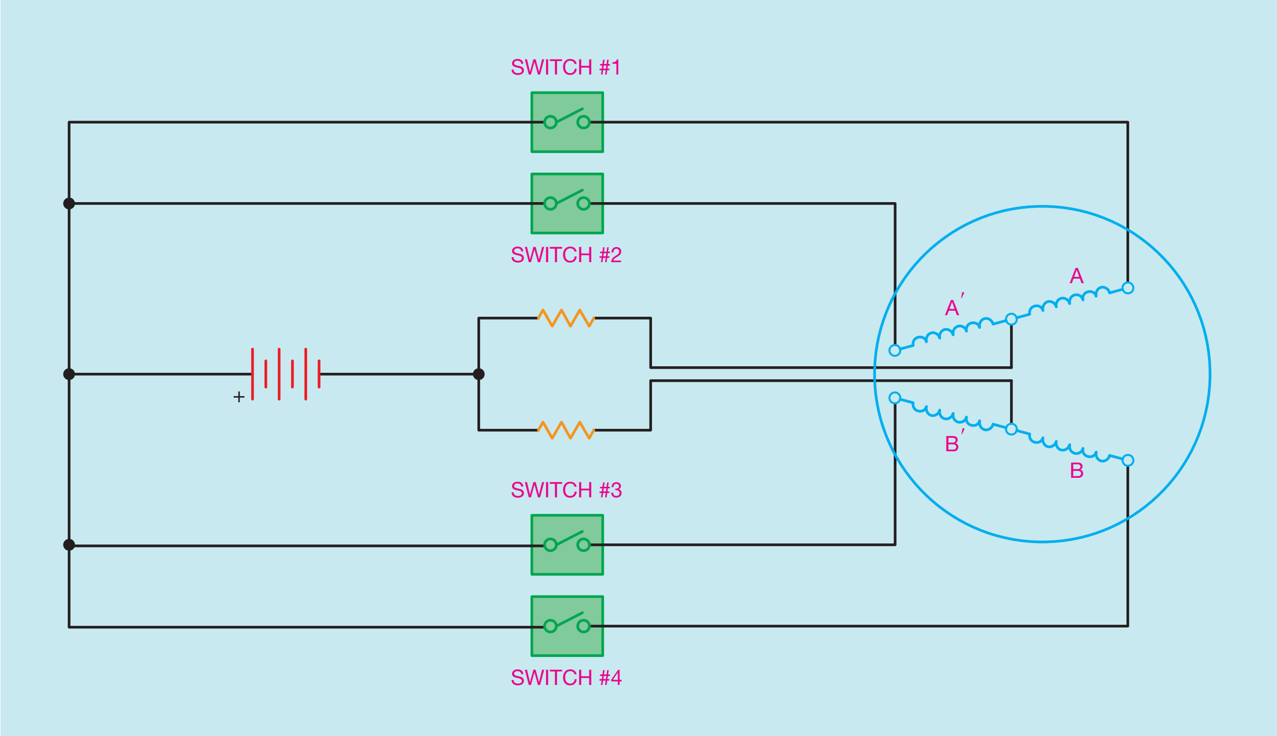


Figure 35–8 Eight-step switching. (Source: Delmar/Cengage Learning.)

STEP	SW #1	SW #2	SW #3	SW #4
1	ON	OFF	ON	OFF
2	ON	OFF	OFF	OFF
3	ON	OFF	OFF	ON
4	OFF	OFF	OFF	ON
5	OFF	ON	OFF	ON
6	OFF	ON	OFF	OFF
7	OFF	ON	ON	OFF
8	OFF	OFF	ON	OFF
1	ON	OFF	ON	OFF

Figure 35–9 Eight-step switching sequence. (Source: Delmar/Cengage Learning.)

control. A sample circuit of this type is shown in Figure 35–13. The correct values of resistance and capacitance are necessary for proper operation. Incorrect values can result in random direction of rotation when the motor is started, change of direction when the load is varied, erratic and unstable operation, as well as failure of the motor to start. The correct values of resistance and capacitance will be different with different stepping motors. The manufacturer's recommendations should be followed for the particular type of stepping motor used.

Motor Characteristics

When stepping motors are used as two-phase synchronous motors, they have the ability to start, stop, or reverse direction of rotation almost instantly. The motor will start within about 1½ cycles of the applied voltage and stop within 5 to 25 milliseconds. The motor can maintain a stalled condition without harm to it. Because the rotor is a permanent magnet, no induced current is in the rotor, and no high in-rush of current occurs when the motor is started. The starting and running currents are the same. This simplifies the power requirements of the circuit used to supply the motor. Due to the permanent magnetic structure of the rotor, the motor does provide holding torque when turned off. If more holding torque is needed, DC

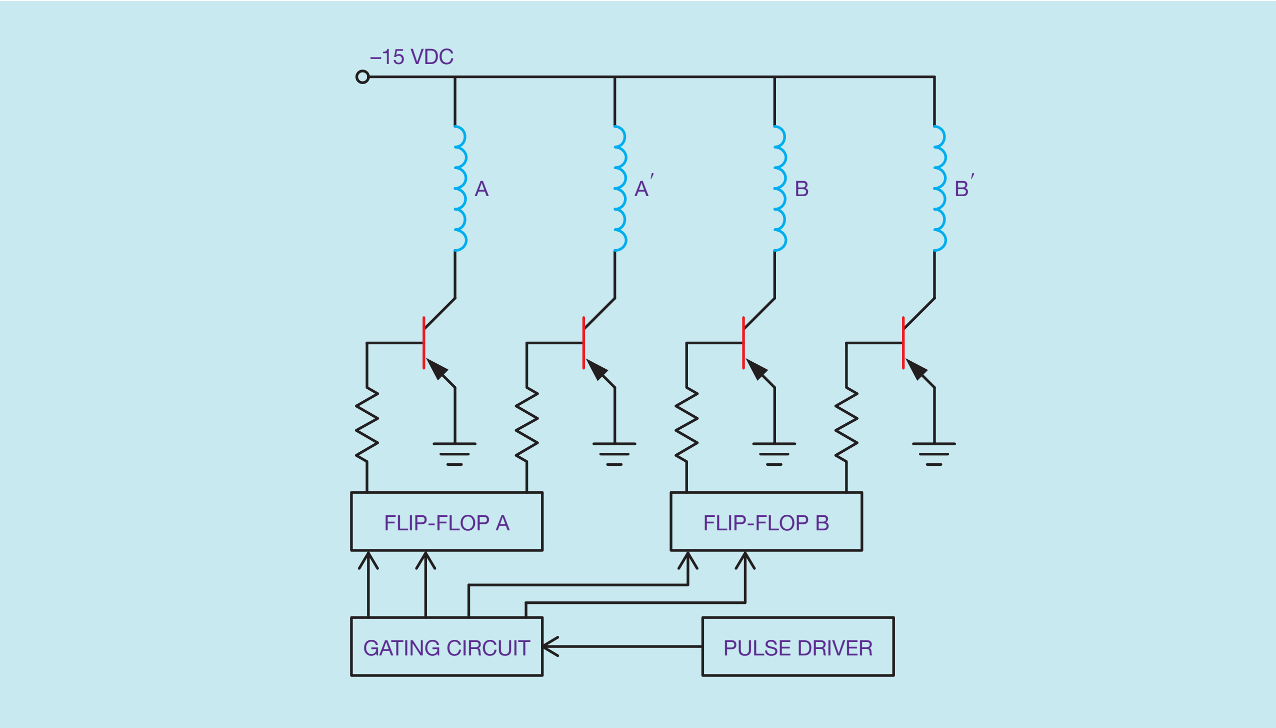


Figure 35–10 Solid state drive for eight-step switching circuit. (Source: Delmar/Cengage Learning.)

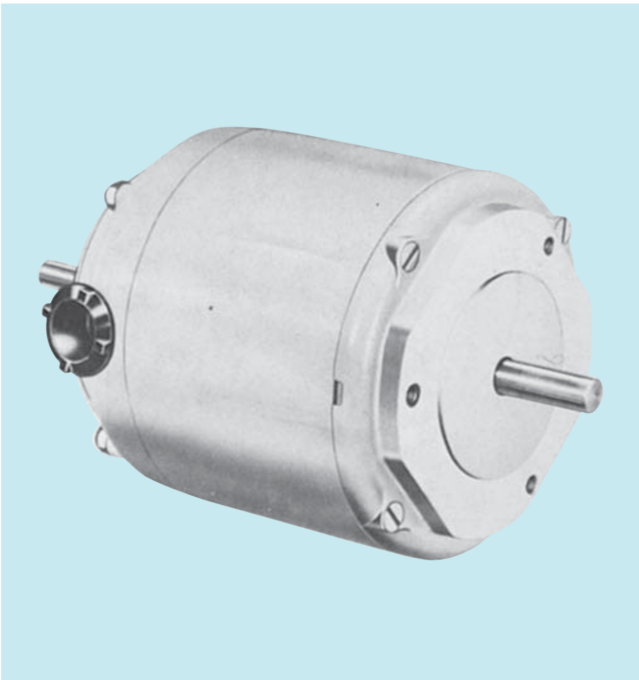


Figure 35–11 DC stepping motor. (Courtesy The Superior Electric Company.)

voltage can be applied to one or both windings when the motor is turned off. An example circuit of this type is shown in Figure 35–14. If DC voltage is applied to one winding, the holding torque will be approximately 20% greater than the *rated* torque of the motor. If DC voltage is applied to both windings, the holding torque will be about 1½ times greater than the rated torque.

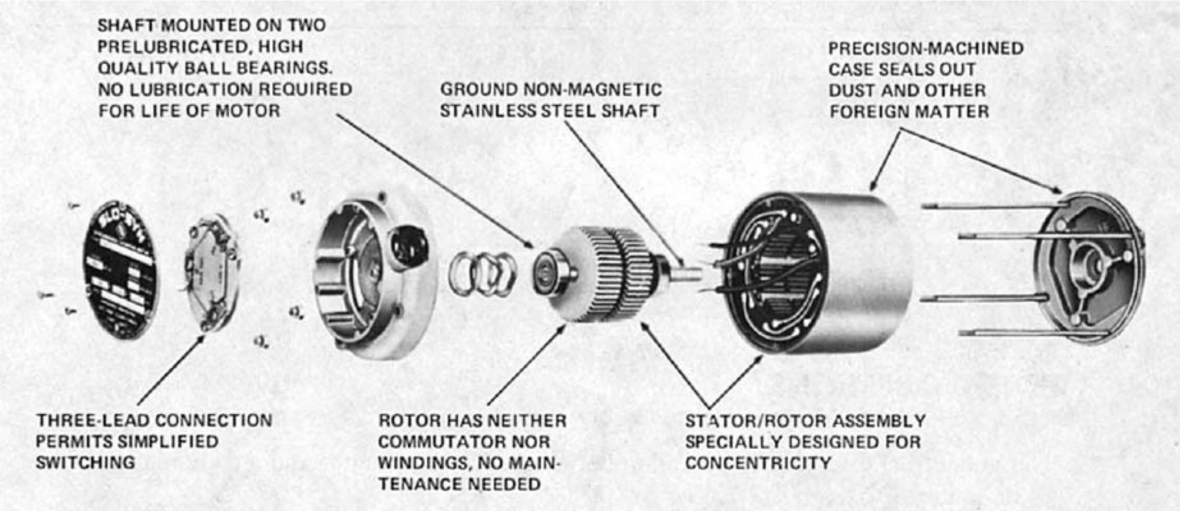


Figure 35–12 Exploded diagram of a stepping motor. (Courtesy The Superior Electric Company.)

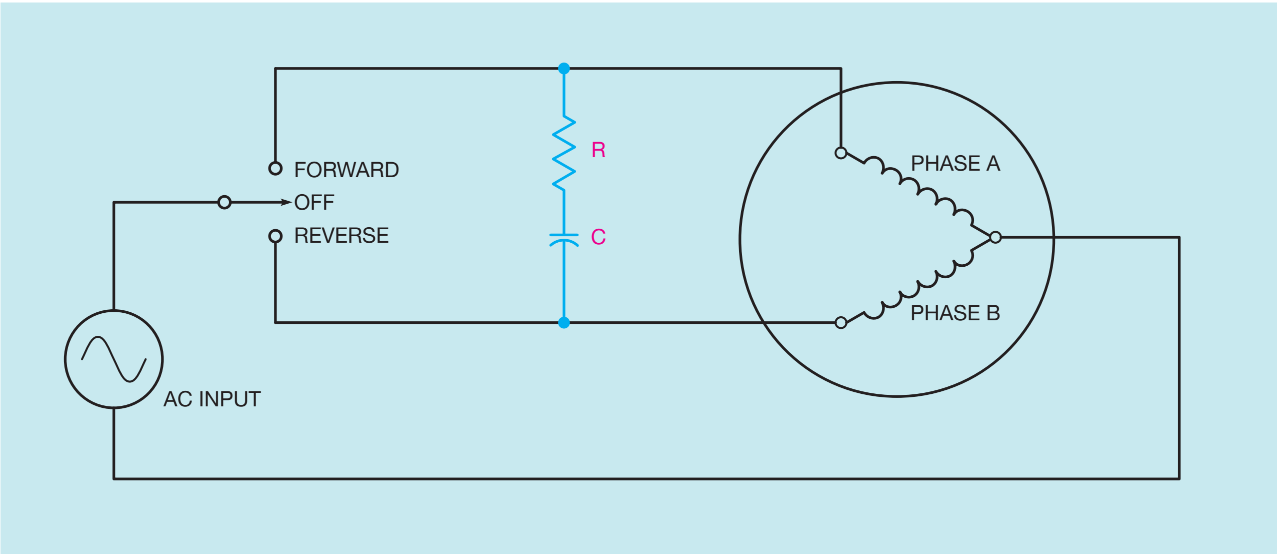


Figure 35–13 Phase shift circuit converts single-phase into two-phase. (Source: Delmar/Cengage Learning.)

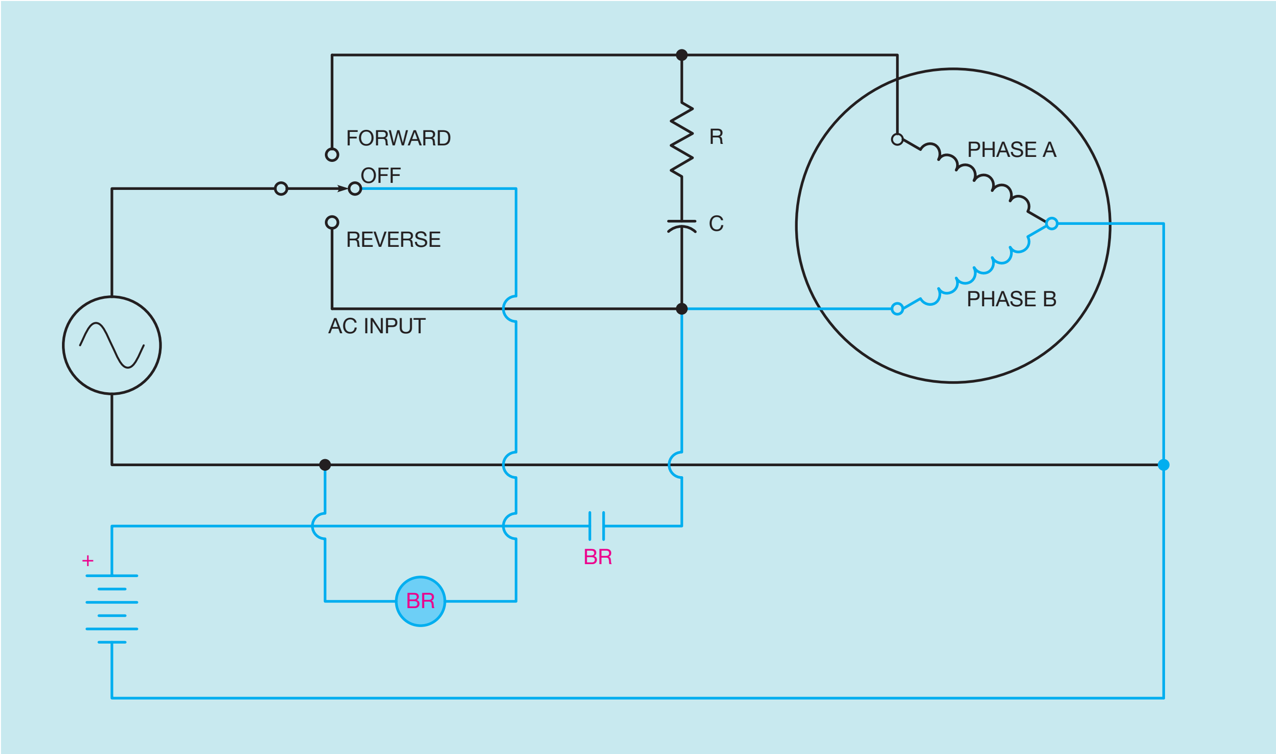


Figure 35–14 Applying DC voltage to increase holding torque. (Source: Delmar/Cengage Learning.)

Review Questions

1. Explain the difference in operation between a stepping motor and a common DC motor.
2. What is the principle of operation of a stepping motor?
3. What does the term bifilar mean?
4. Why do stepping motors have teeth machined in the stator poles and rotor?
5. When a stepping motor is connected to AC power, how many phases must be applied to the motor?
6. How many degrees out of phase are the voltages of a two-phase system?
7. What is the synchronous speed of an eight-pole stepping motor when connected to a two-phase 60 hertz AC line?
8. How can the holding torque of a stepping motor be increased?

CHAPTER 36

THE MOTOR AND STARTING METHODS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of three-phase motors.
- List different methods for starting AC motors.
- Discuss methods for starting single-phase motors.

Three-phase squirrel cage motors are the most popular motors used in industry. They can range in size from fractional horsepower to thousands of horsepower. Squirrel cage type motors receive their name from the type of rotor (rotating member) installed in the motor. The rotor of a squirrel cage motor appears to be a metal cylinder with a shaft through the middle (Figure 36–1). If the laminations were removed, it would be seen that the rotor is actually constructed by connecting metal bars together at each end (Figure 36–2). The type of bars used to construct the rotor has a great effect on the operating characteristics of the motor. The type of rotor is identified by a code letter on the nameplate of a motor. Code letters range from A through V. Table 430.7(B) of the National Electrical Code (NEC) lists these code letters, Figure 36–3.

It may be necessary sometimes to determine the amount of in-rush current when installing a motor, especially in areas where the power company limits the amount of current it supplies. In-rush current is

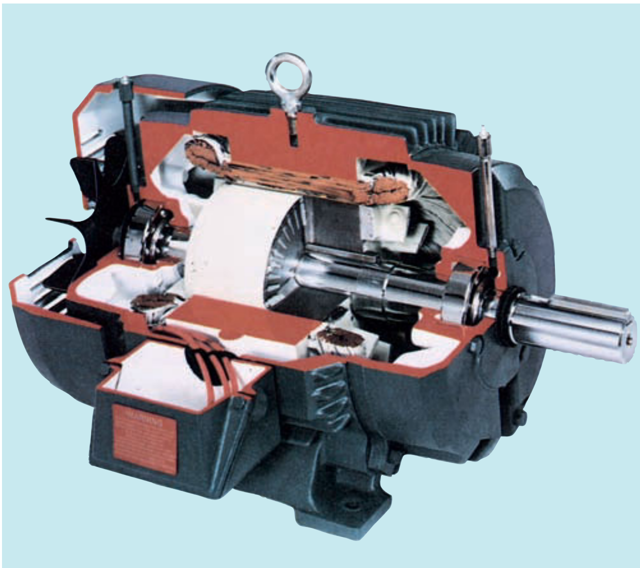


Figure 36–1 Squirrel cage motor. (Courtesy Reliance Electric Co.)

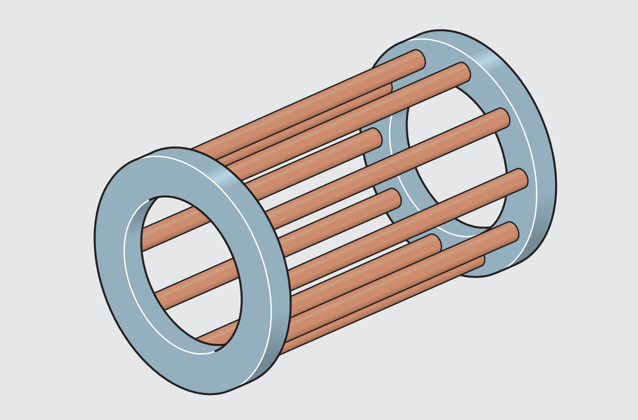


Figure 36–2 Construction of a basic squirrel cage rotor without the laminations. (Source: Delmar/Cengage Learning.)

Code letters	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0 – 3.14
B	3.15 – 3.54
C	3.55 – 3.99
D	4.0 – 4.49
E	4.5 – 4.99
F	5.0 – 5.59
G	5.6 – 6.29
H	6.3 – 7.09
J	7.1 – 7.99
K	8.0 – 8.99
L	9.0 – 9.99
M	10.0 – 11.19
N	11.2 – 12.49
P	12.5 – 13.99
R	14.0 – 15.99
S	16.0 – 17.99
T	18.0 – 19.99
U	20.0 – 22.39
V	22.4 and up

Figure 36–3 Table 430.7(B) of the *NEC*©. (Source: Delmar/Cengage Learning.)

referred to as *locked rotor current,* because it is the amount of current that would flow if the rotor were locked so it could not turn and then the power was turned on. To determine in-rush current for a squirrel cage motor, find the code letter on the motor nameplate. Do not confuse the rotor code letter with the NEMA code letter found on many motors. The nameplate will generally state one as CODE and the other as NEMA CODE. Once the code letter has been determined, it is possible to calculate the starting current for the motor.

EXAMPLE:

Assume a 200 horsepower three-phase squirrel cage motor is connected to 480 volts and has a code letter J. NEC Table 430.7(B) lists 7.1 to 7.99 kilovolt-amperes per horsepower for a motor with code letter J. To determine maximum starting current, multiply 7.99 by the horsepower.

$$7.99 \times 200 \text{ Hp} = 1598 \text{ kVA}$$

Since the motor is three-phase, the formula shown can be used to calculate the starting current.

$$I = \frac{VA}{E \times \sqrt{3}}$$

$$I = \frac{1{,}598{,}000}{480 \times 1.732}$$

$$I = 1{,}922.15 \text{ A}$$

Across-the-line starting is the simplest of all starting methods. It is accomplished by connecting the motor directly to the power line. The size of motor that can be started across the line can vary from one area to another, depending on the power limitations of the electrical service. In heavily industrialized areas, motors of over one thousand horsepower are often started across the line. In other areas, motors of less than one hundred horsepower may require some type of starter that limits the amount of starting current. A simple across-the-line starting circuit for a three-phase AC motor is shown in Figure 36–4.

Large horsepower motors often require an amount of starting current that exceeds the limitations of the power system. When this is the case, some method of reducing the in-rush current must be provided. Some common methods of reducing in-rush current are:

- Resistor or reactor starting
- Autotransformer starting

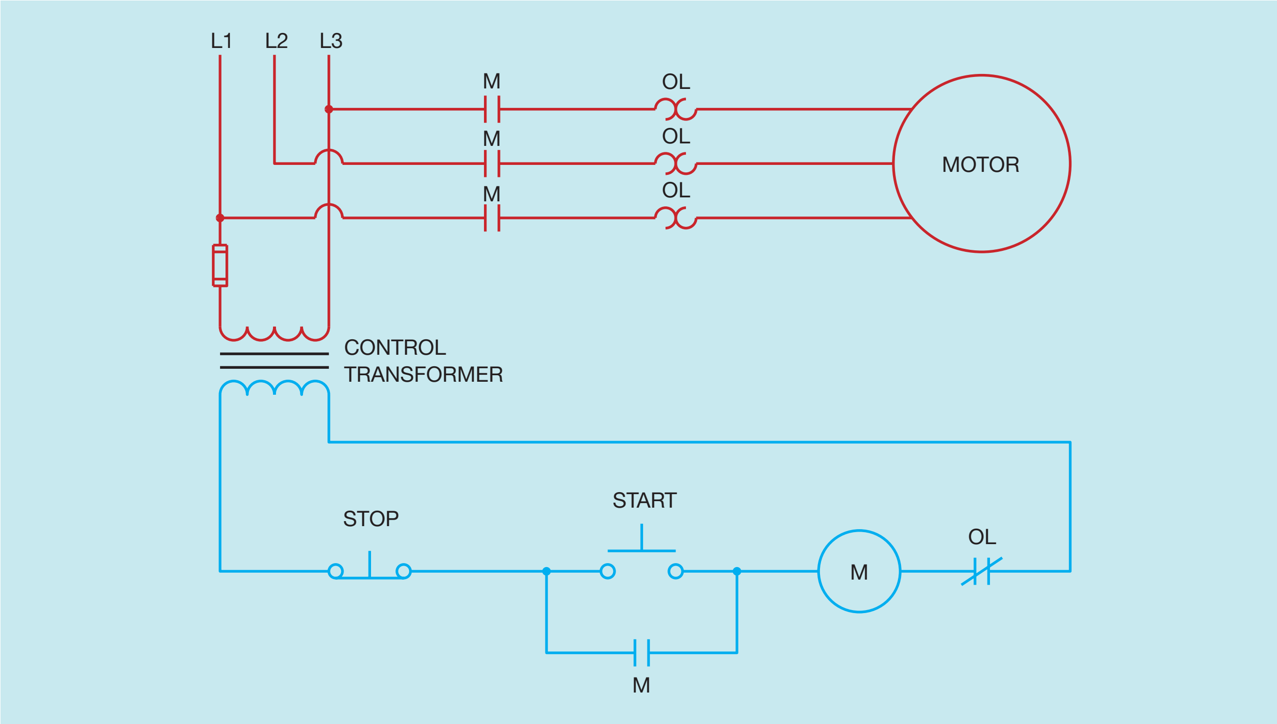


Figure 36–4 Basic control circuit for across-the-line starting of a three-phase motor. (Source: Delmar/Cengage Learning.)

- Wye-delta starting
- Part winding starting

These methods will be discussed in greater detail later in this text. It should be noted that when voltage or current is reduced during starting, the torque is also reduced. If the voltage is reduced by 50%, the current will be reduced by 50% also, but the starting torque will be reduced to 25% of the amount developed when the motor is started with full voltage applied to the motor.

Starting Methods for Single-Phase Motors

Starting methods for single-phase motors involve disconnecting the start winding of a split-phase motor when the motor reaches about 75% of its rated speed, as opposed to how the motor is connected to the power line. Single-phase motors are small horsepower and almost all are started across the line. There are several different types of single-phase motors. The motors described in this chapter are the split-phase type.

Split-phase motors derive their name from the manner in which they produce a rotating magnetic field in the stator winding. A rotating magnetic field is used to start the rotor turning and cannot be produced with a single phase. At least two phases must be present to produce a rotating field. Split-phase motors simulate the currents of a two-phase system, which are 90° out of phase with each other. This is accomplished by placing two separate windings in the core of the stator 90° apart, Figure 36–5. The run winding is made of larger wire and is placed deeper in the slots of the core material. The start winding is made with smaller wire and placed near the top of the slots in the core material. The run winding, therefore, has less resistance and more inductance than the start winding.

When the motor is started, these two windings are connected in parallel, Figure 36–6. Since the run winding has more inductive reactance and less resistance than the start winding, the current flow through the run winding lags the voltage more than the current flow through the start winding, producing an out of phase condition for these two currents. It is this out of phase condition that produces the rotating magnetic field. This type of split-phase motor is called a *resistance start* motor and produces a phase angle of about 35° to 40° between the current in the run winding and the current in the start winding. Although this phase

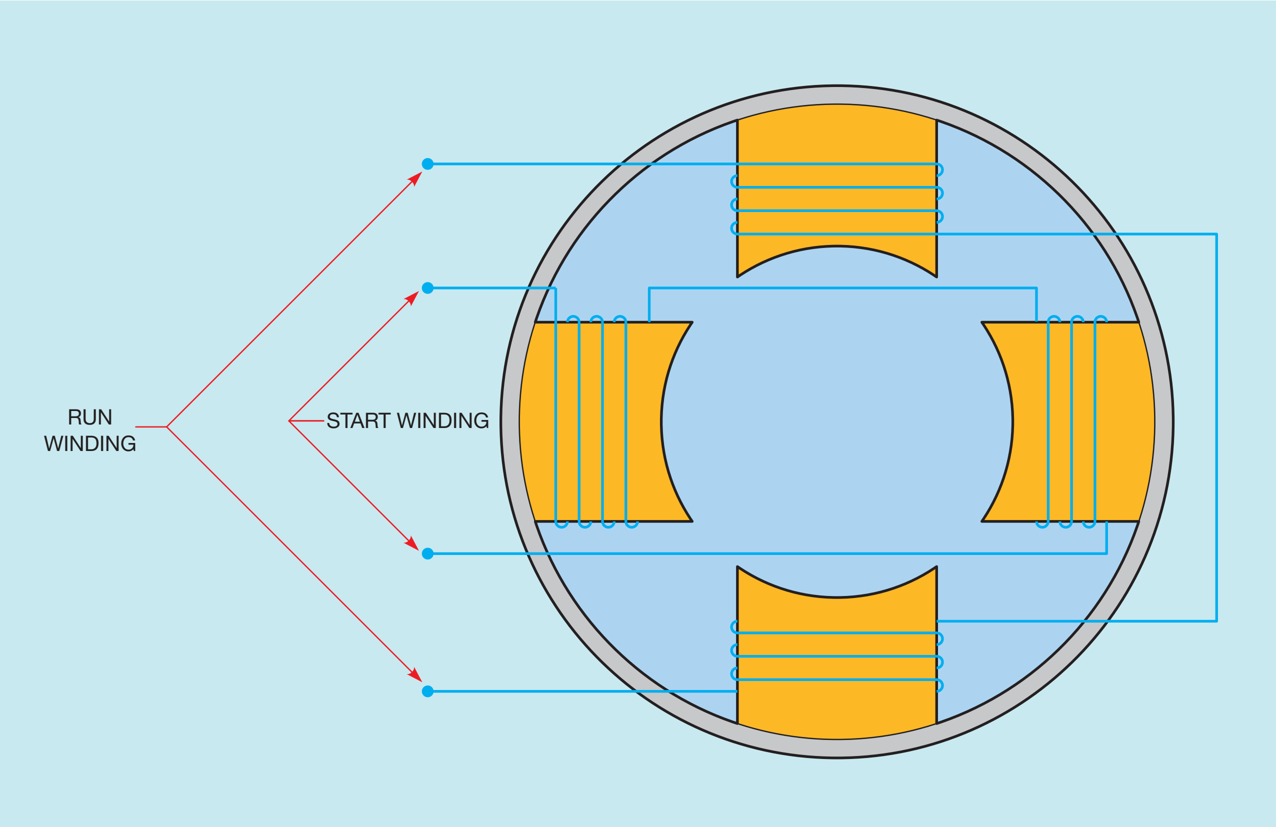


Figure 36–5 The run winding and start winding are connected in parallel with each other. (Source: Delmar/Cengage Learning.)

angle is not 90°, it is enough to produce a rotating magnetic field to start the motor. When the rotor reaches about 75% of its rated speed, the start winding is disconnected and the motor continues to operate with only the run winding energized.

Although the resistance start motor will start with only a 35° to 40° phase shift between run winding current and start winding current, it produces a weak starting torque. Maximum starting torque is obtained when the run winding and start winding currents are 90° out of phase with each other. Some motors accomplish this by inserting an AC electrolytic capacitor in series with the start winding (Figure 36–7). The capacitive reactance of the capacitor causes the start winding current to lead the voltage and produce a 90° phase shift between the run-winding current and start winding current.

Regardless of which method is used to produce the rotating magnetic field, the start winding of either motor must be disconnected from the power line when the rotor reaches about 75% of its rated speed. Failure to do so would result in damage to the start winding.

Centrifugal Switch

Split-phase motors intended to operate in the open accomplish this by the use of a centrifugal switch connected to the shaft of the rotor (Figure 36–8). The centrifugal switch is operated by spring loaded counterweights. When the rotor reaches a certain speed, the counterweights overcome the springs and open the switch, disconnecting the start winding from the power line.

Hot-Wire Starting Relay

Centrifugal switches cannot be used on all types of split-phase motors, however. Hermetically sealed motors used in refrigeration and air conditioning, or submerged pump motors must use some other means to disconnect the start winding. Although the *hot-wire relay* is seldom used anymore, it is found on some older units that are still in service. The hot-wire relay functions as both a starting relay and an overload relay. In the circuit shown in Figure 36–9, it is assumed that

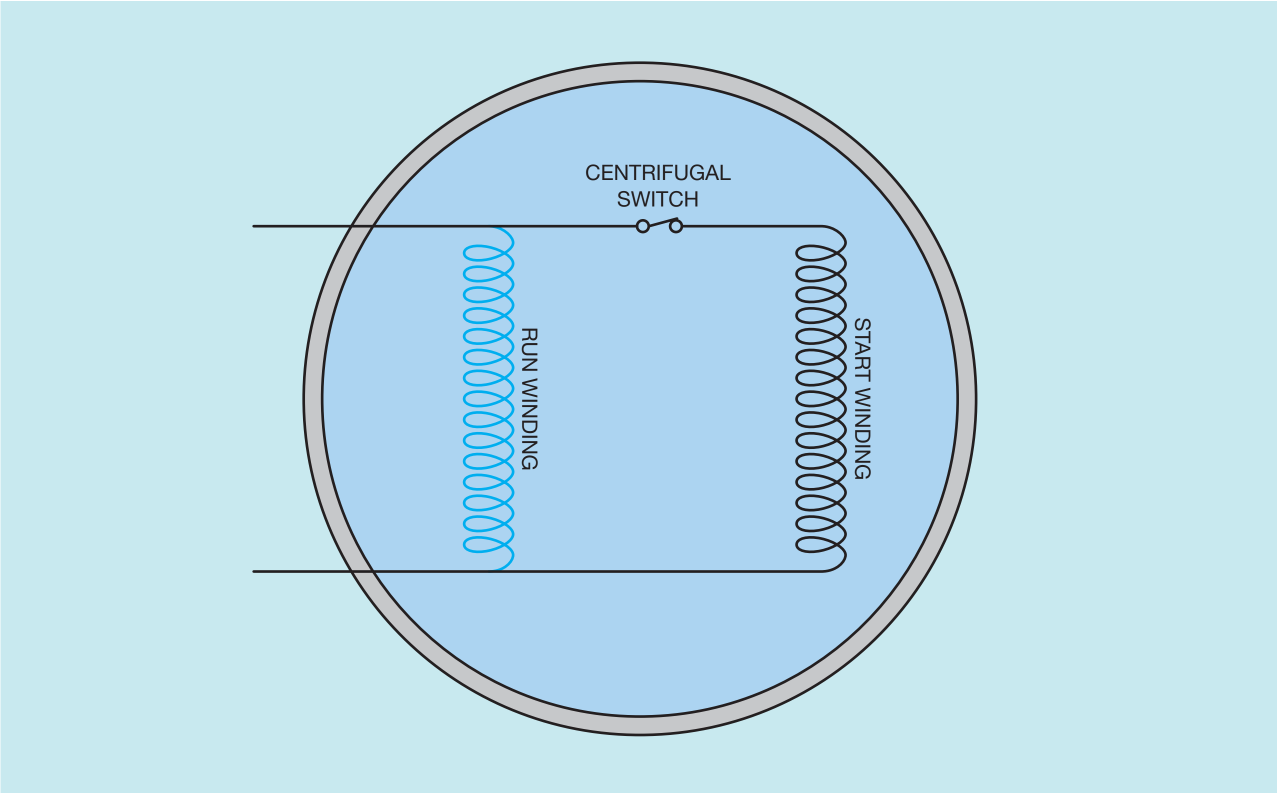


Figure 36–6 The run winding and start winding are connected in parallel with each other. (Source: Delmar/Cengage Learning.)

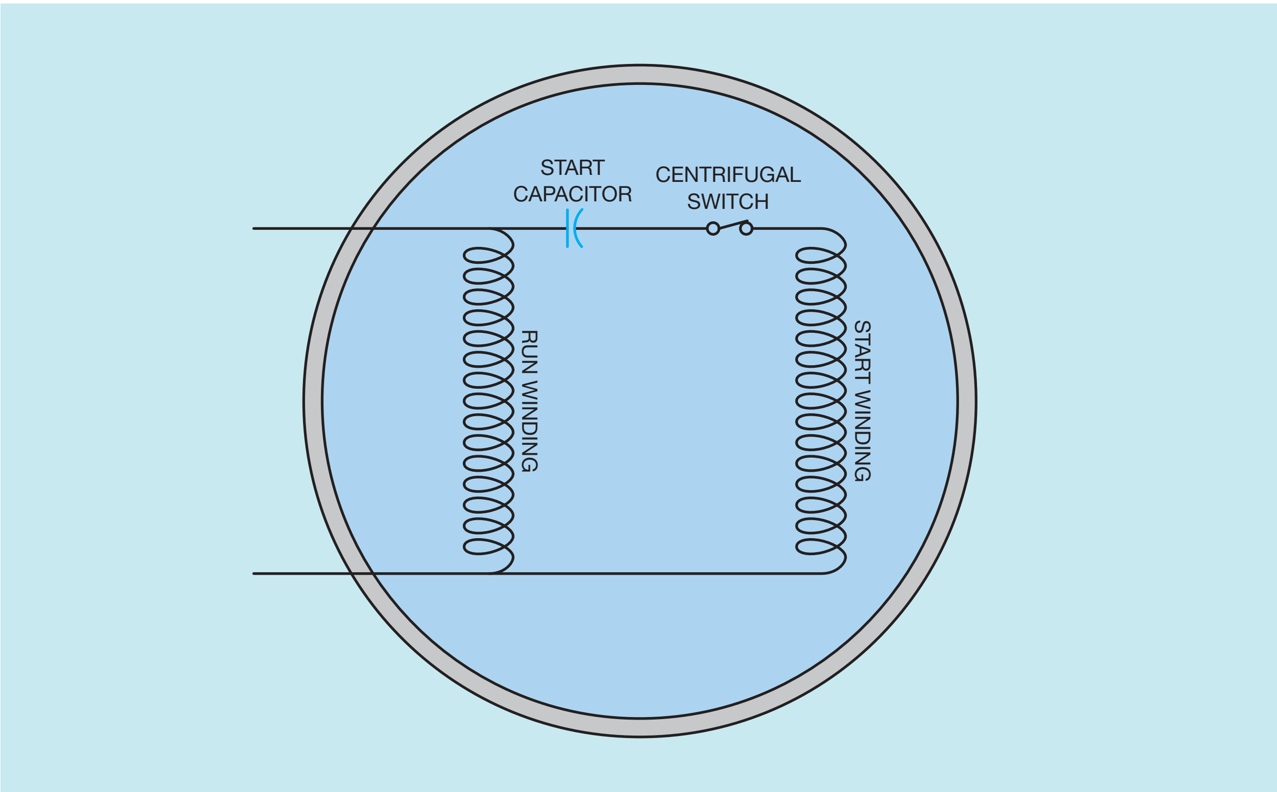


Figure 36–7 The starting capacitor produces a 90° phase shift between run winding current and start winding current. (Source: Delmar/Cengage Learning.)

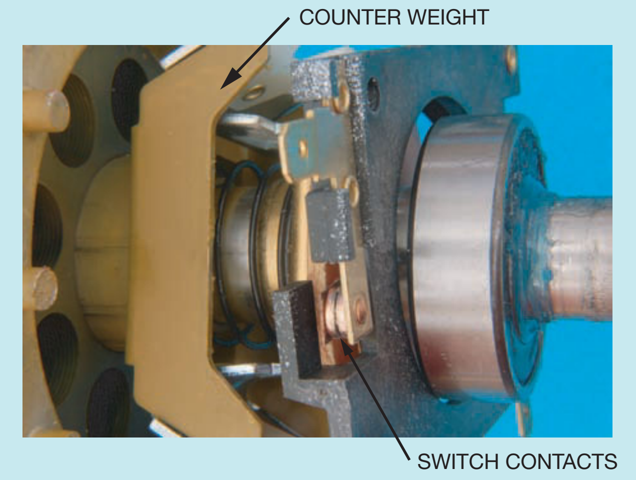


Figure 36–8 Centrifugal switch. (Source: Delmar/Cengage Learning.)

a thermostat controls the operation of the motor. When the thermostat closes, current flows through a resistive wire and two normally closed contacts connected to the start and run windings of the motor. The starting current of the motor is high, which rapidly heats the resistive wire, causing it to expand. The expansion of the wire causes the spring loaded start winding contact to open and disconnect the start winding from the circuit, reducing the motor current. If the motor is not overloaded, the resistive wire never becomes hot enough to cause the overload contact to open, and the motor continues to run. If the motor should become overloaded, however, the resistive wire will expand enough to open the overload contact and disconnect the motor from the line (Figure 36–10).

Current Relay

The *current relay* operates by sensing the amount of current flow in the circuit. This type of relay operates on the principle of a magnetic field instead of expanding metal. The current relay contains a coil with a few turns of large wire and a set of normally open contacts (Figure 36–11). The coil of the relay is connected in series with the run winding of the motor, and the contacts are connected in series with the start winding, as shown in Figure 36–12. When the thermostat contact closes, power is applied to the run

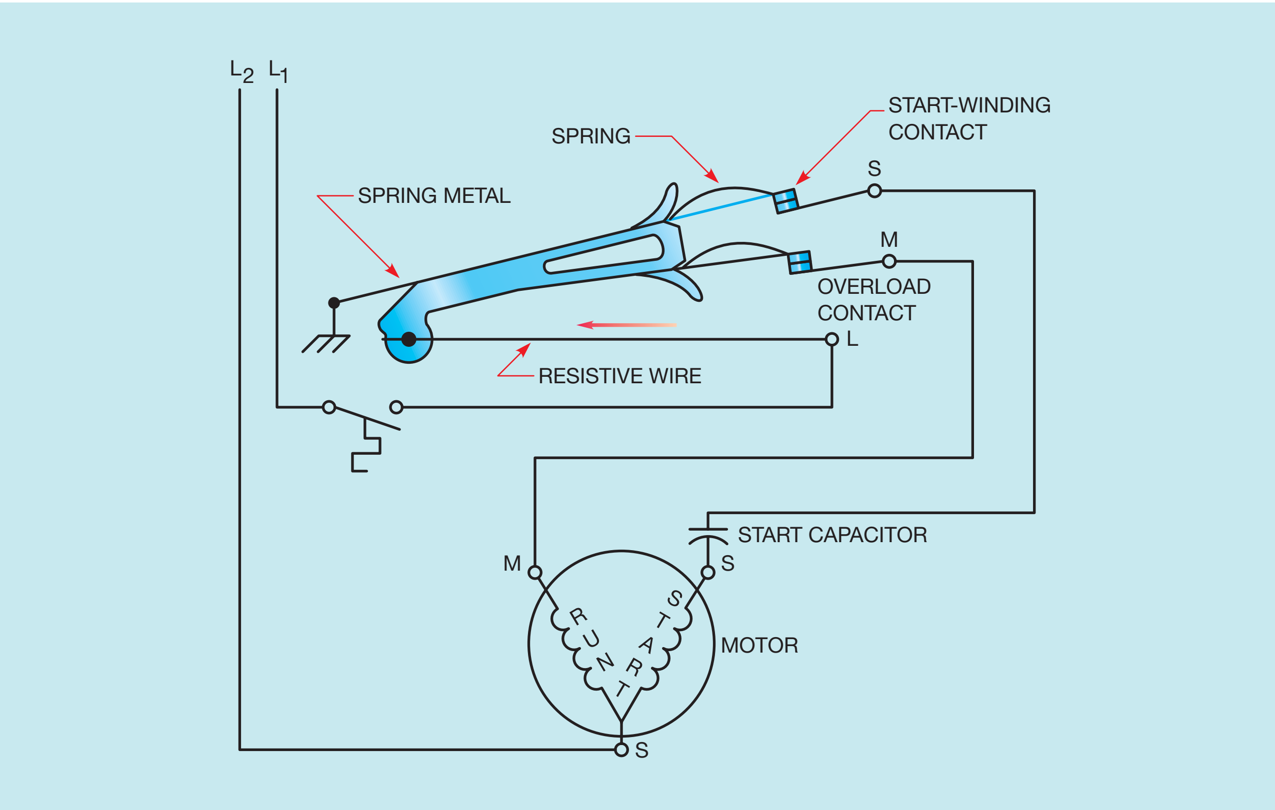


Figure 36–9 Hot-wire relay connection. (Source: Delmar/Cengage Learning.)

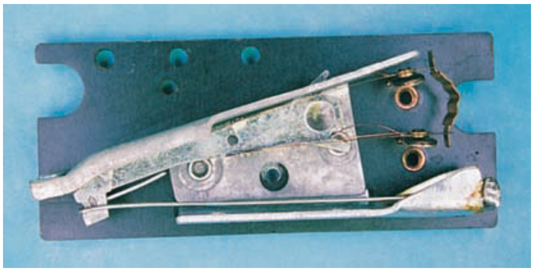


Figure 36–10 Hot-wire type of starting relay. (Source: Delmar/Cengage Learning.)

winding of the motor. Since the start winding is open, the motor cannot start. This causes a high current to flow in the run-winding circuit. This high current flow produces a strong magnetic field in the coil of the relay, causing the normally open contacts to close and connect the start winding to the circuit. When the motor starts, the run winding current is greatly reduced, permitting the start contacts to reopen and disconnect the start winding from the circuit.

Solid-State Starting Relay

The *solid-state starting relay* is rapidly replacing the current starting relay. The solid-state relay uses a solid-state component called a *thermistor,* and therefore has no moving parts or contacts to wear or burn. A thermistor exhibits a rapid change of resistance when the temperature reaches a certain point. This particular thermistor has a positive coefficient of resistance, which means that it increases its resistance with an increase of temperature. The schematic diagram in Figure 36–13 illustrates the connection for a solid-state starting relay.

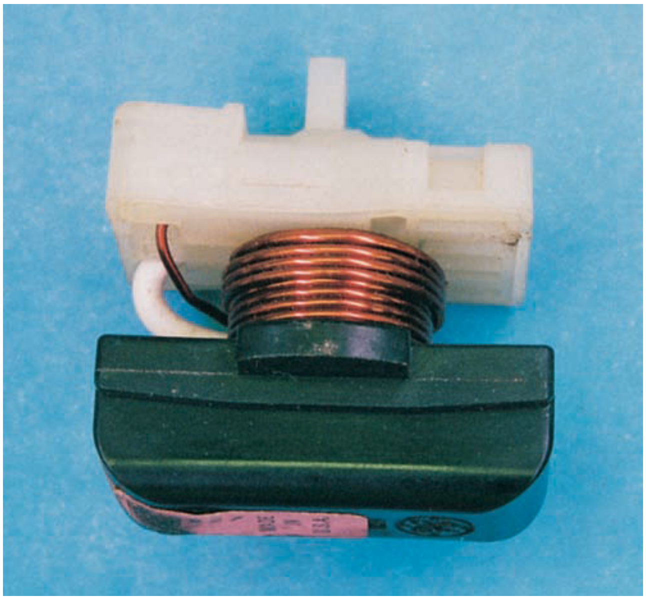


Figure 36–11 Current type of starting relay. (Source: Delmar/Cengage Learning.)

When power is first applied to the circuit, the resistance of the thermistor is relatively low, 3 or 4 ohms, and current flows to both the run and start windings. As current flows through the thermistor, its temperature increases. When the temperature becomes high enough, the thermistor, suddenly changes from a low resistance to a high resistance, reducing the start winding current to approximately 30 to 50 milliamperes. This has the effect of disconnecting the start winding from the circuit.

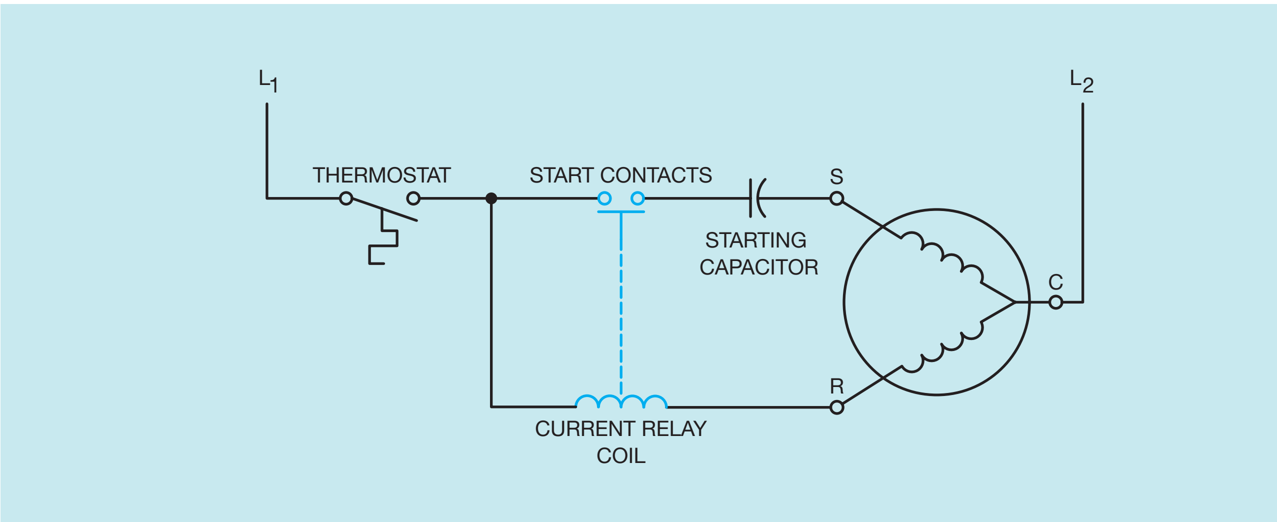


Figure 36–12 Current relay connection. (Source: Delmar/Cengage Learning.)

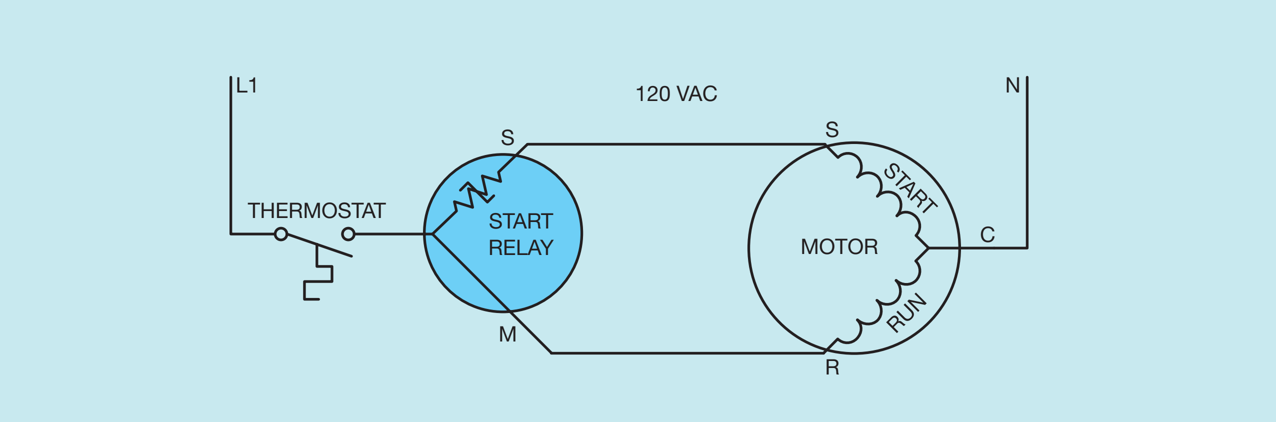


Figure 36–13 Solid state starting relay circuit. (Source: Delmar/Cengage Learning.)

Although a small amount of *leakage current* continues to flow, it has no effect on the operation of the motor. This leakage current maintains the temperature of the thermistor and prevents it from returning to a low resistance while the motor is in operation. When the motor is stopped, a cool-down period of 2 or 3 minutes should be allowed to permit the thermistor to return to a low resistance.

Potential Starting Relay

The *potential starting relay* is used with a different type of split-phase motor called the *capacitor start-capacitor run* or *permanent-split capacitor motor*. This type of split-phase motor does not disconnect the start windings from the circuit. Since the start winding remains energized, it operates very similarly to a true two-phase motor. All of these motors contain a run capacitor that remains connected in the start winding circuit at all times. Many of these motors contain a second capacitor that is used during the starting period only. This capacitor must be disconnected from the circuit when the motor reaches about 75% of its rated speed. Open case motors generally use a centrifugal switch to perform this function, but hermetically sealed motors generally depend on a potential starting relay (Figure 36–14). The potential relay operates by sensing the increase of voltage induced in the

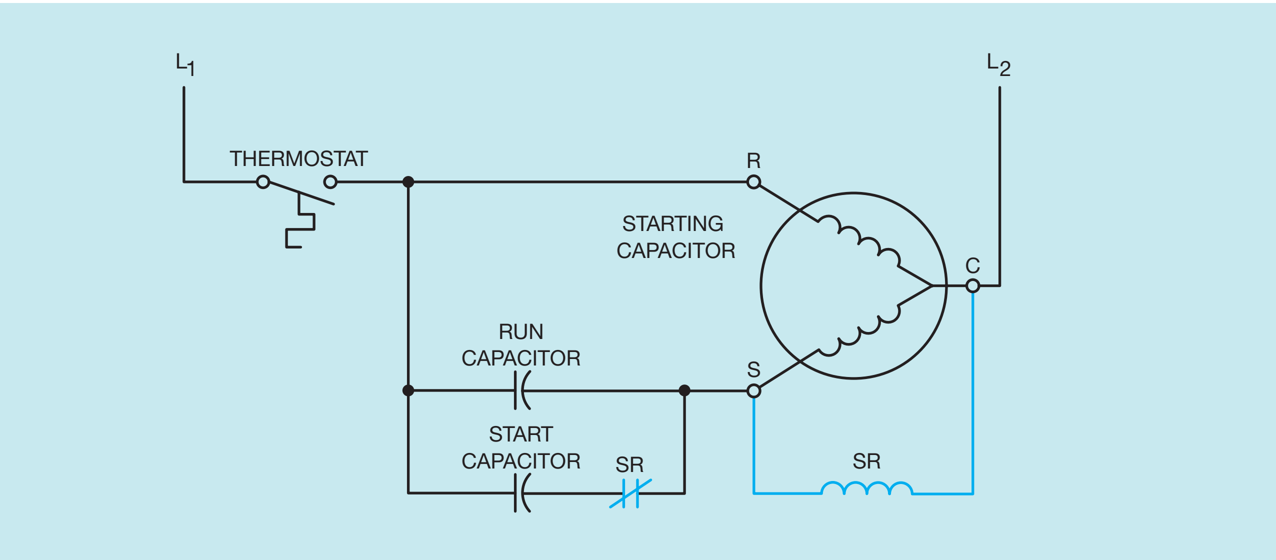


Figure 36–14 Potential relay connection. (Source: Delmar/Cengage Learning.)

start winding when the motor is in operation. The coil of the relay is connected in parallel with the start winding of the motor. The normally closed SR contact is connected in series with the starting capacitor. When power is connected to the motor, both the run and start windings are energized. At this time, both the run and start capacitors are connected in the start winding circuit.

The rotating magnetic field of the stator induces a current in the rotor of the motor. As the rotor begins to turn, its magnetic field induces a voltage into the start winding, increasing the total voltage across the winding. Since the coil of the potential relay is connected in parallel with the start winding, this voltage increase is applied to it also, causing the normally closed contact connected in series with the starting capacitor to open and disconnect the starting capacitor from the circuit (Figure 36–15).

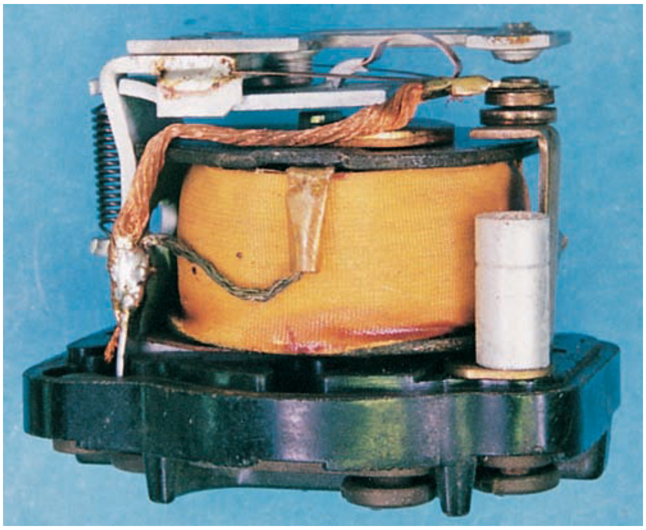


Figure 36–15 Potential starting relay. (Source: Delmar/Cengage Learning.)

Review Questions

1. List five common starting methods for three-phase squirrel cage motors.
2. The nameplate of a three-phase motor has the following information listed: HP 500; Phase 3; Volts 480; Code H; Amps 515; What is the maximum starting current for this motor if it is started across the line?
3. A squirrel cage motor produces 1100 pound feet of torque at starting when full voltage is applied to the motor. If the voltage is reduced to 50% during starting, how much starting torque will the motor develop?
4. What is the most common device used to disconnect the start winding of a resistance start single-phase motor that is intended to operate in the open air?
5. What electronic component is used in the construction of a solid-state starting relay?
6. When connecting a current relay for the purpose of starting a single-phase motor, is the coil of the current relay connected in series with the run winding or the start winding?
7. Which type of split-phase motor starting relay can be used to disconnect the start winding and also to double as an overload protector?
8. The potential starting relay can be used with what type of split-phase motor?
9. When a solid-state starting relay is used to disconnect the start winding of a split-phase motor, what prevents the thermistor from returning to a low value and reconnecting the start winding while the motor is running?
10. A centrifugal switch is generally designed to disconnect the start winding of a split-phase motor when the rotor reaches what percentage of the rated speed?

CHAPTER 37

RESISTOR AND REACTOR STARTING FOR AC MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss why resistor and reactor starting is used for starting alternating current motors.
- Discuss how resistor starting is used with direct current motors.
- Discuss different methods of accomplishing resistor and reactor starting.
- Explain the difference between resistor and reactor starting.

There are conditions where it is not possible to start a motor across the line due to excessive starting current or excessive torque. Some power systems are not capable of providing the high initial currents produced by starting large horsepower motors. When this is the case, some means must be employed to reduce the amount of starting current. Two of the most common methods are resistor starting and reactor starting. Although these two methods are very similar, they differ in the means used to reduce the amount of starting current.

Resistor Starting

Resistor starting is accomplished by connecting resistors in series with the motor during the starting period (Figure 37–1). When the Start button is pressed, motor starter coil M energizes and closes all M contacts. The three M load contacts connect the motor and resistors to the line. Since the resistors are connected in series with the motor, they limit the amount of in-rush current. When the M auxiliary contact connected in series with coil TR closes, the timer begins its timing sequence. At the end of the time period, timed contact TR closes and energizes contactor R. This causes the three R contacts connected in parallel with the resistors to close. The R contacts shunt the resistors out of the line and the motor is now connected to full power.

The circuit in Figure 37–1 uses time delay to shunt the resistors out of the circuit after some period of time. Time delay is one of the most popular methods of determining when to connect the motor directly to the power line because it is simple and inexpensive, but it is not the only method. Some control circuits sense

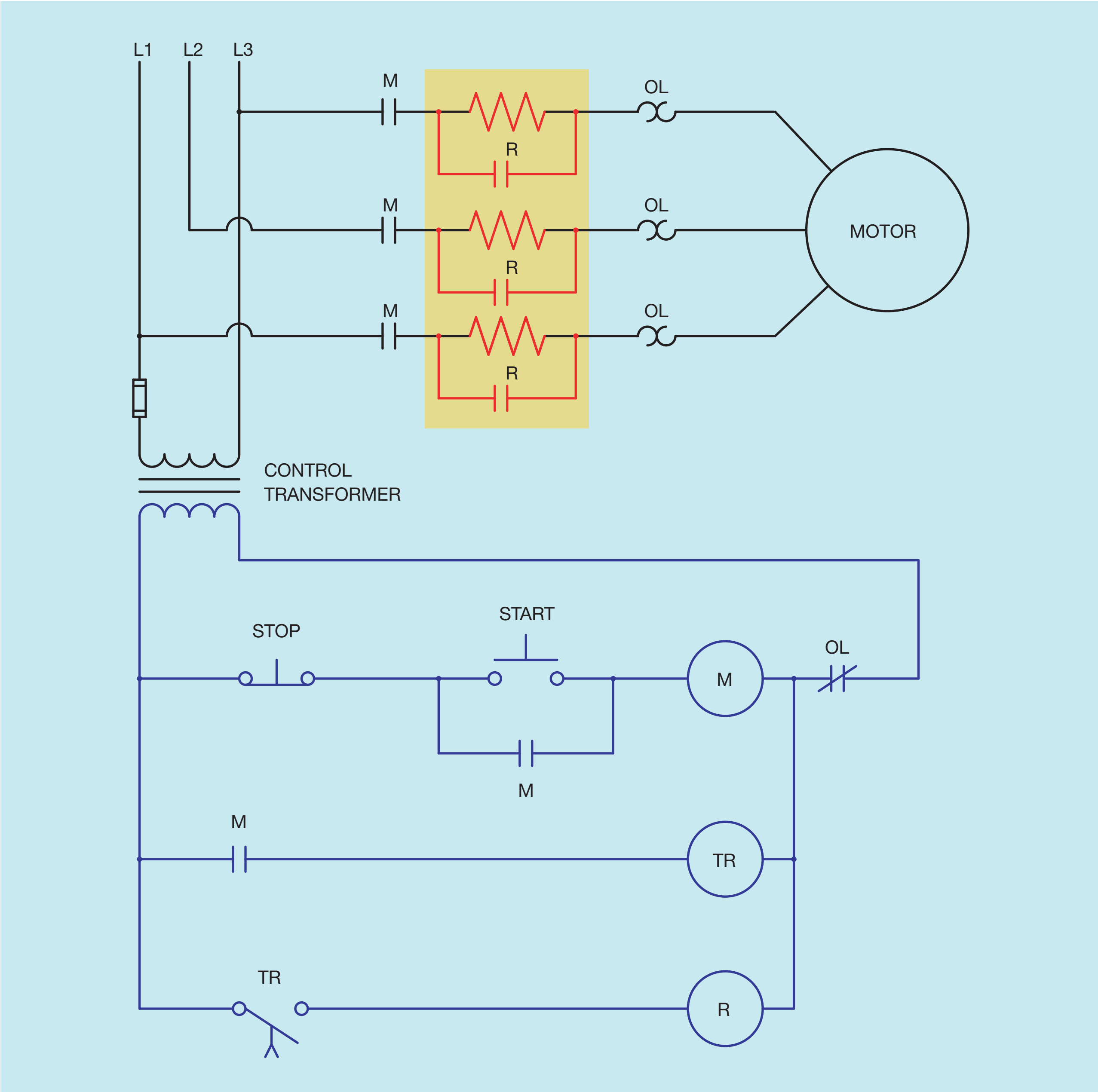


Figure 37–1 Resistors are connected in series with the motor during starting. (Source: Delmar/Cengage Learning.)

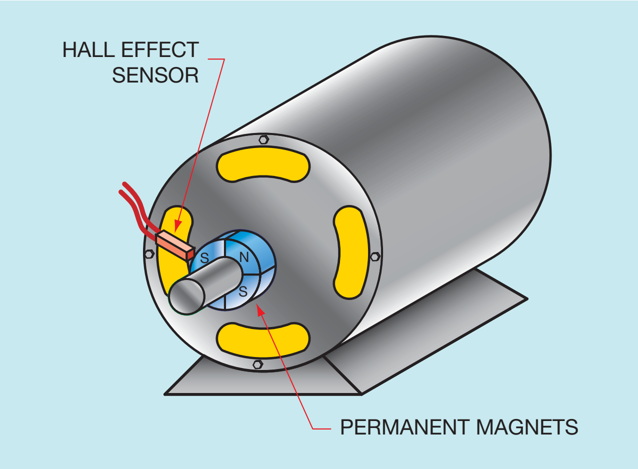


Figure 37–2 Hall effect sensor is used to determine motor speed. (Source: Delmar/Cengage Learning.)

motor speed to determine when to shunt the resistors out of the power line (Figure 37–2). In the illustration, permanent magnets are attached to the motor shaft, and a Hall effect sensor determines the motor speed. When the motor speed reaches a predetermined level, contactor R energizes and shunts the resistors out of the line (Figure 37–3).

Another way of determining when to shunt the resistors out of the circuit is by sensing motor current. Current transformers are used to sense the amount of motor current (Figure 37–4). In this circuit, the current sensor contacts are normally closed. When the motor starts, high current causes the sensor contacts to open. An on-delay timer provides enough time delay to permit the motor to begin starting before contactor coil R can energize. This timer is generally set for a very short time delay. As the motor speed increases, the current drops. When the current drops to a low enough level, the current sensor contact re-closes and permits contactor R to energize.

Reactor Starting

A reactor starter is the same basic control except that reactors or choke coils are used to limit in-rush current instead of resistors (Figure 37–5). Reactors limit in-rush current with inductive reactance instead of resistance. Reactors have an advantage in current limiting circuits because of the rise time of current in an inductive circuit. In a resistive circuit, the current will reach its full Ohm's Law value instantly. In an inductive circuit, the current must rise at an exponential rate (Figure 37–6). This exponential rise time of current further reduces the inrush current.

Step-Starting

Some resistor and reactor starters use multiple steps of starting. This is accomplished by tapping the resistor or reactor to provide different values of resistance or inductive reactance (Figure 37–7). When the Start button is pressed, M load contacts close and connect the motor and inductors to the line. The M auxiliary contact closes and starts timer TR1. After a time delay, TR1 contact closes and energizes S1 coil. This causes half of the series inductors to be shunted out, reducing the inductive reactance connected in series with the motor. Motor current increases, causing the motor speed to increase. The S1 auxiliary contact closes at the same

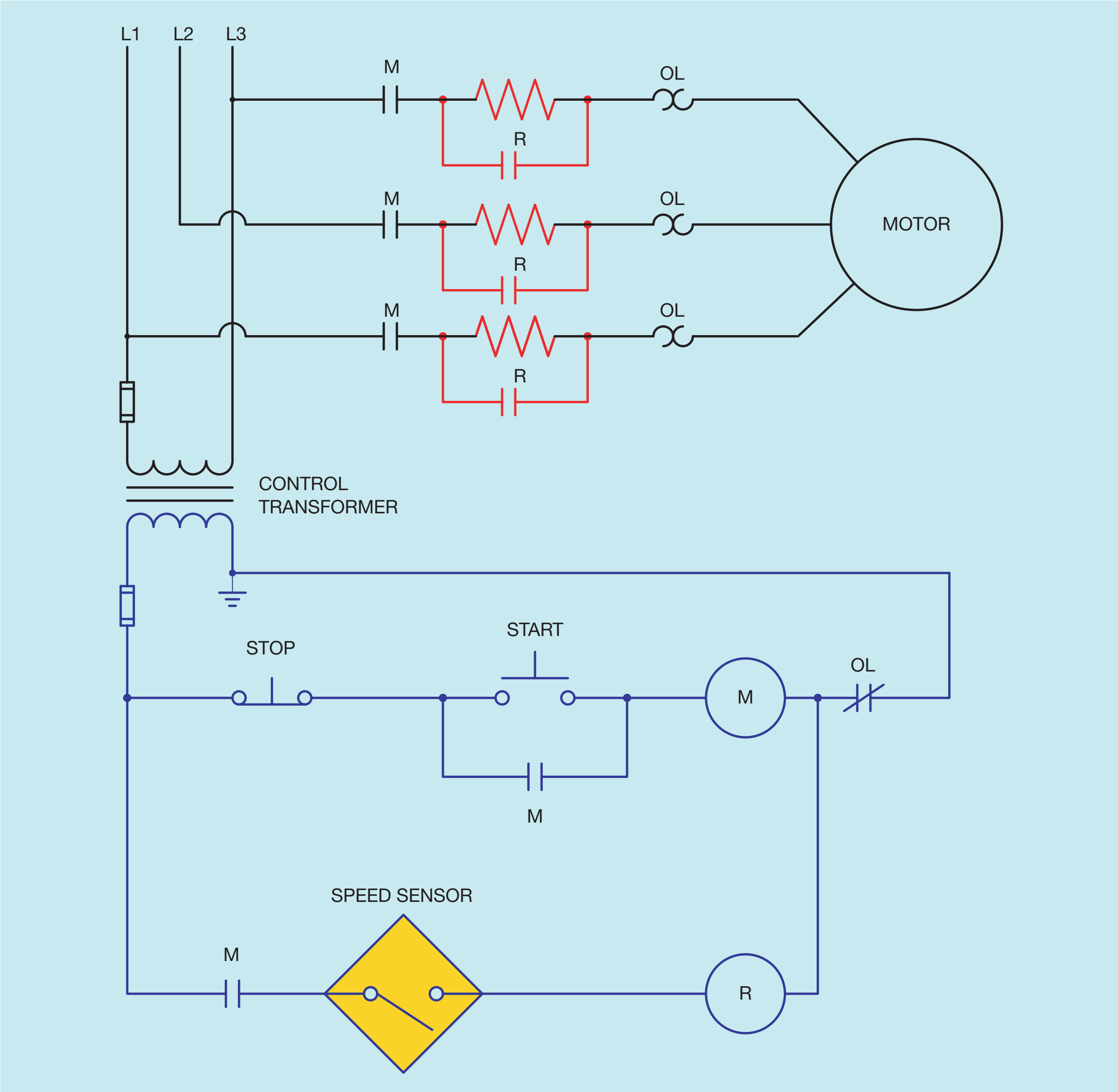


Figure 37–3 A speed sensor is used to shunt the resistors out of the circuit. (Source: Delmar/Cengage Learning.)

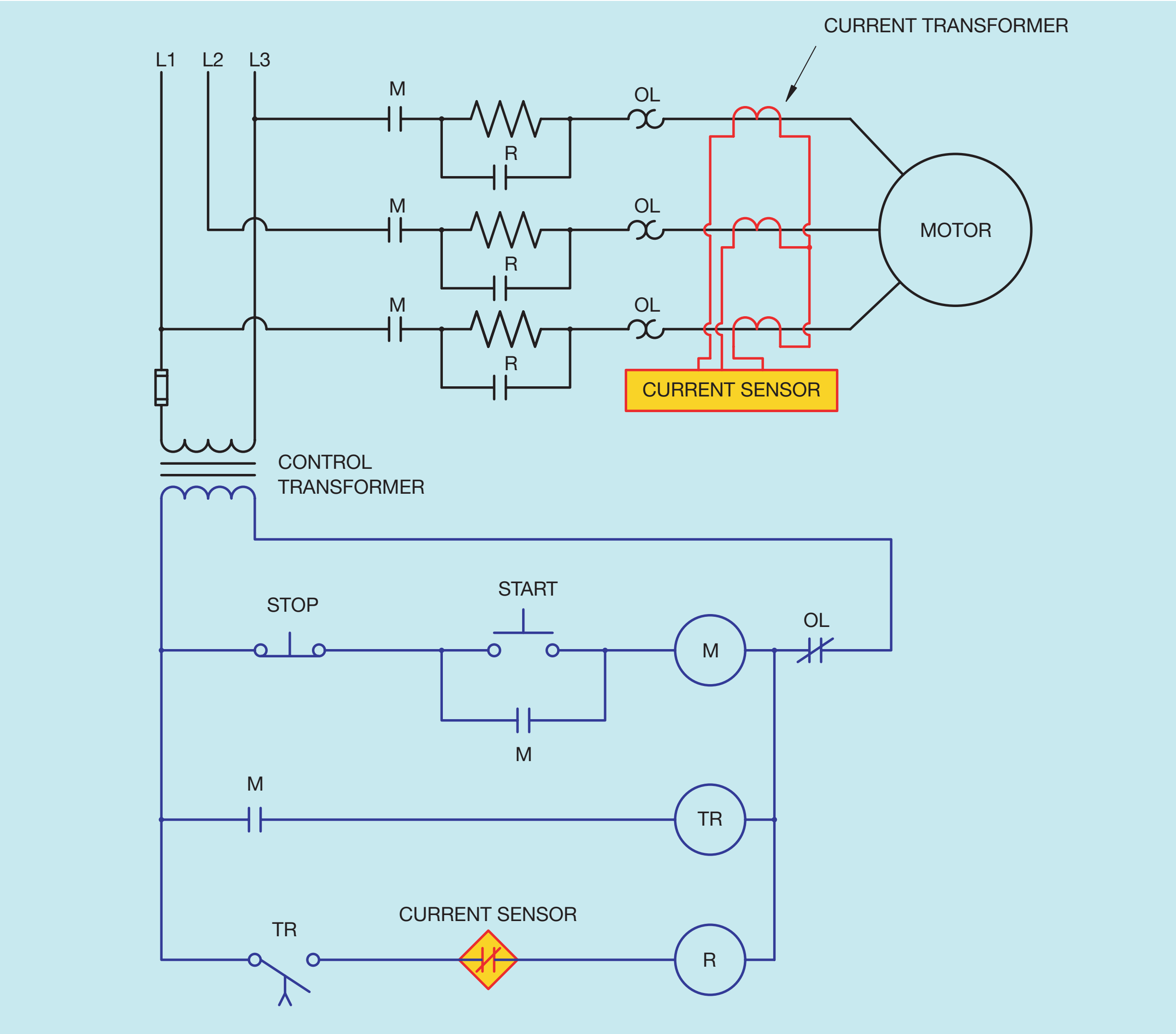


Figure 37–4 Current sensors determine when the resistors are shunted out of the line. (Source: Delmar/Cengage Learning.)

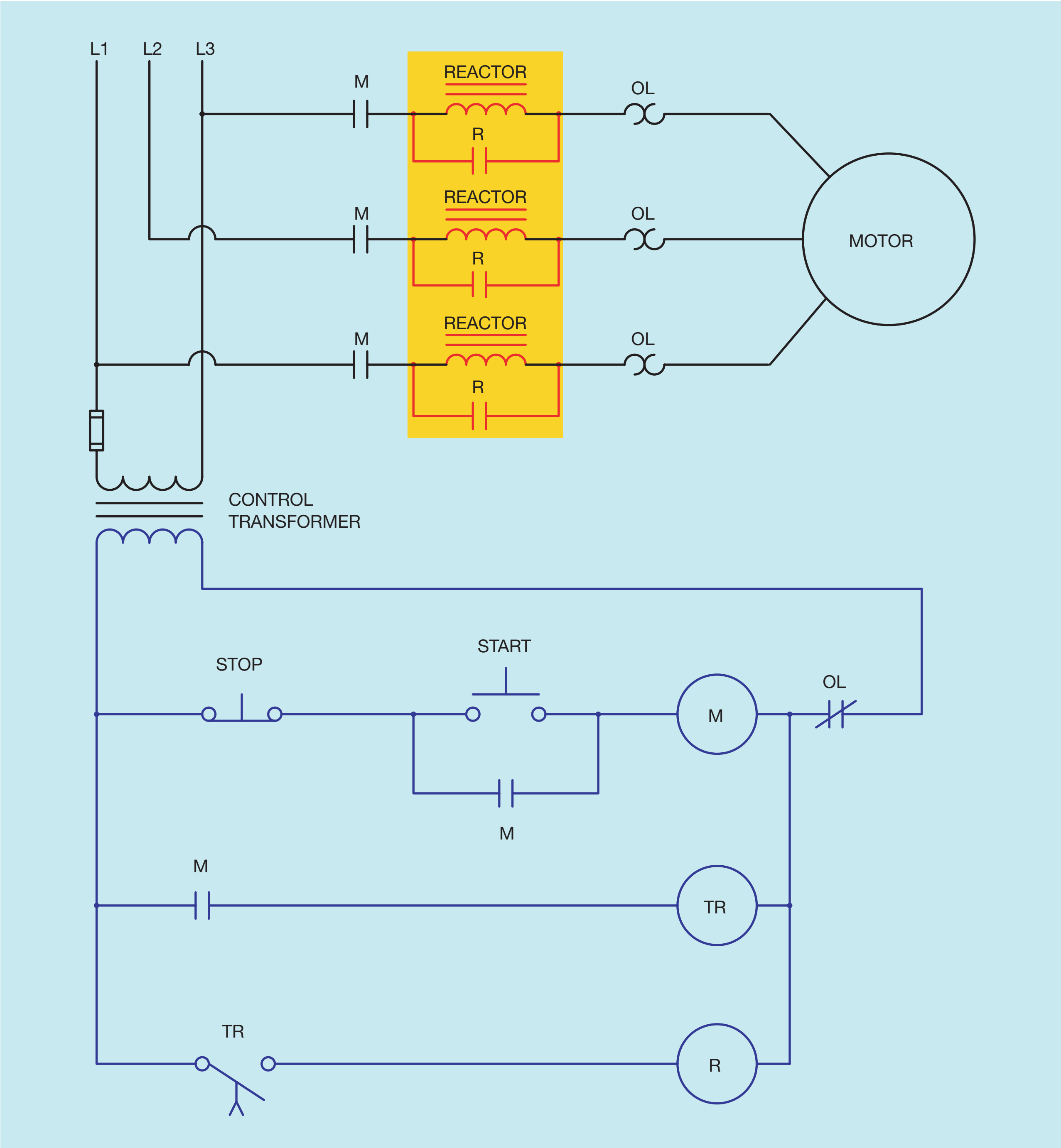


Figure 37–5 Reactors (Chokes) limit motor current during starting. (Source: Delmar/Cengage Learning.)

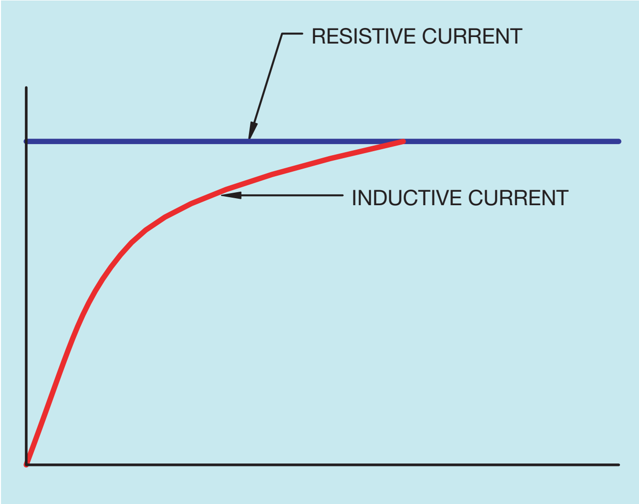


Figure 37–6 Current rises at an exponential rate in an inductive circuit. (Source: Delmar/Cengage Learning.)

time, causing timer TR2 to start its timing sequence. When TR2 contact closes, contactor S2 energizes, causing all of the inductance to be shunted out. The motor is now connected directly to the power line. Some circuits may use several steps of starting, depending on the circuit requirements.

Review Questions

1. What two electrical components are commonly connected in series with a motor to limit starting current?
2. What advantage does a reactor have when limiting in-rush current that is not available with a resistor?
3. Refer to the circuit shown in Figure 37–1. Assume that timer TR is set for a delay of 10 seconds. When the Start button is pressed, the motor starts in low speed. After a delay of 30 seconds, the motor is still in its lowest speed and has not accelerated to normal speed. Which of the following could **not** cause this condition?
   a. The Start button is shorted.
   b. Timer coil TR is open.
   c. Contactor coil R is open.
   d. Timed contact TR did not close after a delay of 10 seconds.
4. Refer to the circuit shown in Figure 37–7. Assume that each timer is set for a delay of 5 seconds. When the Start button is pressed, the motor starts at its lowest speed. After a delay of 5 seconds, the motor accelerates to second speed. After another delay of 5 seconds, the motor stops running. During troubleshooting you discover that the control transformer fuse is blown. Which of the following could cause this condition?
   a. TR1 coil is shorted.
   b. S1 coil is open.
   c. S2 coil is shorted.
   d. TR2 coil is open.
5. Refer to the circuit shown in Figure 37–7. Assume that each timer is set for a delay of 5 seconds. When the Start button is pressed, the motor starts at its highest speed. Which of the following could cause this condition?
   a. The Stop button is shorted.
   b. TR1 timer coil is open.
   c. S1 auxiliary contact is shorted.
   d. TR2 timer coil is shorted.

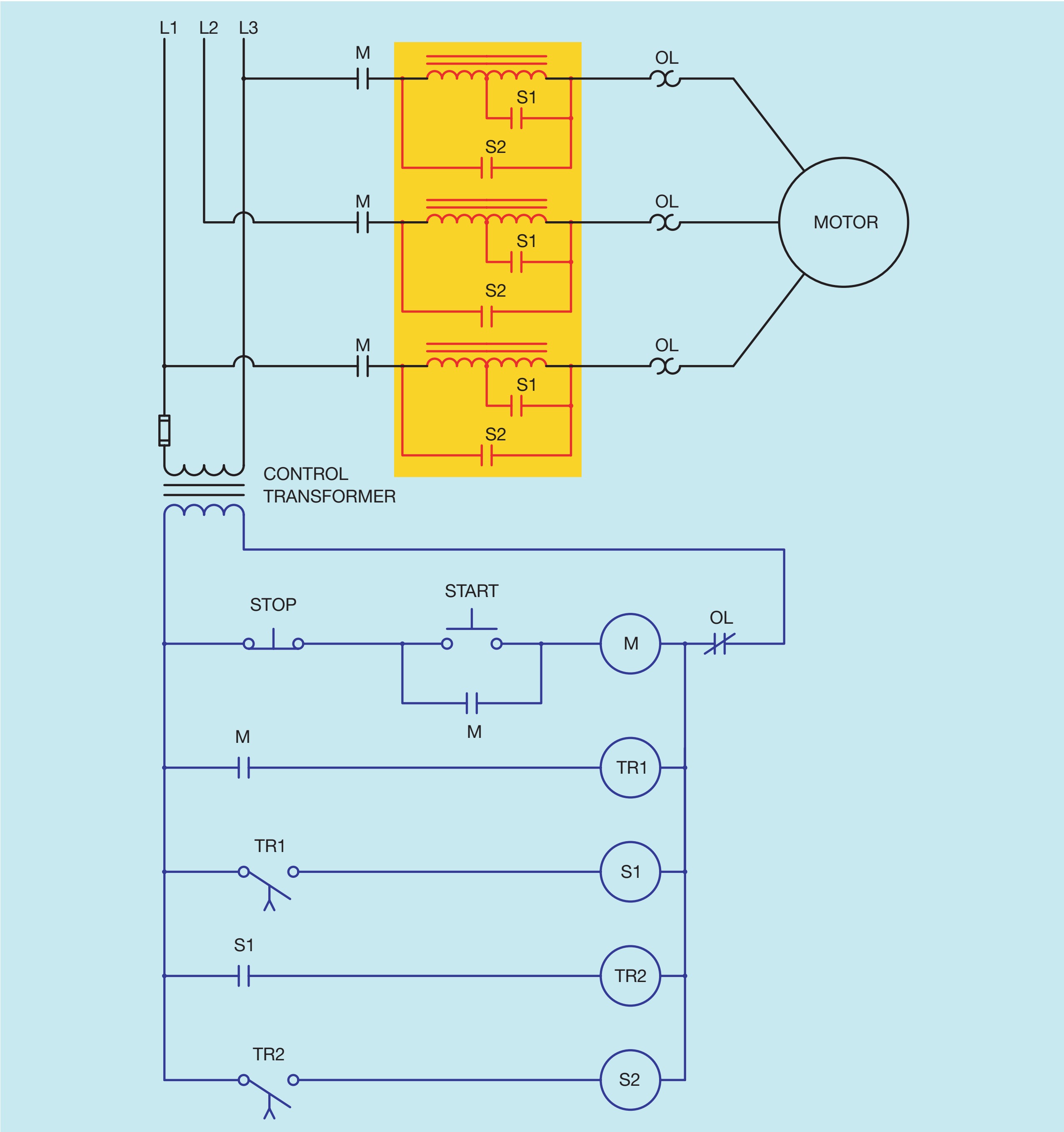


Figure 37–7 Three step reactor starting circuit. (Source: Delmar/Cengage Learning.)

CHAPTER 38

AUTOTRANSFORMER STARTING

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss autotransformer starting.
- Discuss different types of autotransformer starters.
- Explain the difference between wye or star connected autotransformers and open-delta connected autotransformers.
- Connect an autotransformer starter.
- Define closed and open transition starting.

Autotransformer starters reduce the amount of in-rush current by reducing the voltage applied to the motor during the starting period. Many autotransformer starters contain taps that can be set for 50%, 65%, or 80% of the line voltage. Reducing the voltage applied to the motor not only reduces the amount of in-rush current, but also reduces the motor torque. If 50% of the normal voltage is connected to the motor, the in-rush current will drop to 50% also. This will produce a torque that is 25% of the value when full voltage is connected to the motor. If the motor torque is insufficient to start the load when the 50% tap is used, the 65% or 80% taps are available.

Autotransformer starters are generally employed to start squirrel cage type motors. Wound rotor type motors and synchronous motors do not generally use this type of starter. Autotransformer starters are inductive type loads and will affect the power factor during the starting period.

Most autotransformer starters use two transformers connected in open-delta to reduce the voltage applied to the motor during the period of acceleration (Figure 38–1). During the starting period, the motor is connected to the reduced voltage taps on the transformers. After the motor has accelerated to about 75% of normal speed, the motor is connected to full

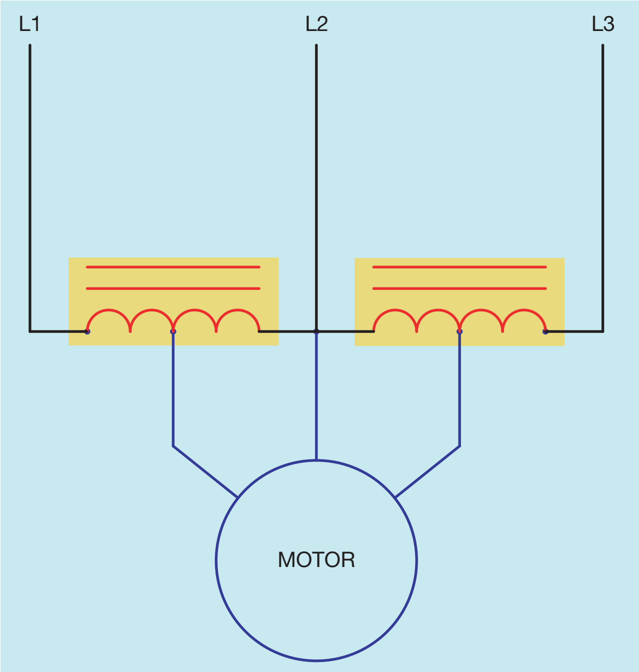


Figure 38–1 Transformers are connected in open-delta. (Source: Delmar/Cengage Learning.)

voltage. A time delay starter of this type is shown in Figure 38–2. To understand the operation of the autotransformer starter more clearly, refer to the schematic diagram shown in Figure 38–2. When the Start button is pressed, a circuit is completed to the coil of control relay CR, causing all CR contacts to close. One contact is employed to hold CR coil in the circuit when the Start button is released. Another completes a circuit to the coil of TR timer, which permits the timing sequence to begin. The CR contact connected in series with the normally closed TR contact supplies power to the coil of S (start) contactor. The fourth CR contact permits power to be connected to R (run) contactor when the normally open timed TR contact closes.

When the coil of S contactor energizes, all S contacts change position. The normally closed S contact connected in series with R coil opens to prevent both S and R contactors from ever being energized at the same time. This is the same interlocking method used with reversing starters. When the S load contacts close, the motor is connected to the power line through the autotransformers. The autotransformers supply 65% of the line voltage to the motor. This reduced voltage produces less in-rush current during starting and also reduces the starting torque of the motor.

When the time sequence for TR timer is completed, both TR contacts change position. The normally closed TR contact opens and disconnects contactor S from the line, causing all S contacts to return to their normal position. The normally open TR contact closes and supplies power through the now closed S contact to coil R. When contactor R energizes, all R contacts change position. The normally closed R contact connected in series with S coil opens to provide interlocking for the circuit. The R load contacts close and connect the motor to full voltage.

When the Stop button is pressed, control relay CR de-energizes and opens all CR contacts. This disconnects all other control components from the power line, and the circuit returns to its normal position. A wiring diagram for this circuit is shown in Figure 38–3.

Open and Closed Transition Starting

Open transition starting is generally used on starters of size 5 and smaller. Open transition simply means that there is a brief period of time when the motor is disconnected from power when the start contactor opens and the run contactor closes. The circuit shown in Figures 38–2 and 38–3 are examples of an open transition starter.

Closed transition starting is generally used on starters size 6 and larger. For closed transition starting, two separate start contactors are used (Figure 38–4). When the motor is started, both S1 and S2 contactors close their contacts. The S1 contacts open first and separately from the S2 contacts. At this point, part of the autotransformer windings are connected in series with the motor and act as series inductors. This permits the motor to accelerate to a greater speed before the R contacts close and the S2 contacts open. Although the R and S2 contacts are closed at the same time, the interval of time between the R contacts closing and the S2 contacts opening is so short that it does not damage the autotransformer winding.

Notice that the circuit in Figure 38–4 contains three current transformers (CTs). This is typical in circuits that control large horsepower motors. The CTs reduce the current to a level that common overload heaters can be used to protect the motor. A schematic

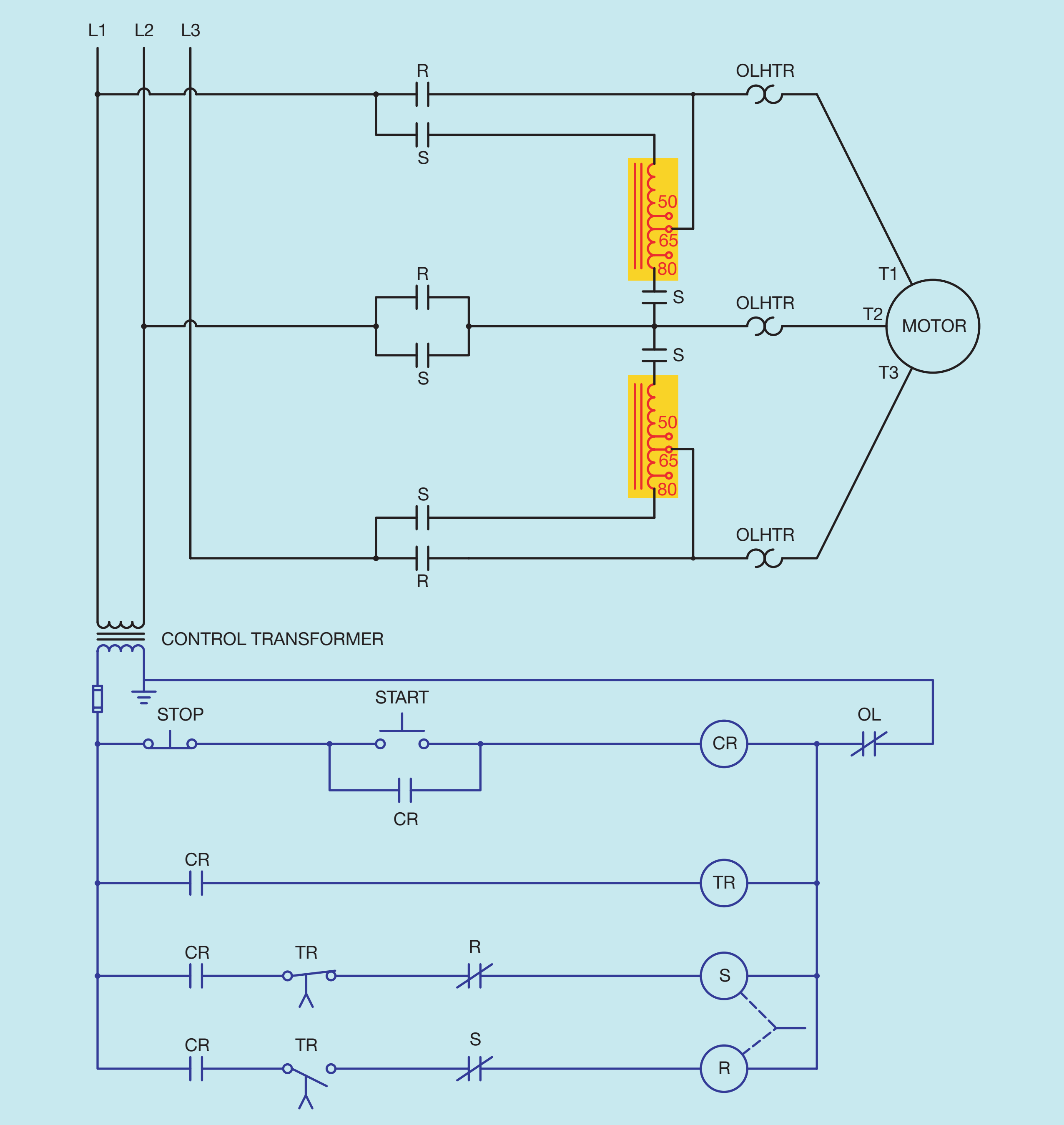


Figure 38–2 Autotransformer starters provide greater starting torque per amp of starting current than any other type of reduced voltage starter. This is a schematic diagram of a time-controlled autotransformer starter. (Source: Delmar/Cengage Learning.)

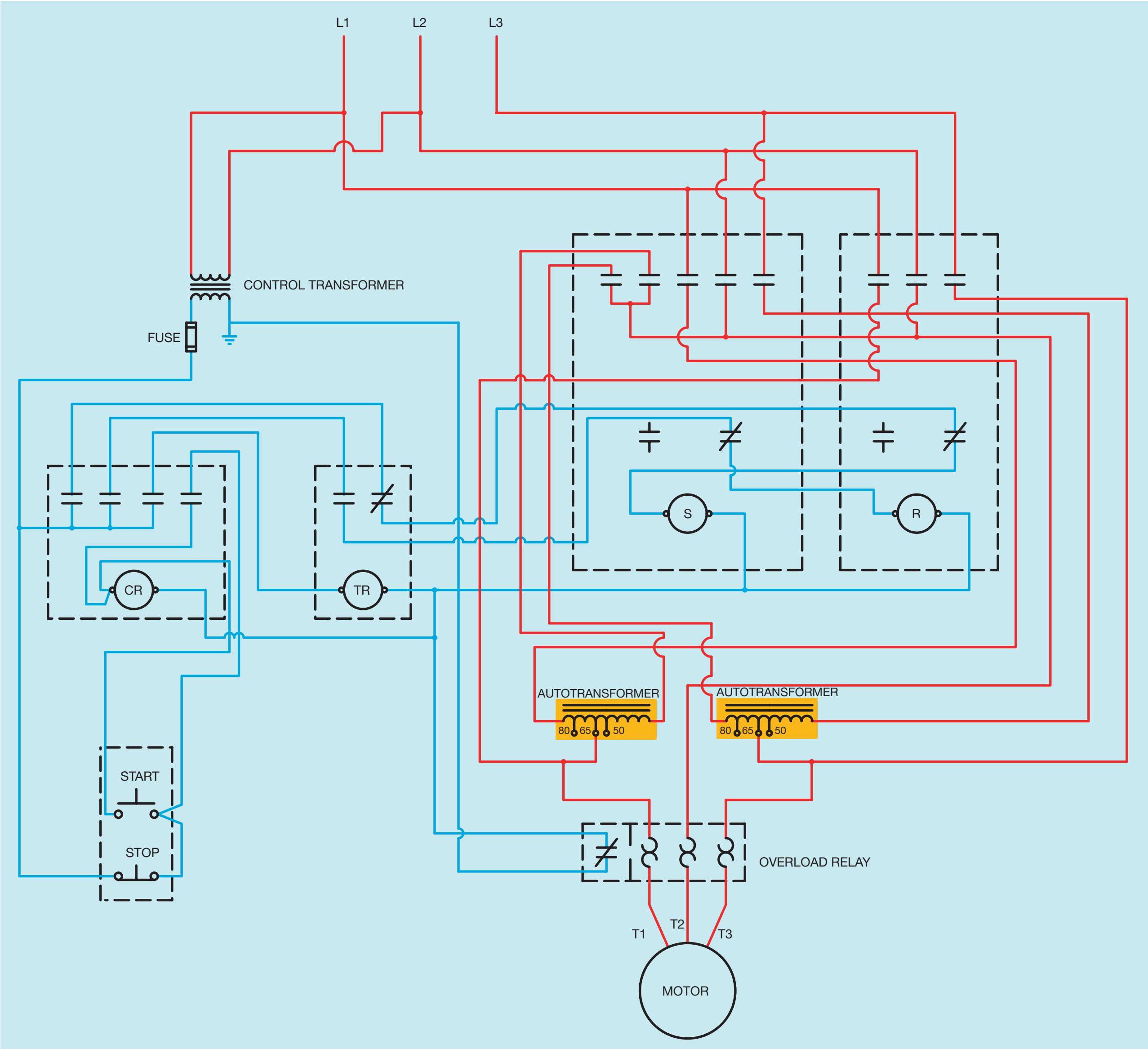


Figure 38–3 Wiring diagram for a typical autotransformer starter. (Source: Delmar/Cengage Learning.)

diagram of a timed circuit for closed transition starting is shown in Figure 38–5. When the motor reaches the run stage, it is connected directly to the power line and the autotransformer is completely disconnected from the circuit. This is done to conserve energy and extend the life of the transformers. A typical autotransformer starter is shown in Figure 38–6.

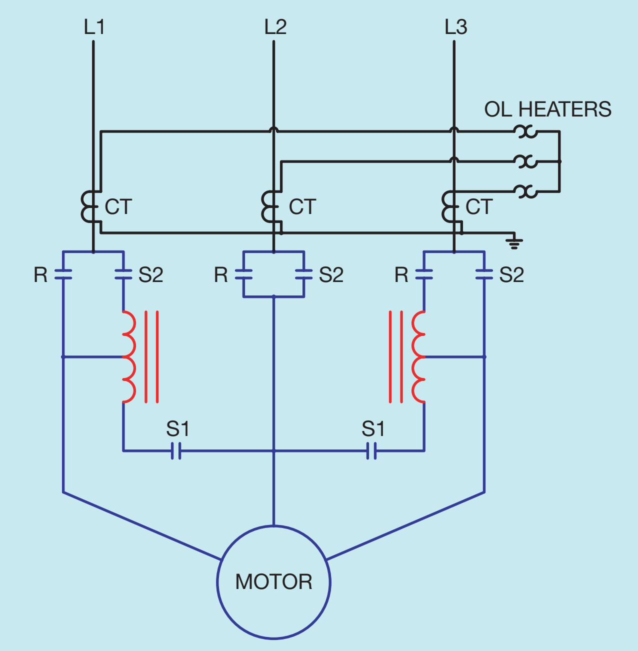


Figure 38–4 Closed transition starting uses two separate starting contactors. (Source: Delmar/Cengage Learning.)

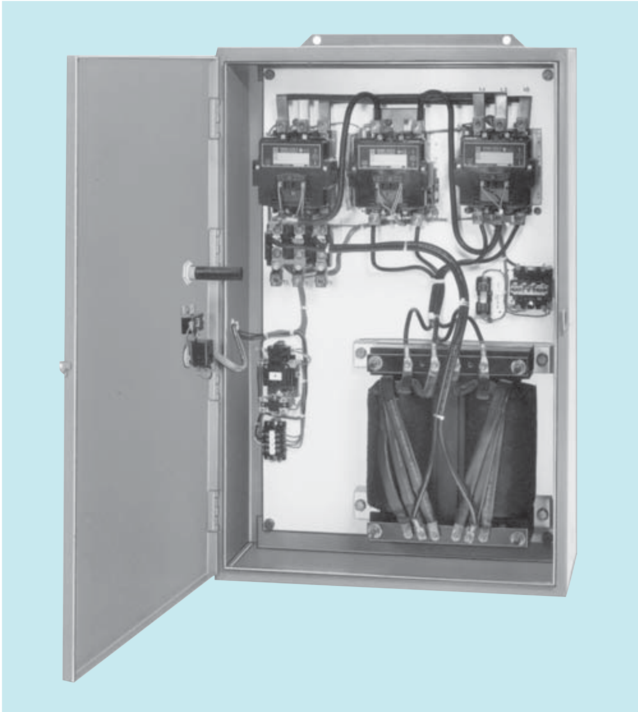


Figure 38–6 Typical autotransformer starter. (Courtesy Square D Co.)

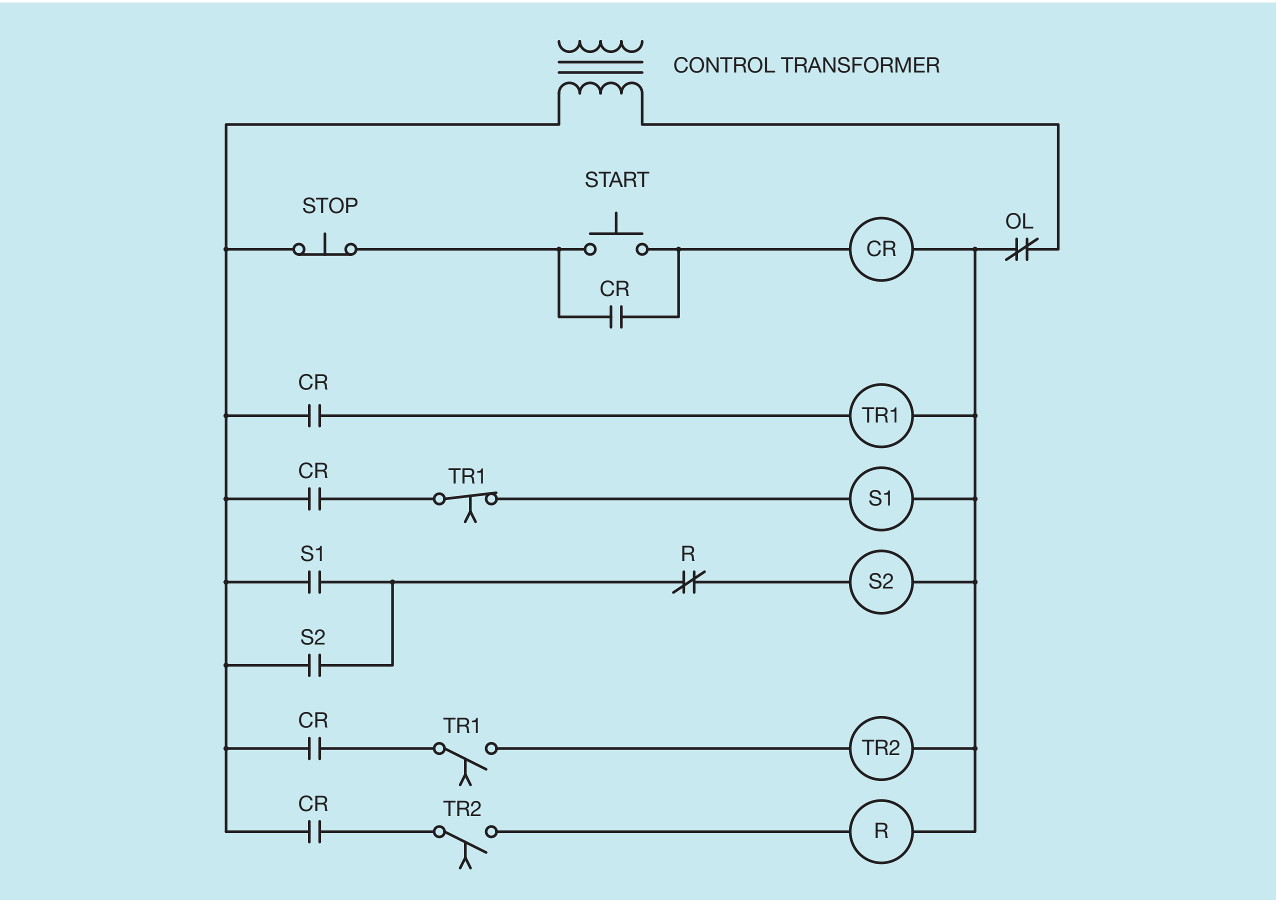


Figure 38–5 Closed transition starting circuit. (Source: Delmar/Cengage Learning.)

Review Questions

1. Why is it desirable to disconnect the autotransformer from the circuit when the motor reaches the run stage?
2. Explain the differences between open and closed transition starting.
3. Autotransformers often contain taps that permit different percentages of line voltages to be connected to the motor during starting. What are three common percentages?
4. Refer to the circuit shown in Figure 38–2. Assume that timer TR1 is set for a time delay of 10 seconds. When the Start button is pressed, the motor does not start. After a period of 10 seconds, the motor starts with full line voltage applied to it. Which of the following could cause this condition?
   a. Timer TR coil is open.
   b. CR coil is open.
   c. Contactor S coil is open.
   d. Contactor R coil is open.
5. Refer to the circuit shown in Figure 38–2. Assume that timer TR is set for a delay of 10 seconds. Assume that contactor coil R is open. Explain the operation of the circuit if the Start button is pressed.
6. Refer to the circuit shown in Figure 38–5. Assume that timer TR1 is set for a delay of 10 seconds and timer TR2 is set for a delay of 5 seconds. After the Start button is pressed, how long is the time delay before the S1 contacts open?
7. Refer to the circuit shown in Figure 38–5. Assume that timer TR1 is set for a delay of 10 seconds and timer TR2 is set for a delay of 5 seconds. From the time the Start button is pressed, how long will it take the motor to be connected to full line voltage?
8. Refer to the circuit shown in Figure 38–5. Explain the steps necessary for coil S2 to energize.
9. Refer to the circuit shown in Figure 38–5. What causes contactor coil S2 to de-energize after the motor reaches the full run stage?
10. Refer to the circuit shown in Figure 38–5. Assume that timer TR1 is set for a delay of 10 seconds and timer TR2 is set for a delay of 5 seconds. When the Start button is pressed, the motor starts. After 10 seconds, the S1 contacts open and the motor continues to accelerate but never reaches full speed. After a delay of about 30 seconds, the motor trips out on overload. Which of the following could cause this problem?
    a. TR1 coil is open.
    b. S2 coil is open.
    c. S1 coil is open.
    d. R coil is open.

CHAPTER 39
WYE-DELTA STARTING

OBJECTIVES

After studying this chapter, the student will be able to:

- Calculate starting current for a motor with its windings connected in delta.
- Calculate starting current for a motor with its windings connected in wye.
- List requirements for wye-delta starting.
- Connect a motor for wye-delta starting.
- Discuss open and closed transition starting.

Wye-delta starting is often used with large horsepower motors to reduce in-rush current during the starting period and to reduce starting torque. Wye-delta starting is accomplished by connecting the motor stator windings in wye or star during the starting period and then reconnecting them in delta during the run period. This is sometimes called *soft starting*. If the stator windings of a motor are connected in delta during the starting period, the starting current will be three times the value if the windings were connected in wye. Assume that a motor is to be connected to a 480 volt three-phase power line. Also assume that the motor windings have an impedance of 0.5 ohms when the motor is first started. If the stator windings are connected in delta (Figure 39–1), the voltage across each phase winding will be 480 volts because line voltage and phase voltage are the same in a delta connection. The amount of

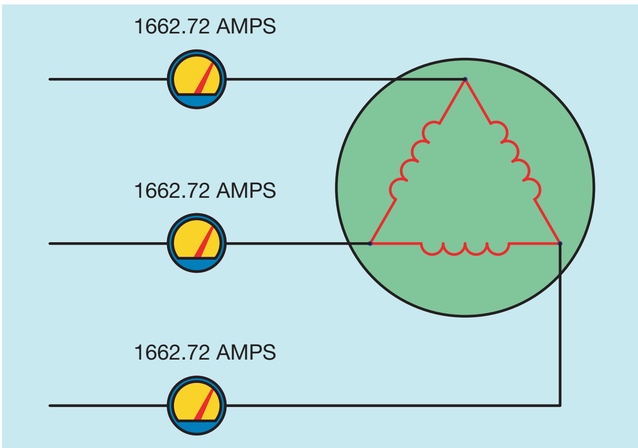


Figure 39–1 Stator windings are connected in delta during the starting period. (Source: Delmar/Cengage Learning.)

current flow in each phase winding (stator winding) can be determined with Ohm's Law.

$$I_{\text{PHASE}} = \frac{E_{\text{PHASE}}}{Z_{\text{PHASE}}}$$

$$I_{\text{PHASE}} = \frac{480}{0.5}$$

$$I_{\text{PHASE}} = 960 \text{ A}$$

In a delta connection, the line current is greater than the phase current by a value of the square root of 3($\sqrt{3}$) or 1.732. Therefore, the amount of line current will be:

$$I_{\text{LINE}} = I_{\text{PHASE}} \times 1.732$$

$$I_{\text{LINE}} = 960 \times 1.732$$

$$I_{\text{LINE}} = 1662.72 \text{ A}$$

If the stator windings are connected in wye (Figure 39–2), the voltage across each phase winding will be 277 volts, because in a wye connected load, the phase voltage is less than the line voltage by a factor of the square root of 3 or 1.732.

$$E_{\text{PHASE}} = \frac{E_{\text{LINE}}}{1.732}$$

$$E_{\text{PHASE}} = \frac{480}{1.732}$$

$$E_{\text{PHASE}} = 277 \text{ V}$$

The amount of in-rush current can be determined using Ohm's Law.

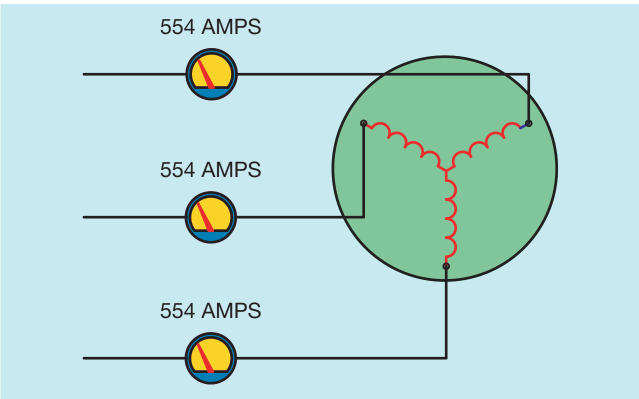


Figure 39–2 The stator windings are connected in wye during the starting period. (Source: Delmar/Cengage Learning.)

$$I_{\text{PHASE}} = \frac{E_{\text{PHASE}}}{Z_{\text{PHASE}}}$$

$$I_{\text{PHASE}} = \frac{277}{0.5}$$

$$I_{\text{PHASE}} = 554 \text{ A}$$

In a wye connected load, the line current and phase current are the same. Therefore, the starting current has been reduced from 1662.72 amperes to 554 amperes by connecting the stator windings in wye instead of delta during the starting period.

Wye-Delta Starting Requirements

There are two requirements that must be met before wye-delta starting can be used.

1. The motor must be designed for the stator windings to be connected in delta during the run period. Motors can be designed to operate with their stator windings connected in either wye or delta. The actual power requirements are the same, depending on motor horsepower. The speed of a three-phase induction motor is determined by the number of stator poles per phase and the frequency of the applied voltage. Therefore, the motor will operate at the same speed regardless of which connection is used when the motor is designed.

2. All stator windings leads must be accessible. Motors designed to operate on a single voltage commonly supply three leads labeled T1, T2, and T3 at the terminal connection box located on the motor. Dual voltage motors commonly supply nine leads labeled T1 through T9 at the terminal connection box. If a motor is designed to operate on a single voltage, six terminal leads must be provided. The numbering for these six leads is shown in Figure 39–3. Notice that the lead numbers are standardized for each of the three phases. The opposite end of terminal lead T1 is T4, the opposite end of T2 is T5, and the opposite end of T3 is T6. If the stator windings are to be connected in delta, terminals T1 and T6 are connected together, T2 and T4 are connected, and T3 and T5 are connected. If the stator windings are to be connected in wye, T4, T5, and T6 are connected together. Motors not intended for wye-delta starting would have these connections made internally and only three leads would be supplied at the terminal connection box. A motor with a delta connected stator, for example, would have T1 and T6

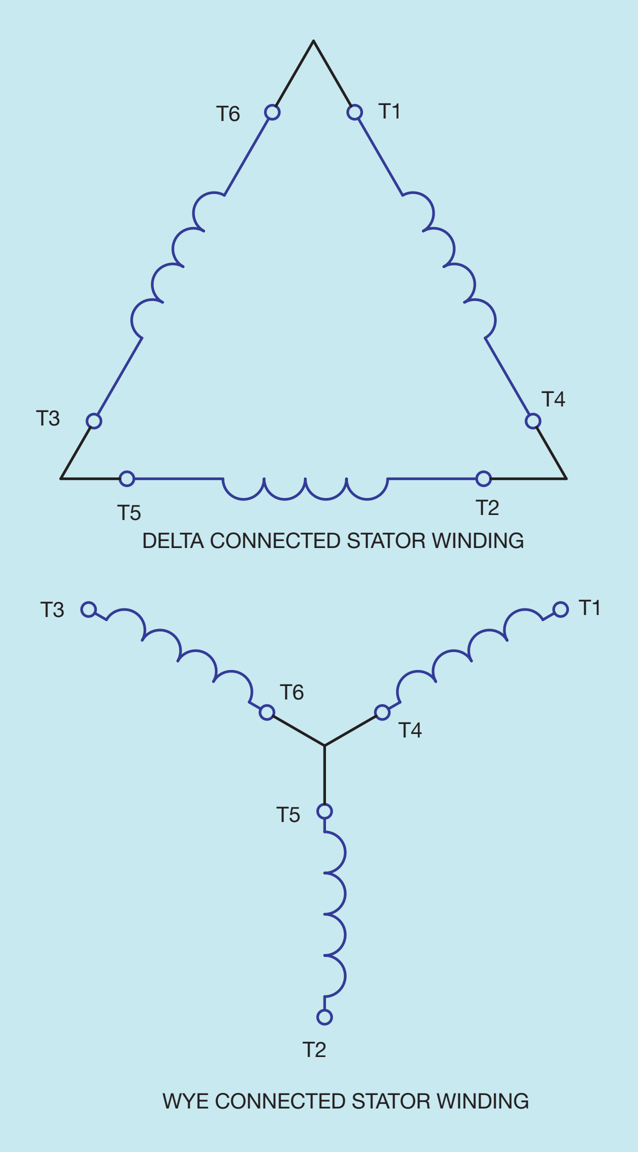


Figure 39–3 Standard lead numbers for single voltage motors. (Source: Delmar/Cengage Learning.)

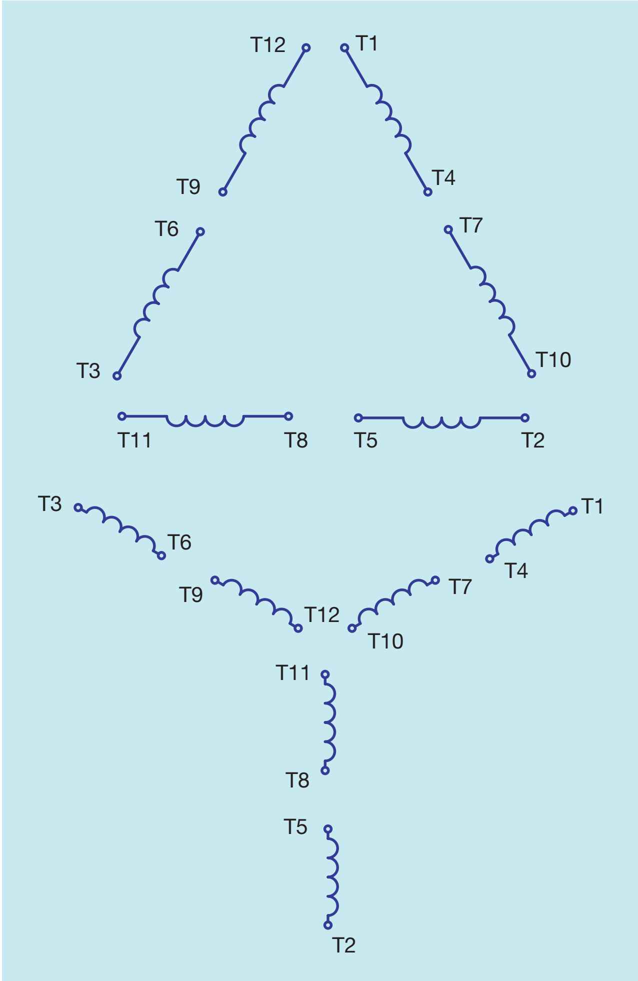


Figure 39–4 Standard lead numbers for dual voltage motors. (Source: Delmar/Cengage Learning.)

connected internally and a single lead labeled T1 would be provided for connection to the power line. Wye connected motors have T4, T5, and T6 connected internally.

Dual Voltage Connections

Motors that are intended to operate on two voltages, such as 240 or 480 volts, contain two separate windings for each phase (Figure 39–4). Notice that dual voltage motors actually contain 12 T leads. Dual voltage motors not intended for wye-delta connection will have certain terminals tied internally, as shown in Figure 39–5. Although all three-phase dual voltage motors actually contain 12 T leads, only terminal leads T1 through T9 are brought out to the terminal connection box for motors not intended for wye-delta starting.

If the motor is to be operated on the higher voltage, the stator leads will be connected in series, as shown in Figure 39–6. If the motor is to be connected for operation on the lower voltage, the stator windings will be connected in parallel as shown in Figure 39–7.

Although dual voltage motors designed for wye-delta starting will supply all 12 T leads at the terminal connection box, it will be necessary to make the proper connections for high or low voltage. The connection diagrams for dual voltage motors with 12 T leads are shown in Figure 39–8. Note that the diagrams do not show connection to power leads. These connections are made as part of the control circuit.

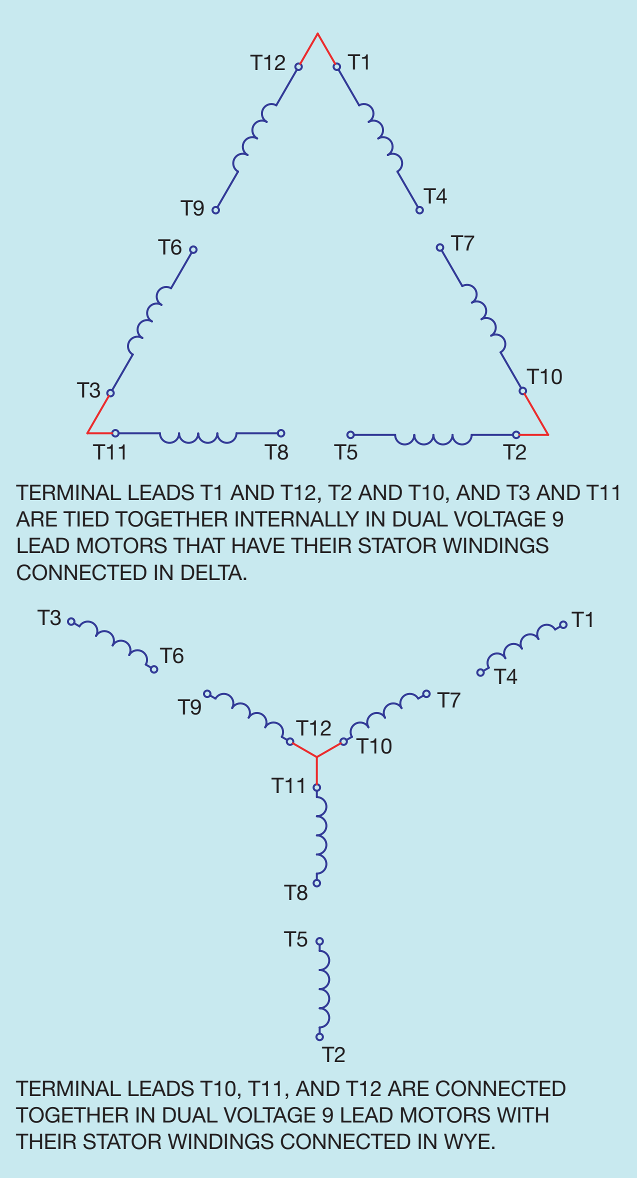


Figure 39–5 Nine lead dual voltage motors have some stator windings connected together internally. (Source: Delmar/Cengage Learning.)

Connecting the Stator Leads

Wye-delta starting is accomplished by connecting the stator windings in wye during the starting period and then reconnecting them in delta for normal run operation. For simplicity, it will be assumed that the motor illustrated is designed for single voltage operation and has leads T1 through T6 brought out at the terminal connection box. If a dual voltage motor is to be connected, make the proper stator winding connections for high or low voltage operation and then change T4, T5, and T6 to T10, T11, and T12 in the following connections. A basic control circuit for wye-delta starting is shown in Figure 39–9. This circuit employs time delay to determine when the windings will change from wye to delta. Starting circuits that sense motor speed or motor current to determine when to change the stator windings from wye to delta are also common.

When the Start button is pressed, control relay CR energizes, causing all CR contacts to close. This immediately energizes contactors 1M and S. The motor stator windings are now connected in wye, as shown in Figure 39–10. The 1M load contacts connect power to the motor, and the S contacts form a wye connection for the stator windings.

The 1M auxiliary contact supplies power to the coil of timer TR. After a preset time delay, the two TR timed contacts change position. The normally closed contact opens and disconnects coil S, causing the S load contacts to open. The normally open TR contact closes and energizes contactor coil 2M. The motor stator windings are now connected in delta, Figure 39–11. Note that the 2M load contacts are used to make the delta connection. A diagram showing the connection of all load contacts is shown in Figure 39–12.

The most critical part of connecting a wye-delta starter is making the actual load connections to the motor. An improper connection generally results in the motor stopping and reversing direction when transition is made from wye to delta. It is recommended that the circuit and components be numbered to help avoid mistakes in connection (Figure 39–13).

Closed Transition Starting

The control circuit discussed so far uses open transition starting. This means that the motor is disconnected from the power line during the transition from wye to delta. This may be objectionable in some applications if the transition causes spikes on the power line when the motor changes from wye to delta. Another method that does not disconnect the motor from the power line is called closed transition starting. Closed transition starting is accomplished by adding another three pole contactor and resistors to the circuit (Figure 39–14). The added contactor, designated as 1A, energizes momentarily to connect resistors between the power line and motor when the transition is made from wye to delta. Also note that an on-delay timer (TR2) with a

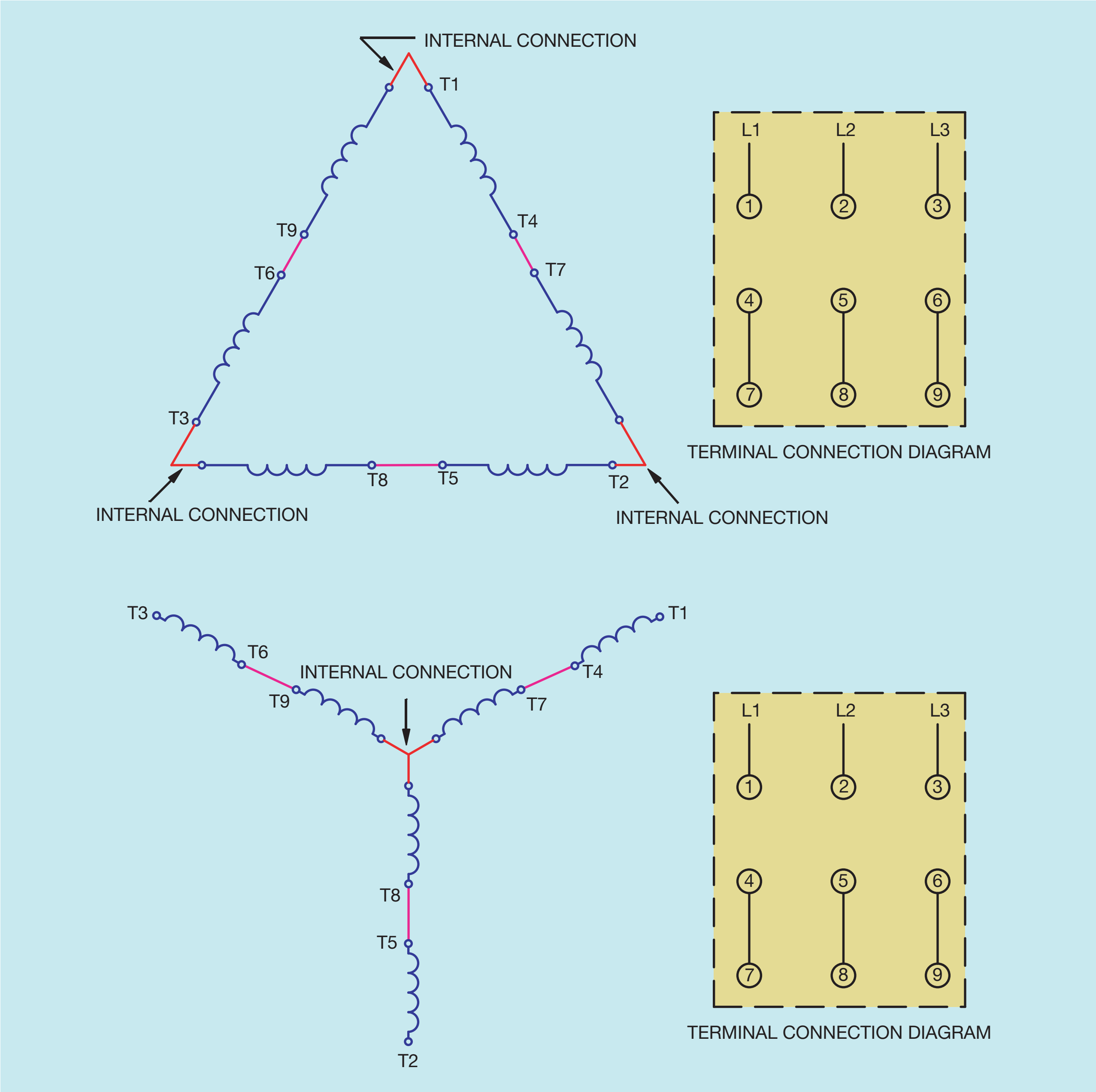


Figure 39–6 High voltage connection for nine lead motors. (Source: Delmar/Cengage Learning.)

delay of 1 second has been added to the control circuit. The purpose of this timer is to prevent a contact race between contactors S and 2M when power is first applied to the circuit. Without timer TR2, it would be possible for contactor 2M to energize before contactor S. This would prevent the motor from being connected in wye. The motor would start with the stator windings connected in delta.

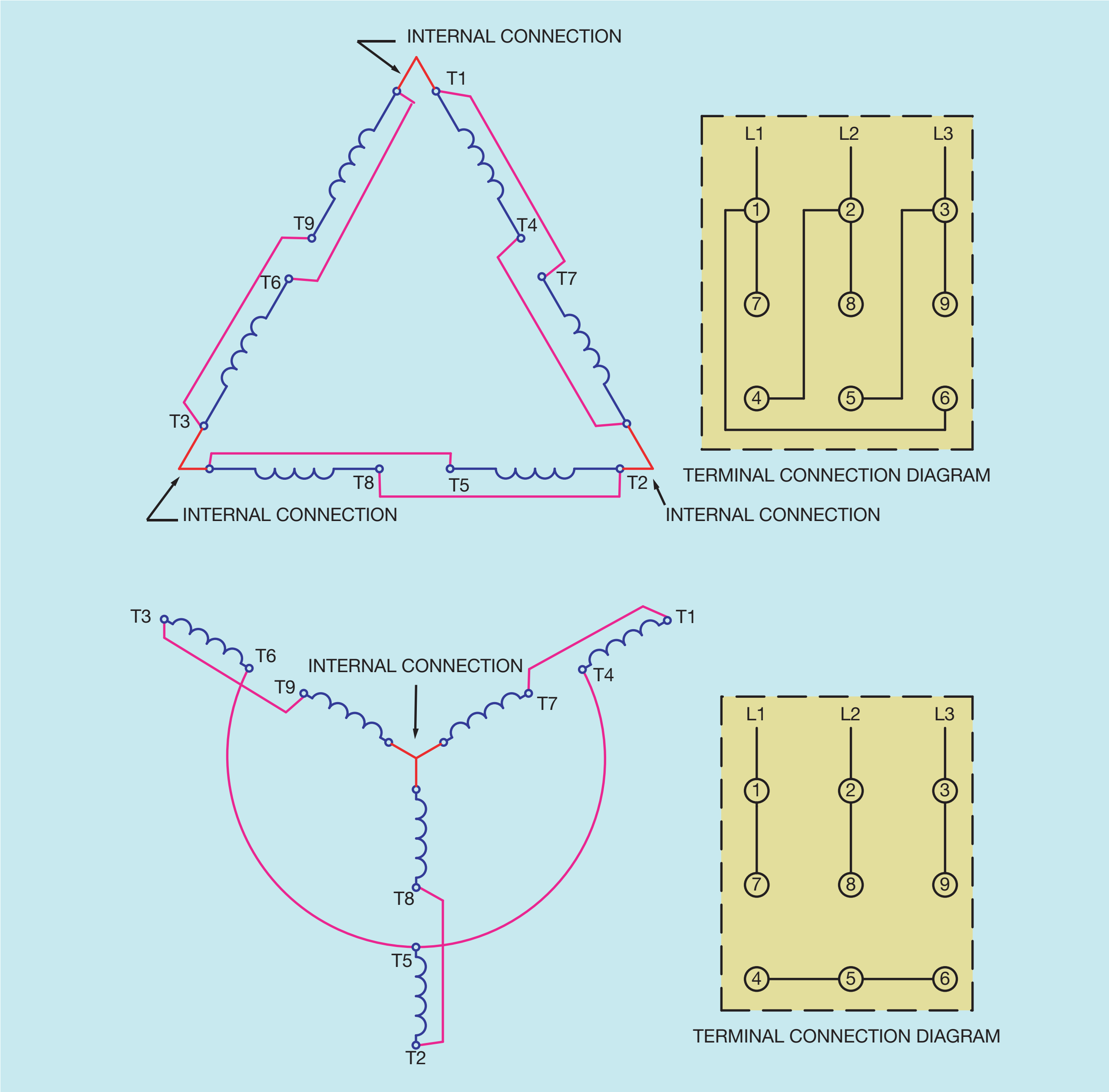


Figure 39–7 Low voltage connection for nine lead motors. (Source: Delmar/Cengage Learning.)

Overload Setting

Notice in Figure 39–12 that the overload heaters are connected in the phase windings of the delta, not the line. For this reason, the overload heater rating must be reduced from the full load current rating on the motor nameplate. In a delta connection, the phase current will be less than the line current by a factor of the square root of 3, or 1.732. Assume, for example, that the nameplate indicates a full load current of 165 amperes.

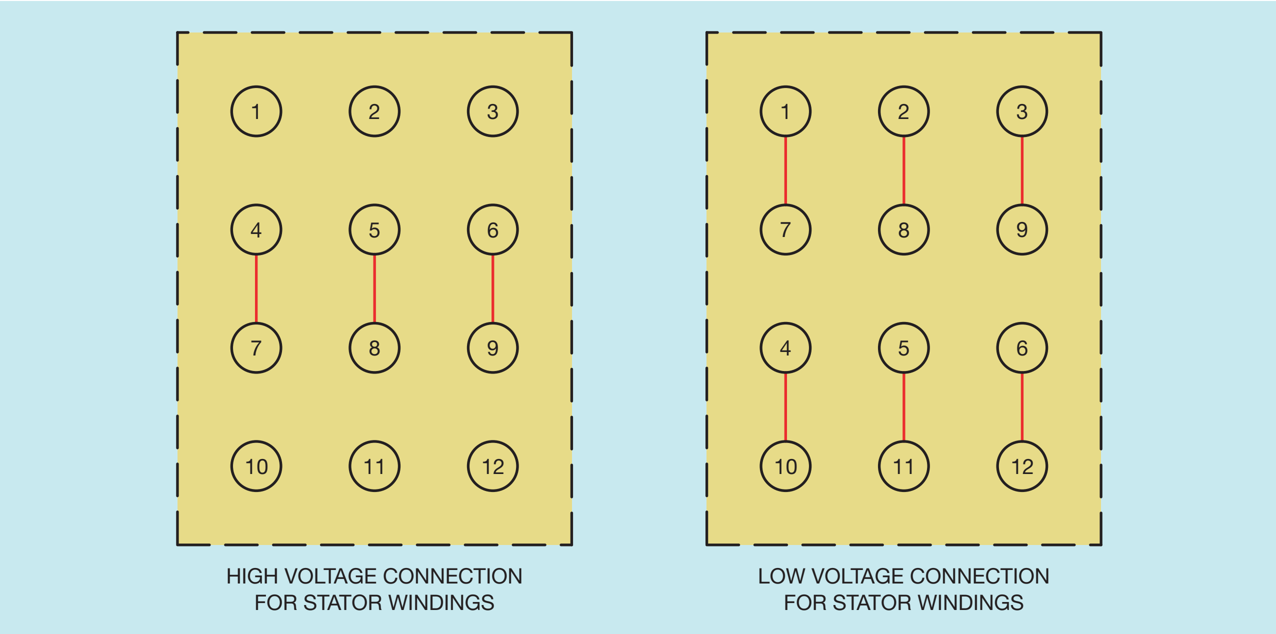


Figure 39–8 Stator winding connections for dual voltage twelve lead motors. (Source: Delmar/Cengage Learning.)

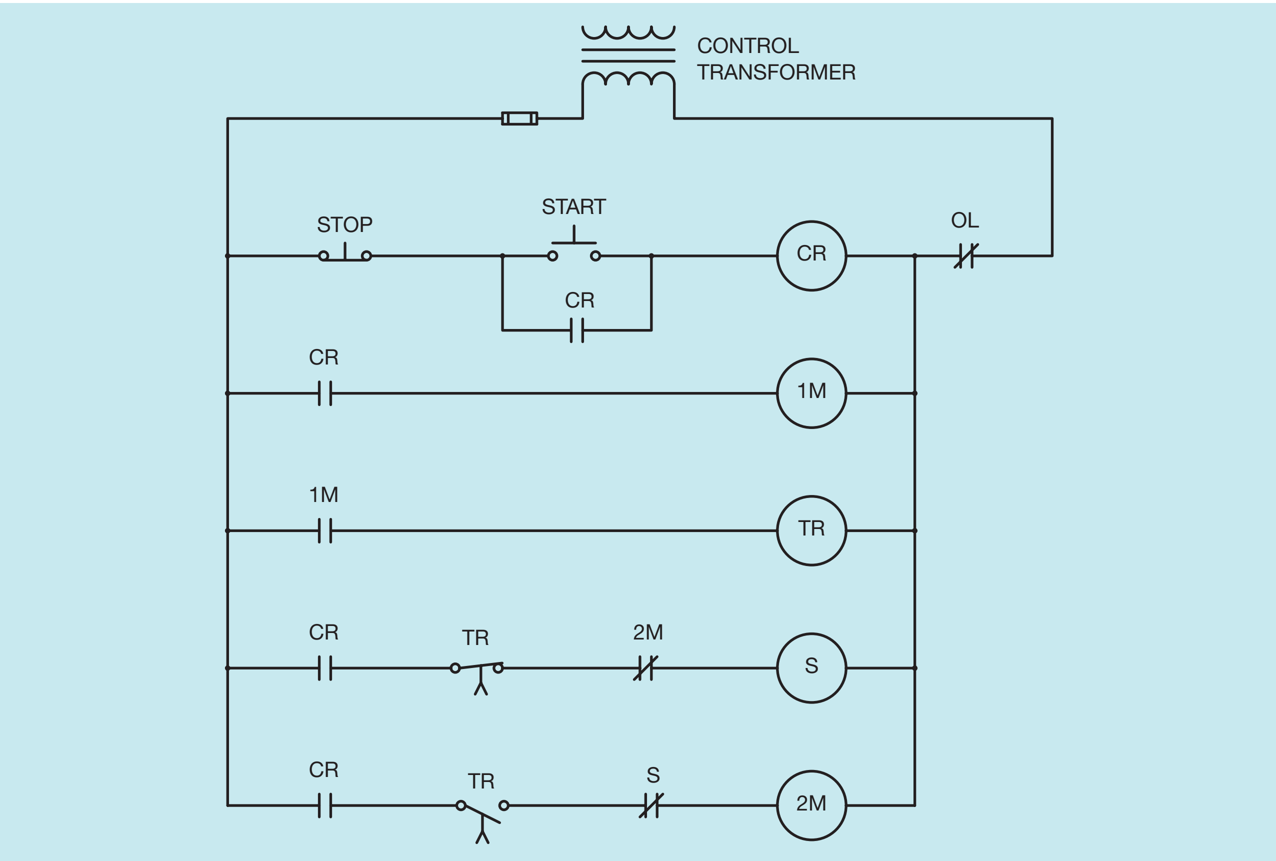


Figure 39–9 Basic control circuit for a wye-delta starter using time delay. (Source: Delmar/Cengage Learning.)

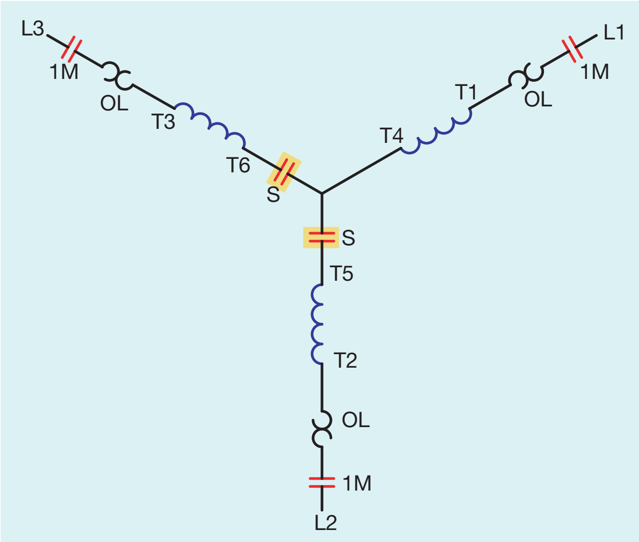


Figure 39–10 The stator windings are connected in wye for starting. (Source: Delmar/Cengage Learning.)

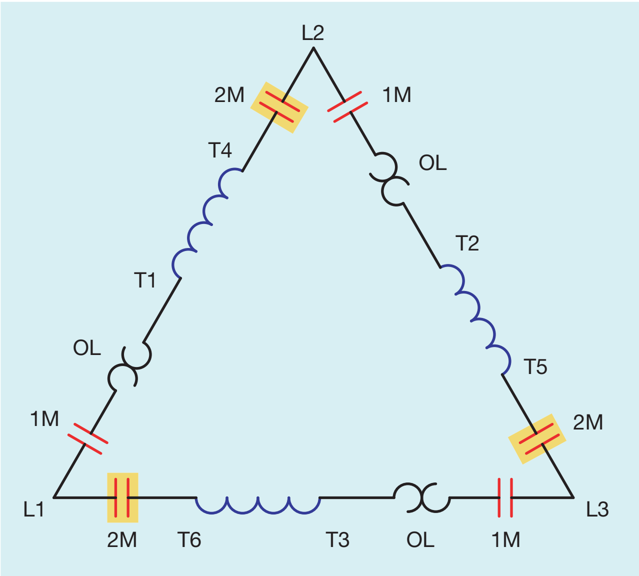


Figure 39–11 The stator windings are connected in delta for running. (Source: Delmar/Cengage Learning.)

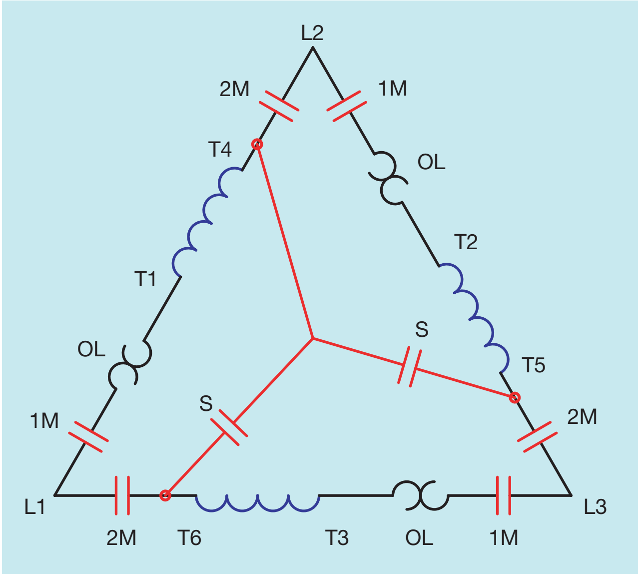


Figure 39–12 Stator winding with all load contacts for wye-delta starting. (Source: Delmar/Cengage Learning.)

If the motor stator windings are connected in delta, the current flow in each phase would be 95.3 amperes (165/1.732). The overload heater size should be based on a current of 95.3 amperes, not 165 amperes.

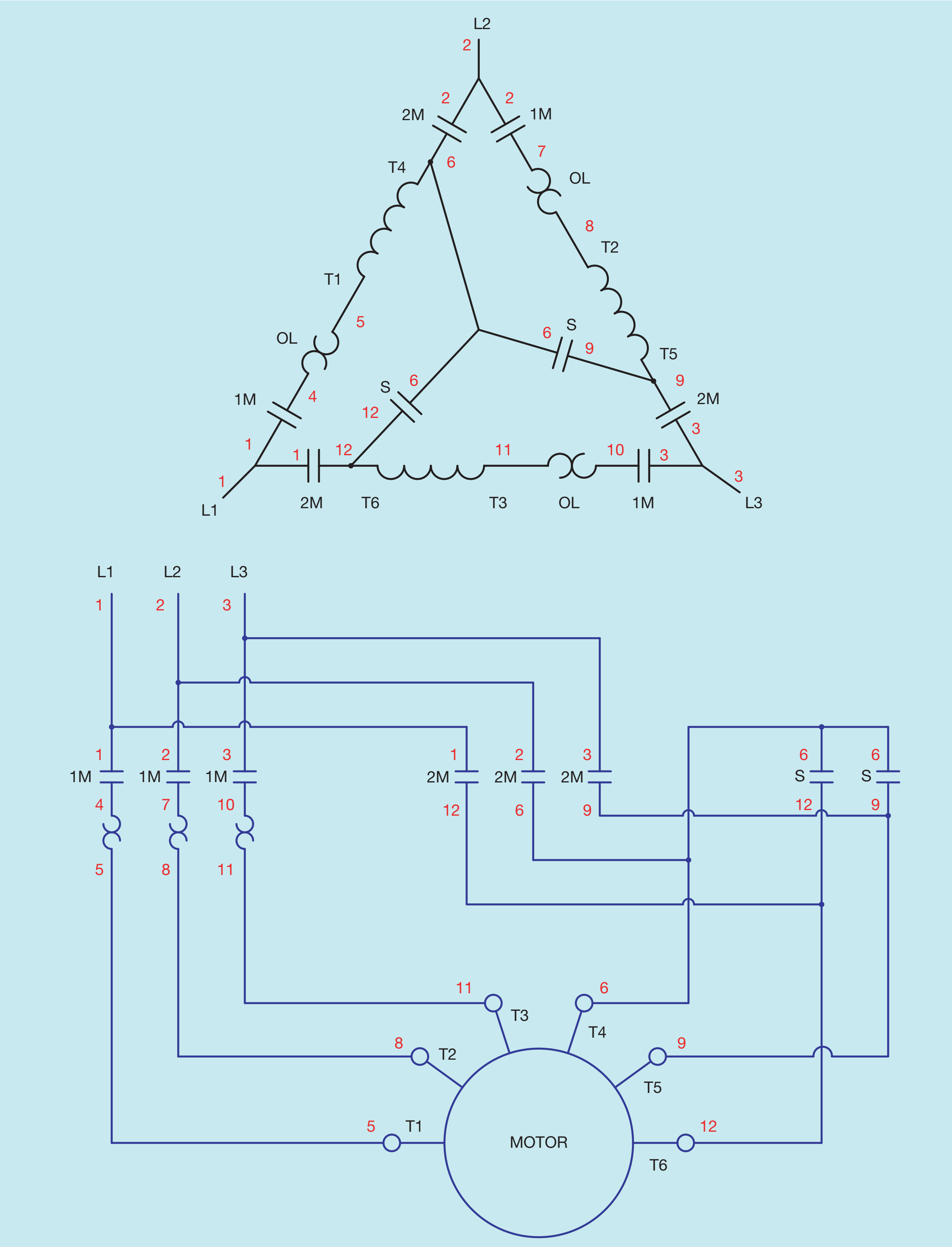


Figure 39–13 Load circuit connections for wye-delta starting. (Source: Delmar/Cengage Learning.)

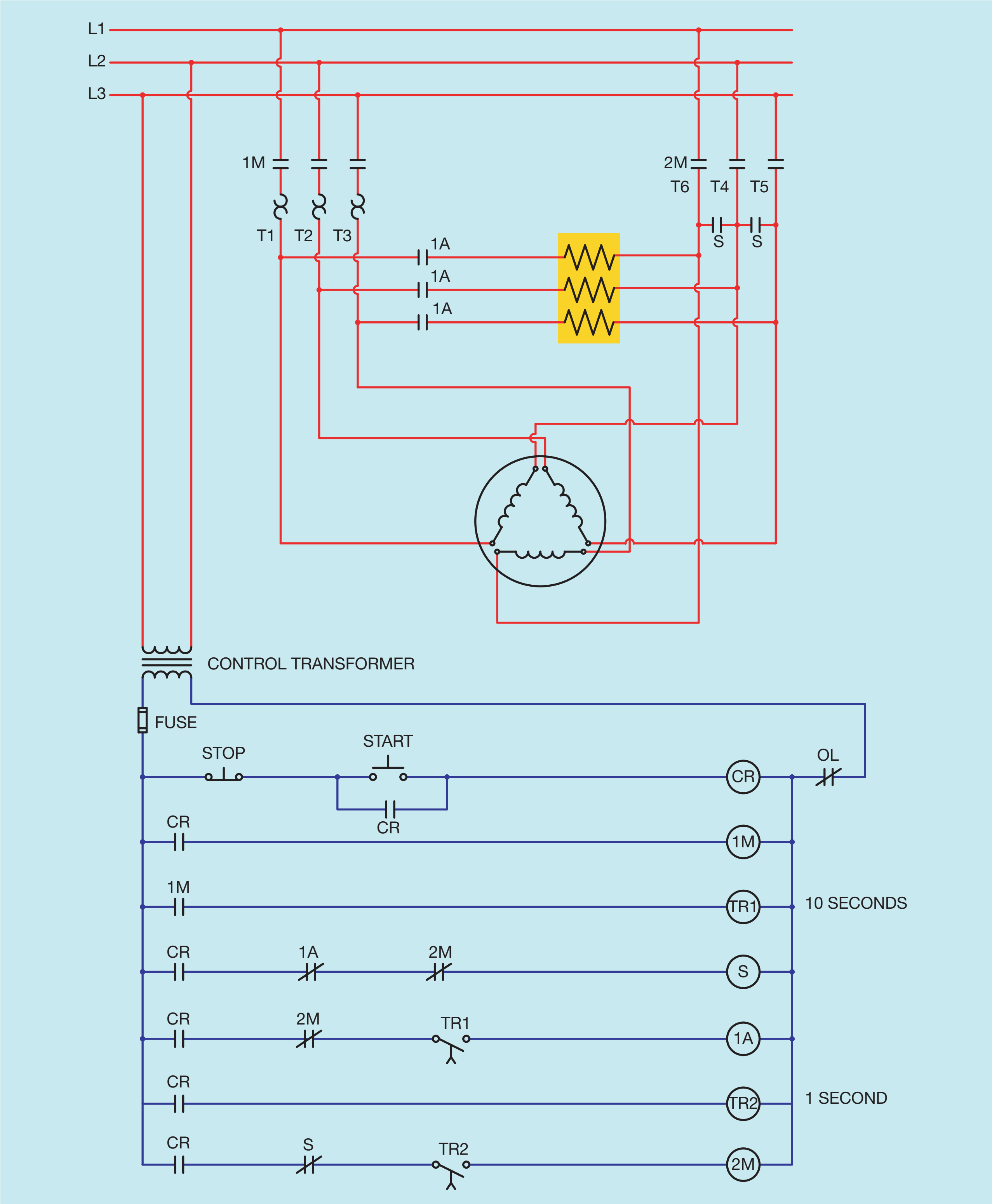


Figure 39–14 Basic schematic diagram Sizes 1, 2, 3, 4, and 5 wye-delta starters with closed transition starting. (Source: Delmar/Cengage Learning.)

Review Questions

1. Name two requirements that must be met before a motor can be used for wye-delta starting.
2. The stator windings of a 2300 volt motor have an impedance of 6 ohms when the motor is first started. What would be the in-rush current if the stator windings were connected in delta?
3. What would be the amount of in-rush current if the motor described in question #2 had the stator windings connected in wye?
4. Refer to the circuit shown in Figure 39–9. Assume that timer TR is set for a delay of 10 seconds. When the Start button is pressed, the motor starts with its windings connected in wye. After a period of one minute, the motor has not changed from wye to delta. Which of the following could cause this condition?
   a. TR timer coil is open.
   b. S contactor coil is open.
   c. 1M starter coil is open.
   d. The control transformer fuse is blown.
5. Refer to the circuit shown in Figure 39–9. Assume that timer TR is set for a delay of 10 seconds. When the Start button is pressed, the motor does not start. After a delay of 10 seconds, the motor suddenly starts with its stator windings connected in delta. Which of the following could cause this problem?
   a. TR timer coil is open.
   b. 2M contactor coil is open.
   c. S contactor coil is open.
   d. 1M starter coil is open.
6. Refer to the circuit shown in Figure 39–9. What is the purpose of the normally closed 2M and S contacts in the schematic?
7. The motor nameplate of a wye-delta starter motor has a full load current of 287 amperes. What current rating should be used to determine the proper overload heater size?
8. Refer to the circuit shown in Figure 39–14. When the motor changes from wye to delta, what causes contactor coil S to de-energize and open S contacts?
9. Refer to the circuit shown in Figure 39–14. What is the purpose of timer TR2?
10. Refer to the circuit shown in Figure 39–14. When the Start button is pressed, the control transformer fuse blows immediately. Which of the following could **not** cause this problem?
    a. Control Relay coil CR is shorted.
    b. Starter coil 1M is shorted.
    c. Contactor coil S is shorted.
    d. Contactor coil 2M is shorted.

CHAPTER 40

PART WINDING STARTERS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the construction of a motor designed to be used for part winding starting.
- Discuss three-step starting for part winding motors.
- Draw a control circuit for a part winding starter.
- Connect a motor for part winding starting.

Part winding starting is another method of reducing the starting current of squirrel cage induction motors. Motors designed to be used for part winding starting contain two separate stator windings (Figure 40–1). The stator windings may be wye or delta connected, depending on the manufacturer. These two windings are designed to the connected in parallel with each other. When the motor is started, only one of the windings is connected to the power line. Since only half the motor winding is used during starting, this method of starting is called *part winding* starting. Part winding starting reduces the normal locked rotor current to approximately 66% of the value if both windings are connected during starting and the torque is reduced to approximately 50%. It should be noted that neither of the two windings is individually capable of withstanding the starting current for more than a few seconds. The first winding will overheat rapidly if the second winding is not connected within a very short period of time. As a general rule, a time delay of two to three seconds is common before the second winding is connected in parallel with the first.

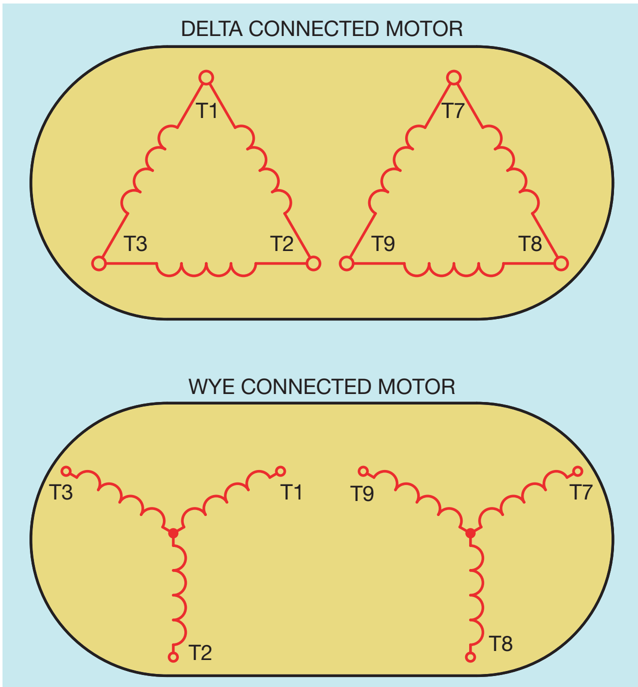


Figure 40–1 Motors designed for part winding starting contain two stator windings intended to be connected in parallel with each other. (Source: Delmar/Cengage Learning.)

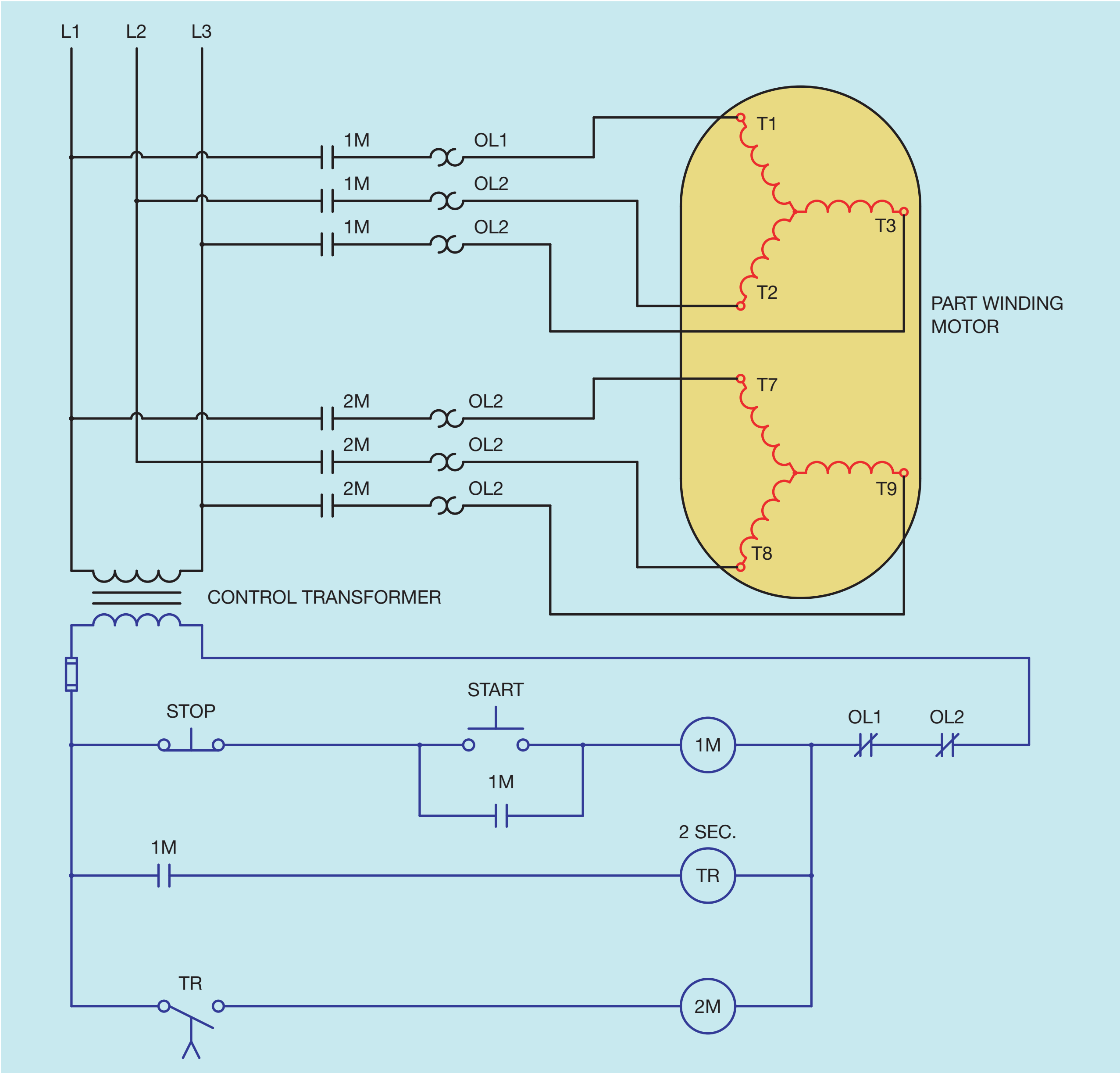


Figure 40–2 Typical part winding starter. (Source: Delmar/Cengage Learning.)

Part winding starting is accomplished by bringing out both sets of motor leads so that external connection is possible (Figure 40–2). When the Start button is pressed, motor starter 1M energizes and connects the first motor windings to the line. The normally open 1M auxiliary contact closes and starts on-delay timer TR. After a 2 second time delay, timed contact TR closes and energizes motor starter 2M. This causes the 2M load contacts to close and connect the second stator winding to the power line.

Overload Protection

Note that two motor starters are used in the circuit, and each contains an overload relay. Each winding is individually protected by thermal overload heaters. The heaters for each overload relay should be sized at one half the motor nameplate current. The contacts of both overload relays are connected in series so that an overload on either relay will disconnect both motor windings. It should also be noted that since each starter

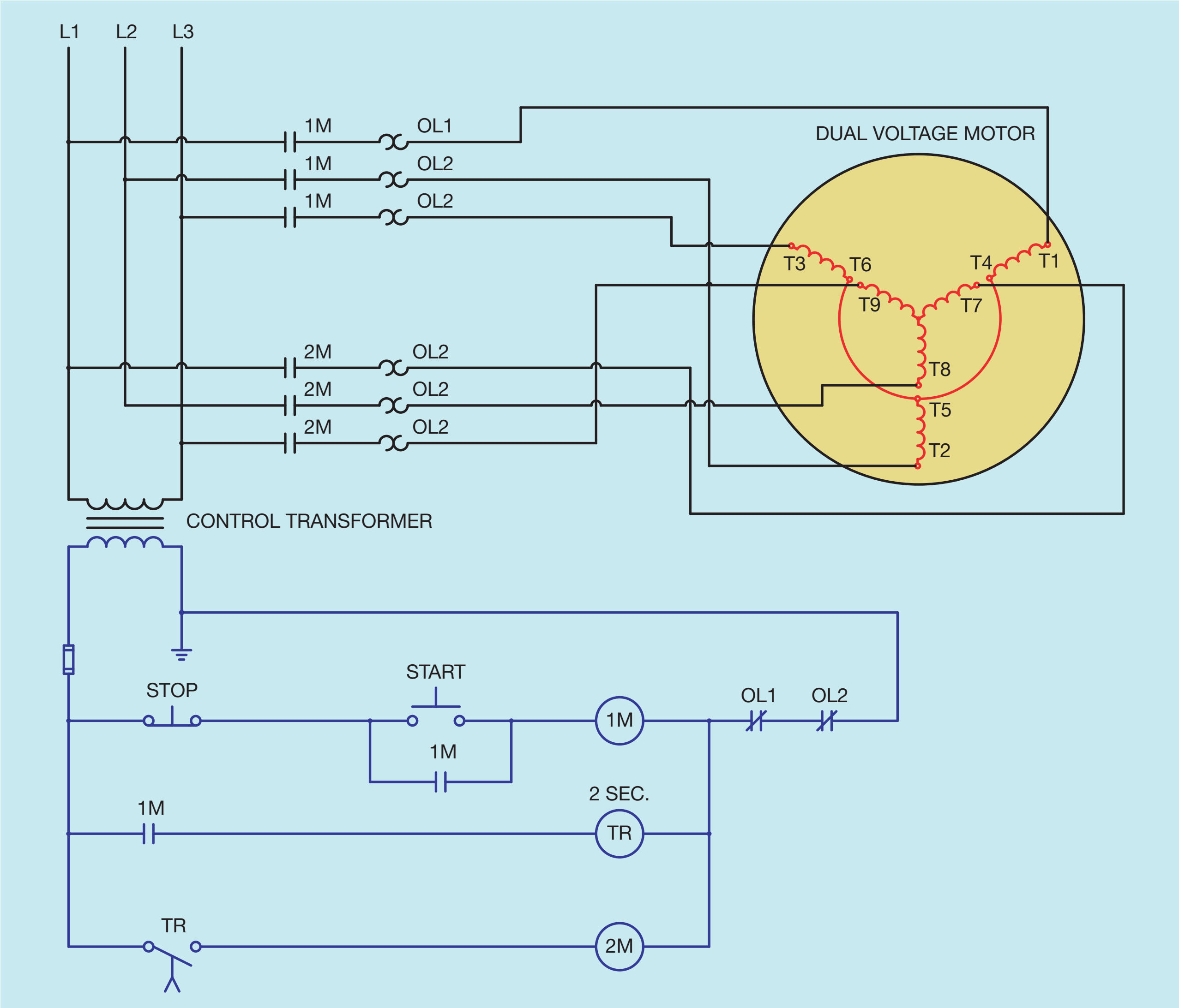


Figure 40–3 Dual voltage motor used for part winding starting. (Source: Delmar/Cengage Learning.)

carries only half the full load current of the motor, the starter size can generally be reduced from what would be required for a single starter. Another advantage of part winding starters is that they provide closed transition starting, since the motor is never disconnected from the power line during the starting time.

Dual Voltage Motors

Some, but not all, dual voltage motors may be used for part winding starting. The manufacturer should be contacted before an attempt is made to use a dual voltage motor in this application. Delta connected dual voltage motors are not acceptable for part winding starting. When dual voltage motors are used, the motor must be operated on the low voltage setting of the motor. A 240/480 volt motor, for example, could only be operated on 240 volts. A dual voltage motor connection is shown in Figure 40–3. Motor terminal leads T4, T5, and T6 are connected together forming a separate wye connection for the motor.

Motor Applications

Part winding starting is typically used for motors that supply the moving force for centrifugal pumps, fans, and blowers. They are often found in air conditioning and refrigeration applications. They are not generally employed to start heavy inertia loads that require an excessive amount of starting time.

Three-Step Starting

The thermal capacity of the stator windings greatly limits the length of starting time for a part winding motor. To help overcome this problem, it is possible to provide a third step in the starting process and further limit starting current. This is accomplished by connecting resistance in series with the stator winding during the starting period (Figure 40–4). The resistors are generally sized to provide about 50% of the line voltage to the stator winding when the motor is first started. This provides approximately three equal increments of starting for the motor. In the circuit shown in Figure 40–4, when the Start button is pressed, motor starter 1M energizes and connects one of the stator windings to the power line through the series resistors. After a delay of 2 seconds, TR1 timed contact closes and energizes contactor S. The S load contacts close and shunt the resistors out of the line. One stator winding is now connected to full line voltage.

After another 2 second delay, motor starter 2M energizes and connects the second stator winding to the power line. The motor now has both stator windings connected to full voltage.

Automatic Shut-Down

Part winding motors are very sensitive to the length of time that one winding can be connected before thermal damage occurs. If the second winding is not connected to the power line within a short period of time, the first winding can be severely damaged. To help prevent damaging the first winding, some circuits contain a timer that disconnects power to the motor if the second winding is not energized within a predetermined time. This timer is often called a *watchdog timer* because its function is to watch for proper operation of the circuit each time the motor is started. A circuit with a watchdog timer is shown in Figure 40–5. Watchdog timers are often set for twice the amount of time necessary for the second winding to energize. When the Start button is pushed, the watchdog timer begins its count. If the circuit operates properly, the normally closed 2M auxiliary contact will disconnect the timer before it times out and de-energizes control relay CR.

Review Questions

1. A dual voltage 240/480 volt motor is to be used for part winding starting. Which voltage must be used and why?
2. Are the stator windings of a motor designed for part winding starting connected in parallel or series?
3. The nameplate of a part winding motor indicates a full load current rating of 72 amperes. What current rating should be used when sizing the overload heaters?
4. What is a watchdog timer?
5. Refer to the circuit shown in Figure 40–5. When the Start button is pressed, the motor does not start. Which of the following could **not** cause this problem?
   a. The control transformer fuse is blown.
   b. Overload contact #2 is open.
   c. TR1 timer coil is open.
   d. Control relay coil CR is open.
6. Refer to the circuit shown in Figure 40–5. When the Start button is pressed, the motor does not start. After a 4 second time delay, control relay CR de-energizes. Which of the following could cause this problem?
   a. TR1 timer coil is open.
   b. 1M starter coil is open.
   c. CR coil is open.
   d. 2M starter coil is open.

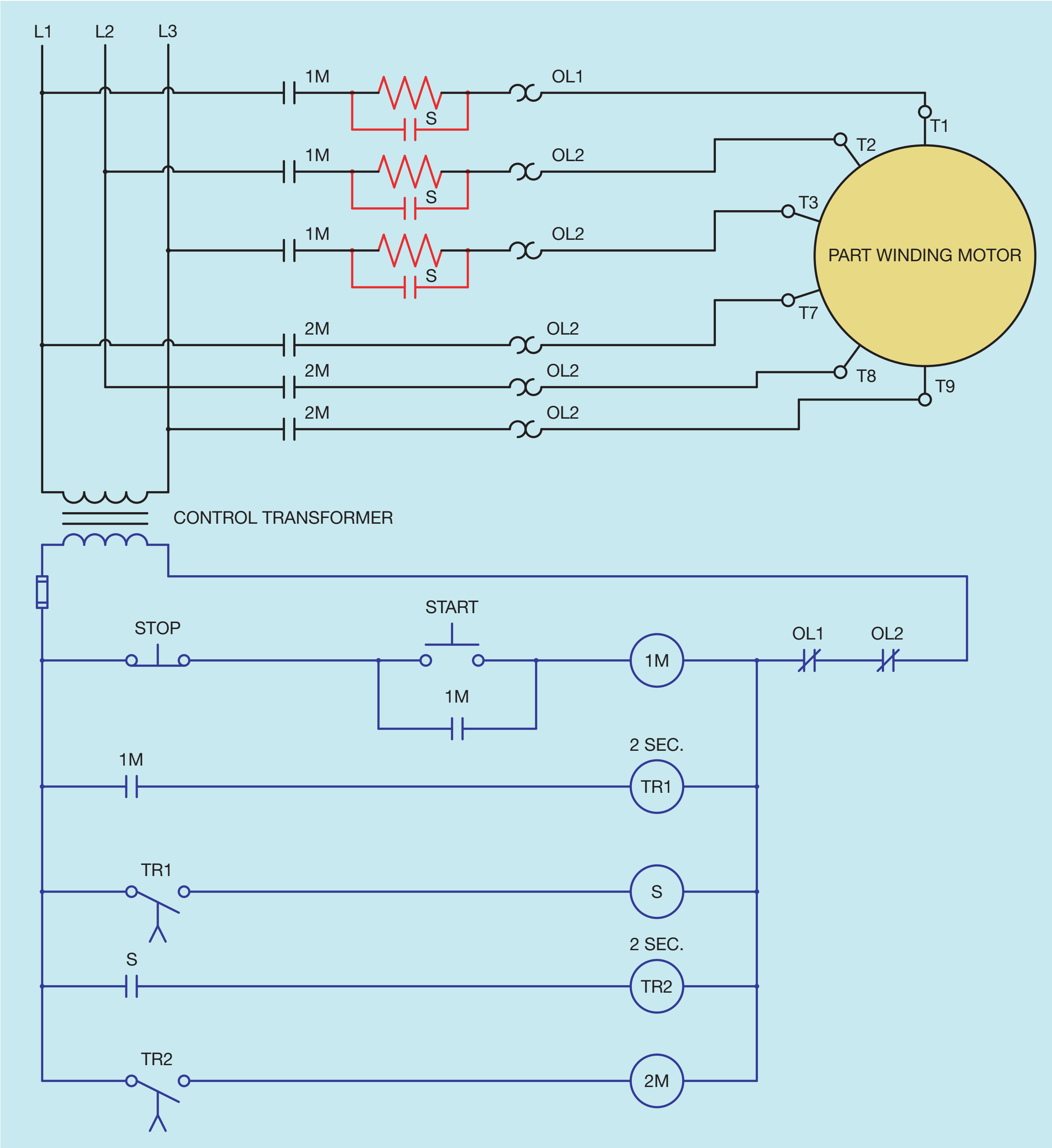


Figure 40–4 Three-step starting for a part winding motor. (Source: Delmar/Cengage Learning.)

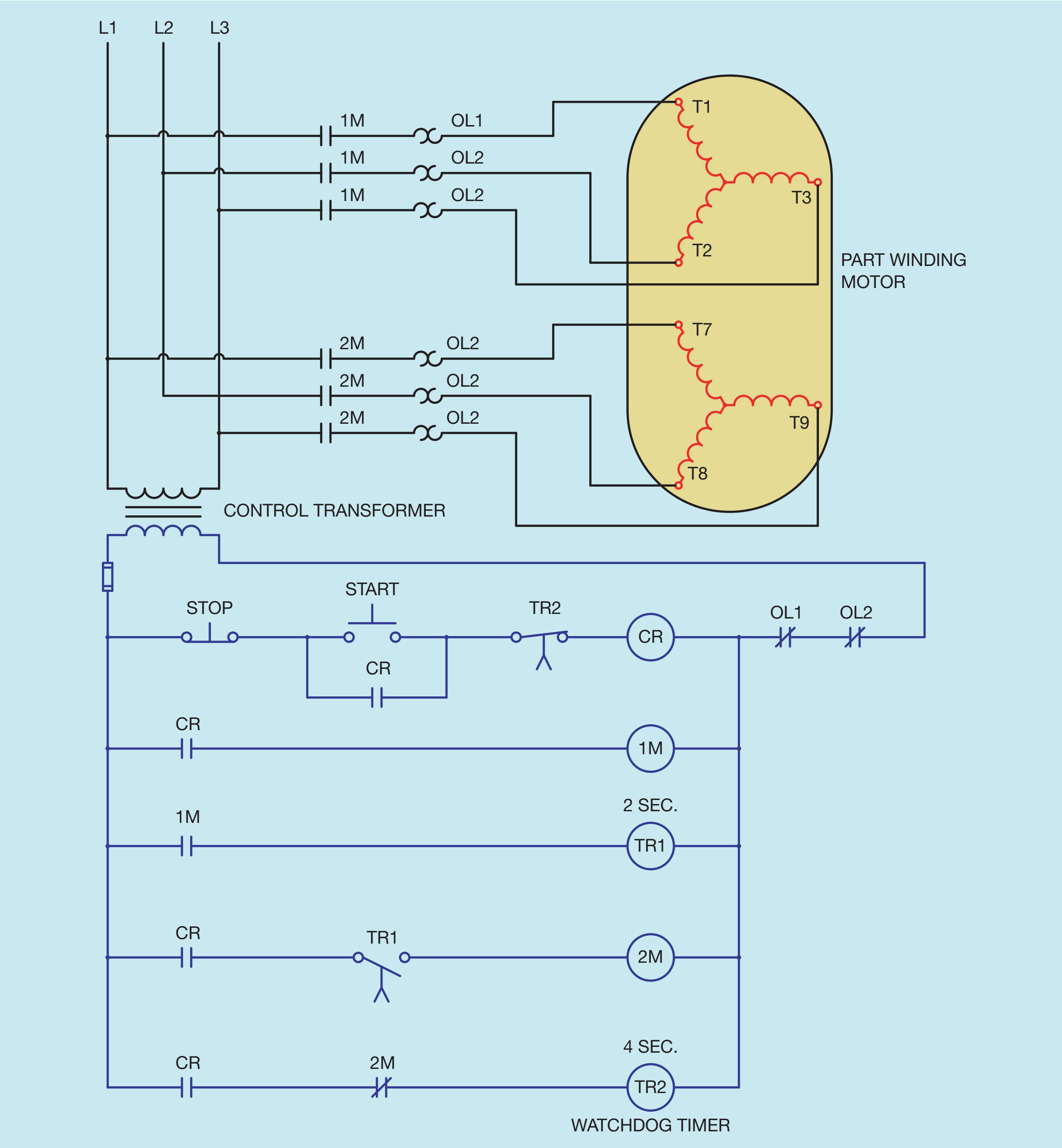


Figure 40–5 Watchdog timer disconnects the motor is the second winding does not energize. (Source: Delmar/Cengage Learning.)

CHAPTER 41
CONSEQUENT POLE MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Identify terminal markings for two-speed, one-winding consequent pole motors.
- Discuss how speed of a consequent pole motor is changed.
- Connect a two-speed, one-winding consequent pole motor.
- Discuss the construction of three-speed consequent pole motors.
- Discuss different types of four-speed consequent pole motors.

Consequent pole motors have the ability to change speed by changing the number of stator poles. There are two factors that determine the synchronous speed of an AC motor:

1. Frequency of the applied voltage
2. Number of stator poles per phase

A chart showing the synchronous speed of 60 and 50 hertz motors with different numbers of poles is shown in Figure 41–1. A three-phase two-pole motor contains six actual poles. The magnetic field will make one revolution of a two-pole motor each complete cycle. If the stator of a motor were to be cut and laid out flat, the magnetic field would traverse the entire length in one cycle (Figure 41–2A). If the number of stator

STATOR POLES PER PHASE	SPEED IN RPM	
	60 HZ.	50 HZ.
2	3600	3000
4	1800	1500
6	1200	1000
8	900	750

Figure 41–1 Synchronous speed is determined by the frequency and number of stator poles per phase. (Source: Delmar/Cengage Learning.)

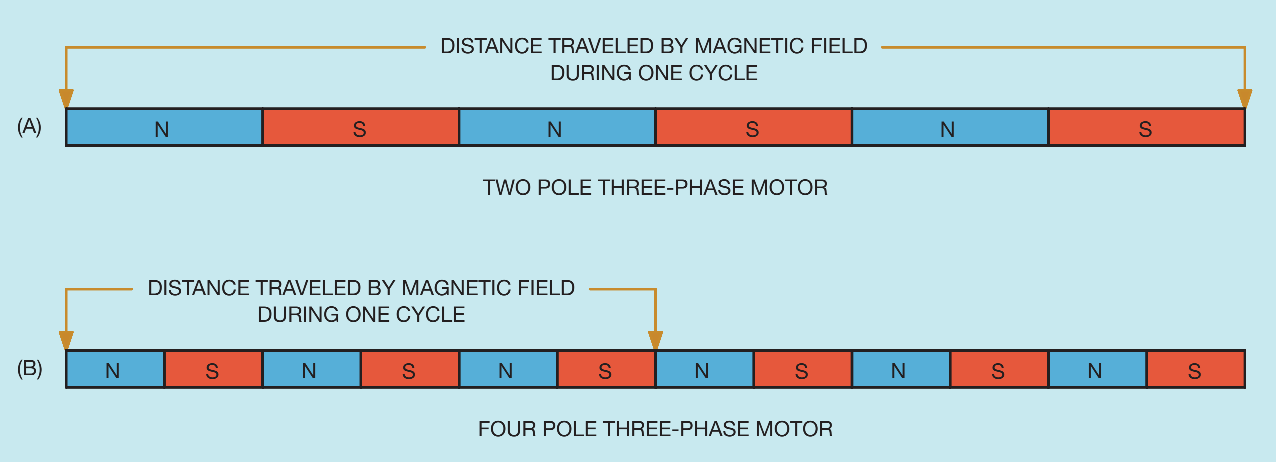


Figure 41–2 The magnetic field will travel through the same number of poles during each complete cycle. (Source: Delmar/Cengage Learning.)

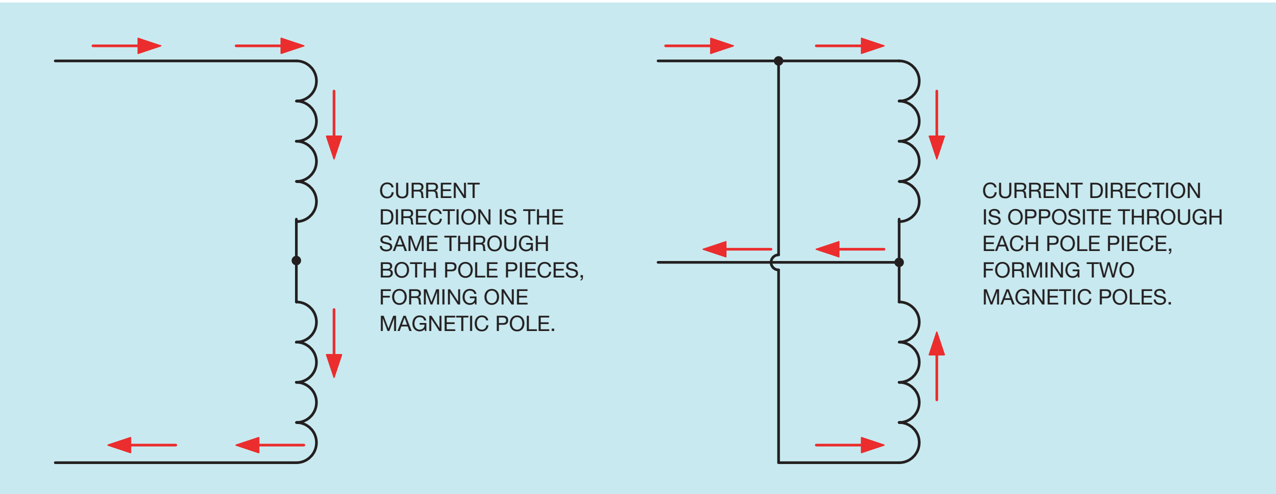


Figure 41–3 The direction of current flow determines the number of poles. (Source: Delmar/Cengage Learning.)

poles is doubled to four per phase (Figure 41–2B), the magnetic field will traverse the same number of stator poles during one cycle. Since the number of poles has been doubled, the magnetic field will travel only half as far during one complete cycle. Consequent pole motors have an advantage over some others types of variable speed alternating current motors in that they maintain a high torque when speed is reduced.

The number of stator poles is changed by redirecting the current through pairs of poles (Figure 41–3). If the current travels in the same direction through two pole pieces, both will produce the same magnetic polarity and are essentially one pole piece. If the current direction is opposite through each pole piece, they will produce opposite magnetic polarities and are essentially two poles.

Two-speed consequent pole motors contain one reconnectable stator winding. A two-speed motor will contain six T leads in the terminal connection box. The motor can be connected to form a series delta or parallel wye (Figure 41–4). If the motor is wound in such a way that the series delta connection gives the high

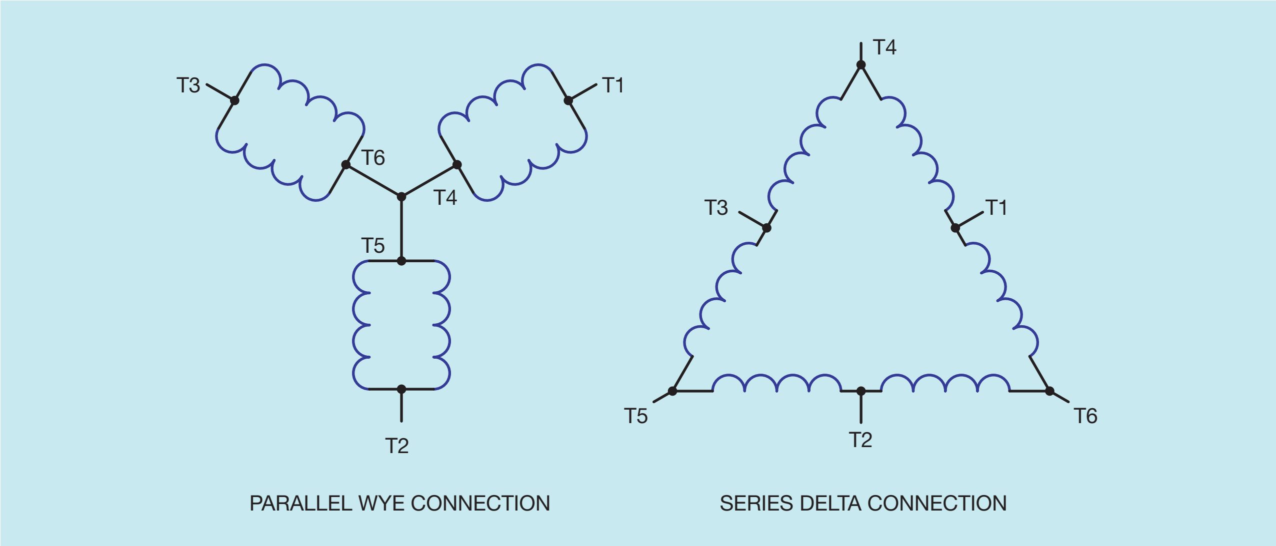


Figure 41–4 Stator windings can be connected as either parallel wye or series delta. (Source: Delmar/Cengage Learning.)

speed and the parallel wye gives the low speed, the horsepower will be the same for either connection. If the winding is such that the series delta gives the low speed and the parallel wye gives the high speed, the torque will be the same for both speeds.

Two-speed consequent pole motors provide a speed ratio of 2:1. For example, a two-speed consequent pole motor could provide synchronous speeds of 3600 and 1800 RPM, or 1800 and 900 RPM, or 1200 and 600 RPM. The connection diagram for a two-speed consequent pole motor is shown in Figure 41–5. A typical controller for a two-speed motor is shown in Figure 41–6. Note that the low speed connection requires six load contacts: three to connect the L1, L2, and L3 to T1, T2, and T3; and three to short leads T4, T5, and T6 together. Although contactors with six load contacts can be obtained, it is common practice to employ a separate three-pole contactor to short T4, T5, and T6 together.

In the circuit shown in Figure 41–6, the Stop button must be pressed before a change of speed can be made. Another control circuit is shown in Figure 41–7 that forces the motor to start in low speed before it can be accelerated to high speed. The Stop button does not have to be pressed before the motor can be accelerated to the second speed. A permissive relay (PR) is used to accomplish this logic. The motor can be returned to the low speed by pressing the Low push button after the motor has been accelerated to high speed. The load connections are the same as shown in Figure 41–6.

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	———	T4, T5, T6
HIGH	T4	T5	T6	ALL OTHERS	

Figure 41–5 Connection diagram for a two speed consequent pole motor. (Source: Delmar/Cengage Learning.)

Three-Speed Consequent Pole Motors

Consequent pole motors that are intended to operate with three speeds contain two separate stator windings. One winding is reconnectable like the winding in a two-speed motor. The second winding is wound for a certain number of poles and is not reconnectable. If one stator winding were wound with six poles and the second were reconnectable for two or four poles, the motor would develop synchronous speeds of 3600 RPM, 1800 RPM, or 1200 RPM when connected to a 60 hertz line. If the reconnectable winding were to be wound for four or eight pole connection, the motor would develop synchronous speeds of 1800 RPM, 1200 RPM, or 900 RPM. Three-speed consequent pole motors can be wound to produce constant horsepower, constant torque, or variable torque. Examples of different connection diagrams for three-speed, two-winding consequent pole motors are shown in Figures 41–8A through 41–8I.

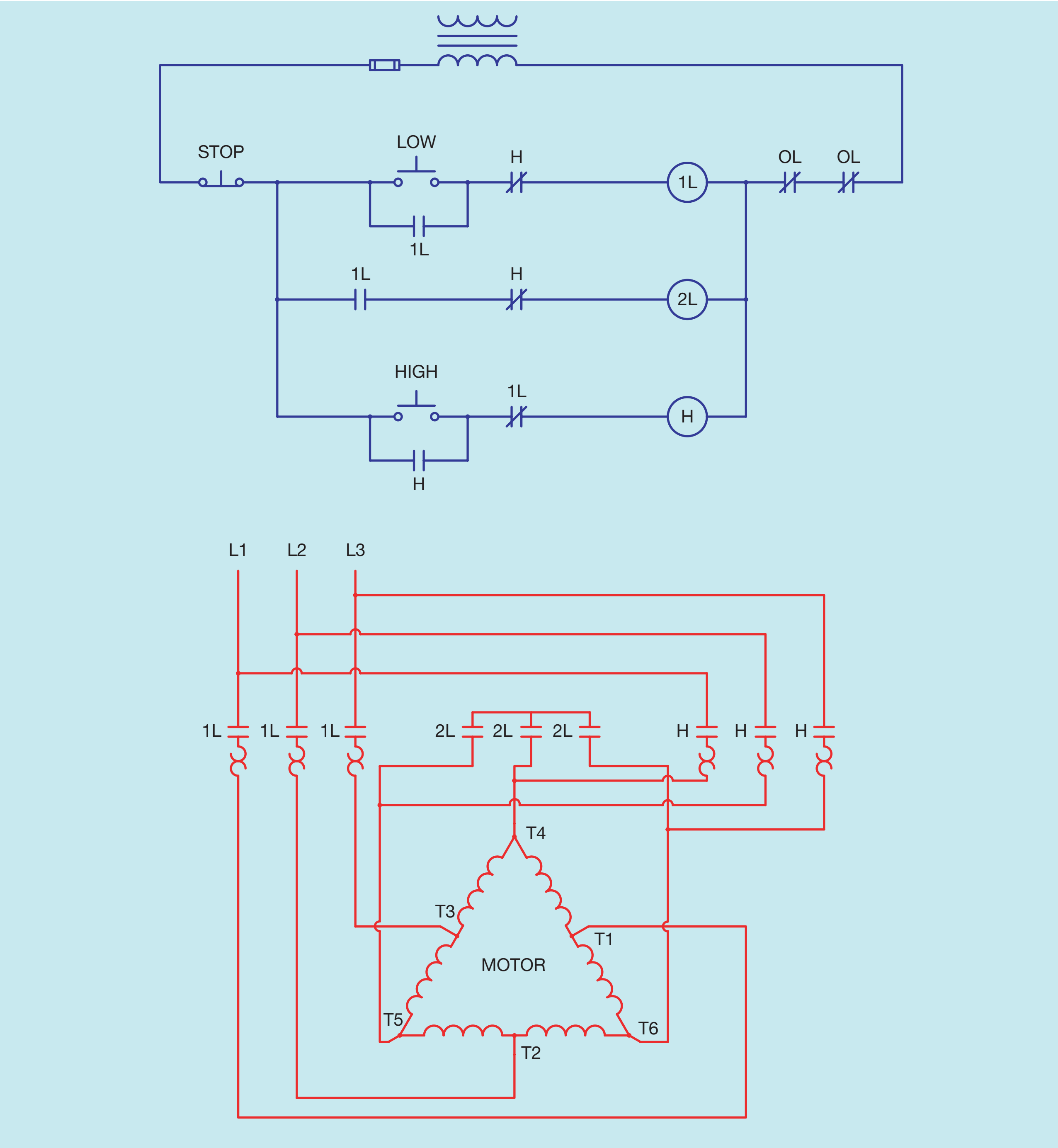


Figure 41–6 Two speed control for a consequent pole motor. (Source: Delmar/Cengage Learning.)

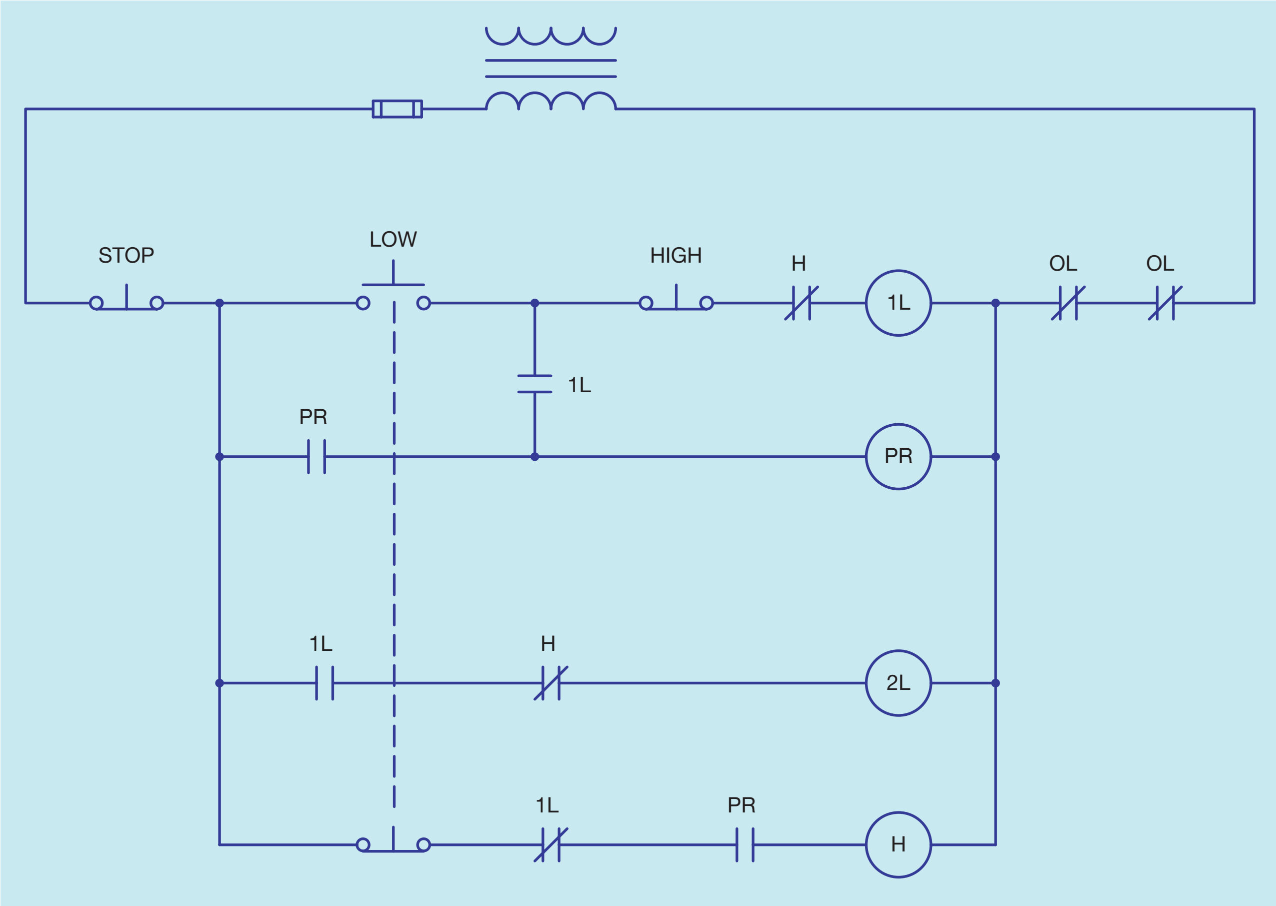
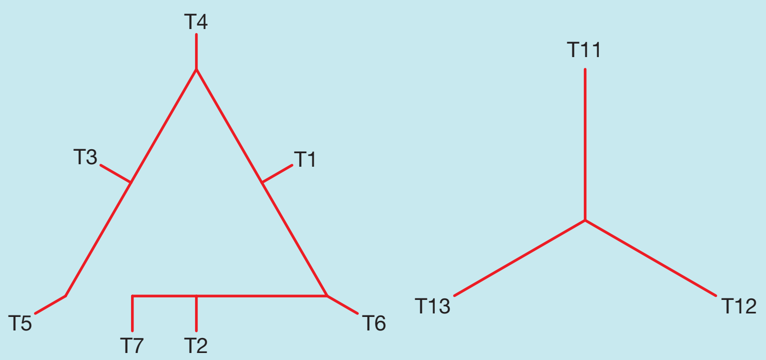


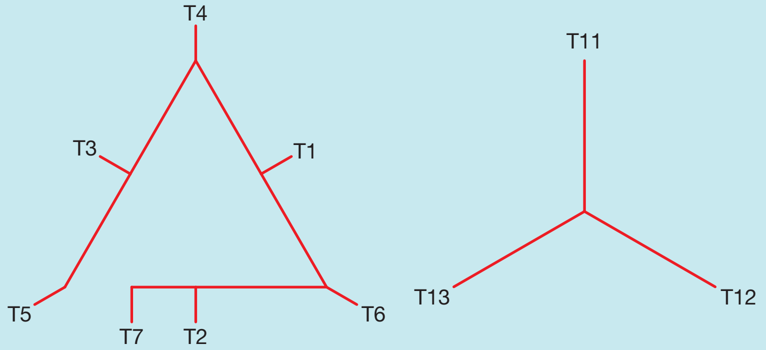
Figure 41–7 The motor must be started in low speed before it can be accelerated to high speed. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T6	T4	T5, T7	ALL OTHERS	————
HIGH	T11	T12	T13	ALL OTHERS	————

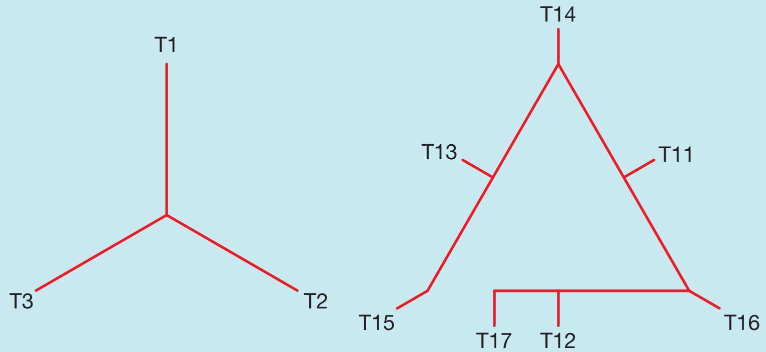
Figure 41–8A Constant horsepower. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T11	T12	T13	ALL OTHERS	———
HIGH	T6	T4	T5, T7	ALL OTHERS	———

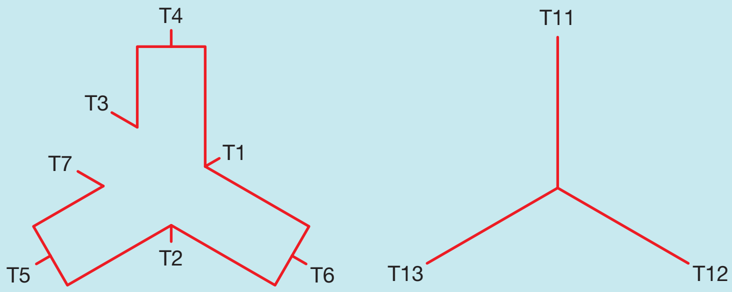
Figure 41–8B Constant horsepower. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	———
2ND	T11	T12	T13	ALL OTHERS	T14, T15, T16, T17
HIGH	T16	T14	T15, T17	ALL OTHERS	———

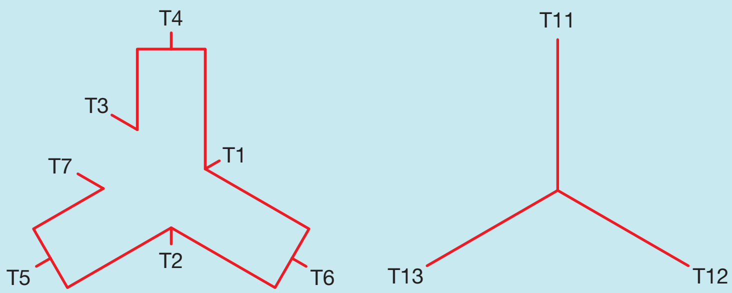
Figure 41–8C Constant horsepower. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7
HIGH	T11	T12	T13	ALL OTHERS	————

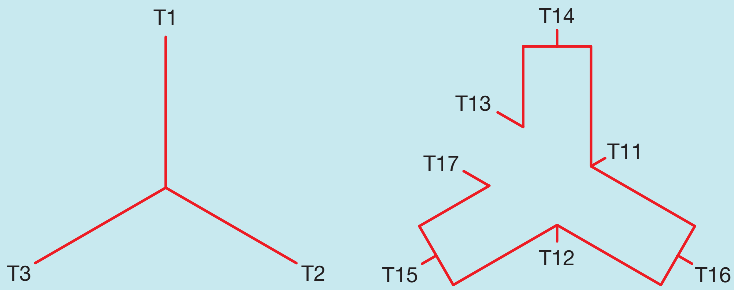
Figure 41–8D Constant torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7

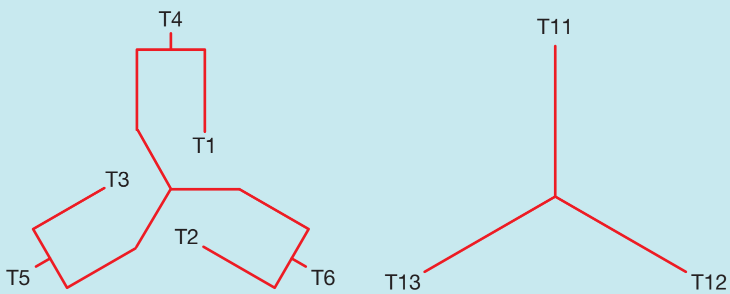
Figure 41–8E Constant torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13, T17	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13, T17

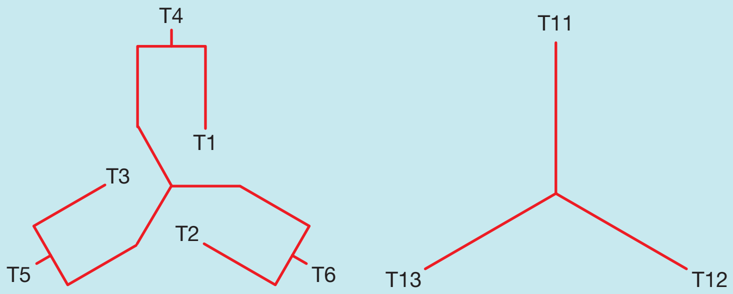
Figure 41–8F Constant torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T6	T4	T5	ALL OTHERS	T1, T2, T3

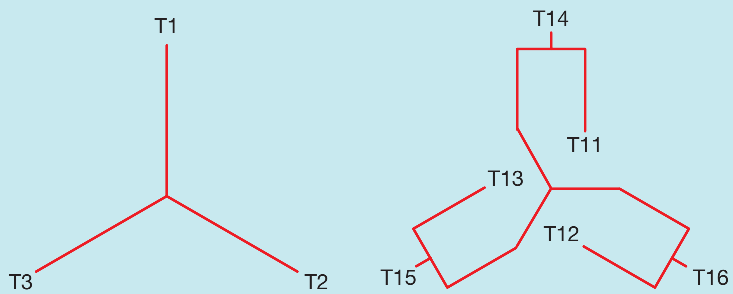
Figure 41–8G Variable torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3
HIGH	T11	T12	T13	ALL OTHERS	————

Figure 41–8H Variable torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 3 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTORS

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13

Figure 41–8I Variable torque. (Source: Delmar/Cengage Learning.)

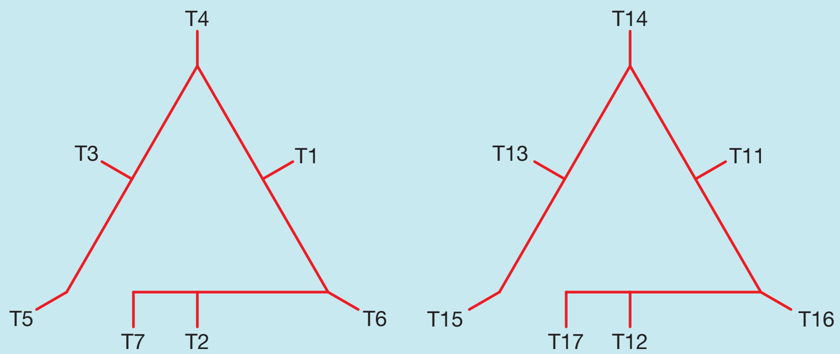
Four-Speed Consequent Pole Motors

Consequent pole motors intended to operate with four speeds use two reconnectable windings. Like two-speed or three-speed motors, four-speed motors can be wound to operate at constant horsepower, constant torque, or variable torque. Some examples of winding connections for four-speed, two-winding three-phase consequent pole motors are shown in Figures 41–9A through 41–9F.

A circuit for controlling a four-speed, three-phase consequent pole motor is shown in Figure 41–10. The control permits any speed to be selected by pushing the button that initiates that particular speed. In this circuit, stacked push buttons are used to break the circuit to any other speed before the starter that controls the selected speed is energized. Electrical interlocks are also used to ensure that two speeds cannot be energized at the same time. Eleven-pin control relays are used to provide interlock protection because they each contain three sets of contacts.

The load contact connection is also shown in Figure 41–10. The circuit assumes the connection diagram for the motor is the same as the diagram illustrated in Figure 41–9F. The circuit also assumes that the starters and contactors each contain three load contacts. Note that 3RD speed and HIGH speed require the use of two contactors to supply the necessary number of load contacts.

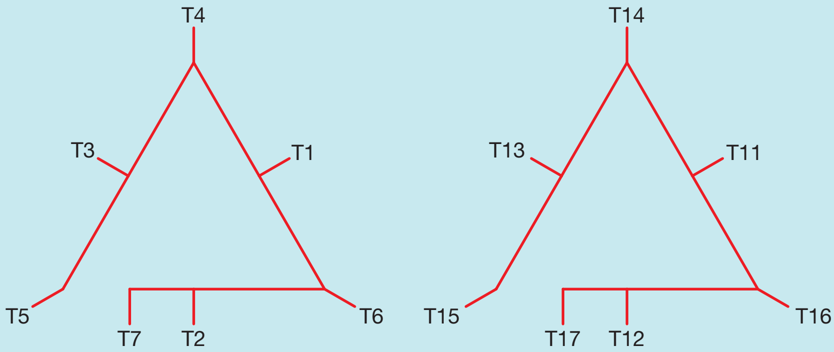
A two-speed, two-winding motor controller and a two-speed, one-winding motor controller are shown in Figure 41–11 and Figure 41–12.



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T6	T4	T5, T7	ALL OTHERS	————
3RD	T11	T12	T13	ALL OTHERS	T14, T15, T16, T17
HIGH	T16	T14	T15, T17	ALL OTHERS	————

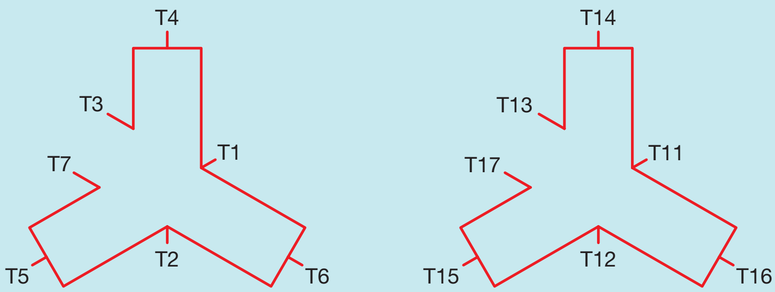
Figure 41–9A Constant horsepower. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	T4, T5, T6, T7
2ND	T11	T12	T13	ALL OTHERS	T14, T15, T16, T17
3RD	T6	T4	T5, T7	ALL OTHERS	———
HIGH	T16	T14	T15, T17	ALL OTHERS	———

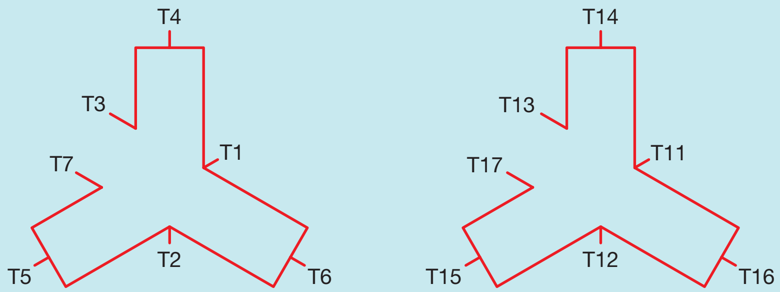
Figure 41–9B Constant horsepower. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	———
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7
3RD	T11	T12	T13, T17	ALL OTHERS	———
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13, T17

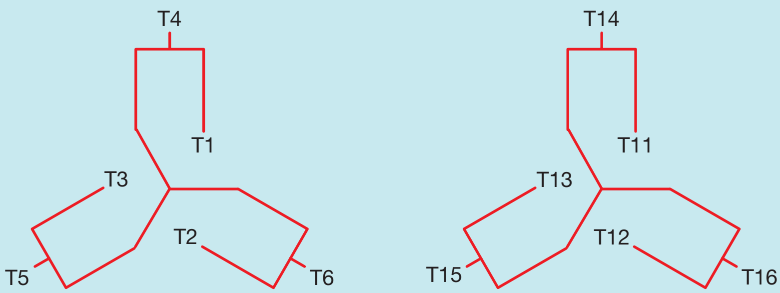
Figure 41–9C Constant torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3, T7	ALL OTHERS	————
2ND	T11	T12	T13, T17	ALL OTHERS	————
3RD	T6	T4	T5	ALL OTHERS	T1, T2, T3, T7
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13, T17

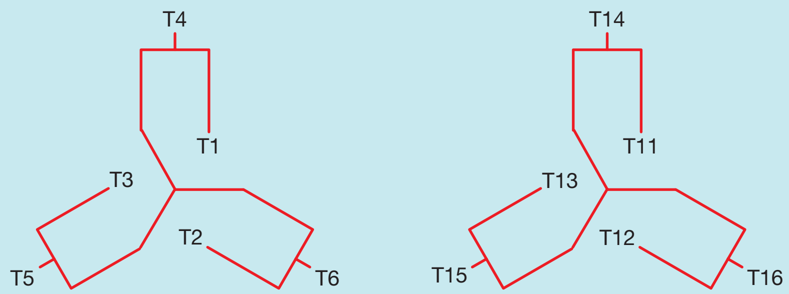
Figure 41–9D Constant torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T6	T4	T5	ALL OTHERS	T1, T2, T3
3RD	T11	T12	T13	ALL OTHERS	————
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13

Figure 41–9E Variable torque. (Source: Delmar/Cengage Learning.)



WINDING ARRANGEMENT FOR 4 SPEED 2 WINDING
CONSEQUENT POLE 3 PHASE MOTOR

SPEED	L1	L2	L3	OPEN	TOGETHER
LOW	T1	T2	T3	ALL OTHERS	————
2ND	T11	T12	T13	ALL OTHERS	————
3RD	T6	T4	T5	ALL OTHERS	T1, T2, T3
HIGH	T16	T14	T15	ALL OTHERS	T11, T12, T13

Figure 41–9F Variable torque. (Source: Delmar/Cengage Learning.)

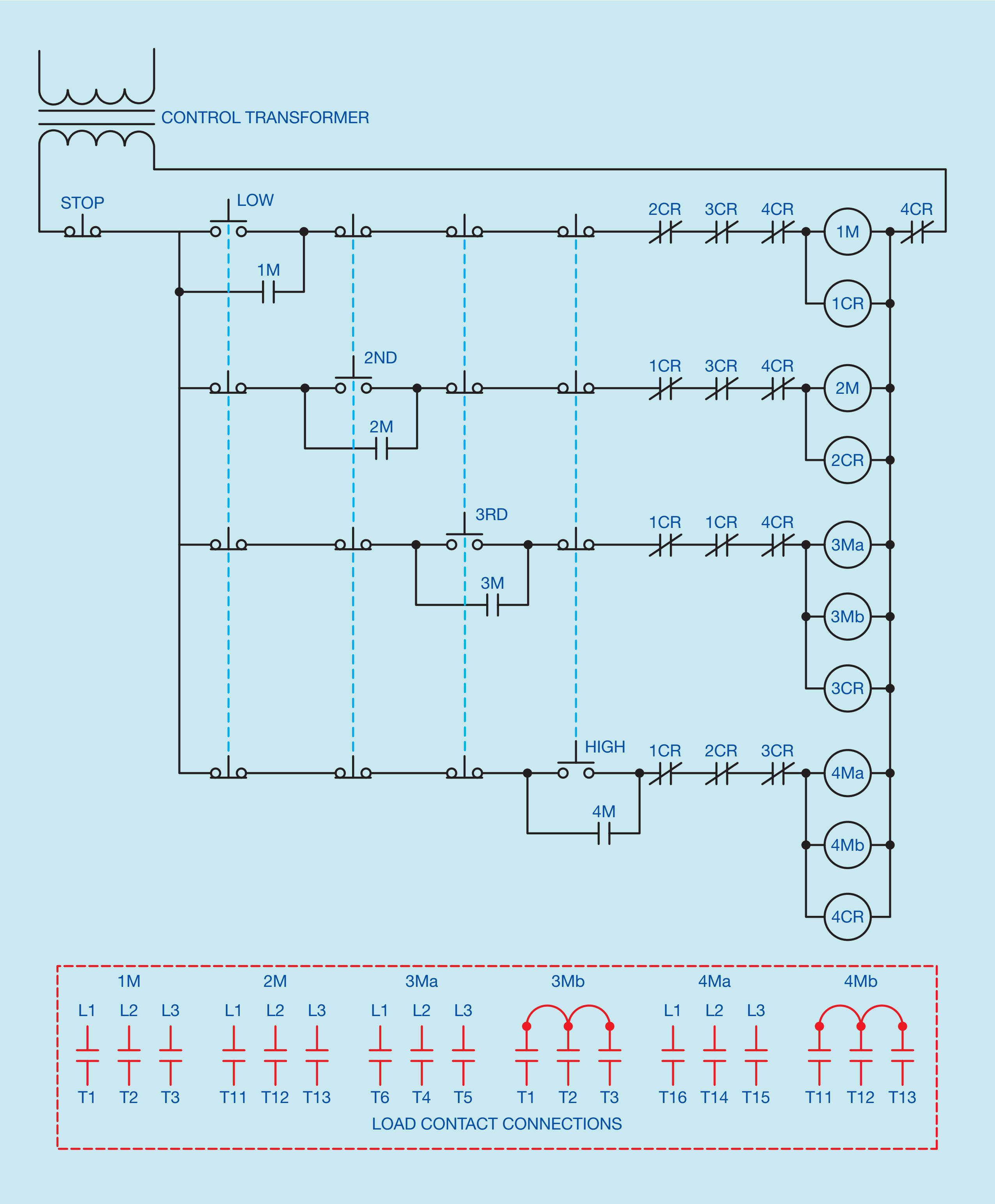


Figure 41–10 Pushbutton control for a 4 speed consequent pole 3 phase motor. (Source: Delmar/Cengage Learning.)

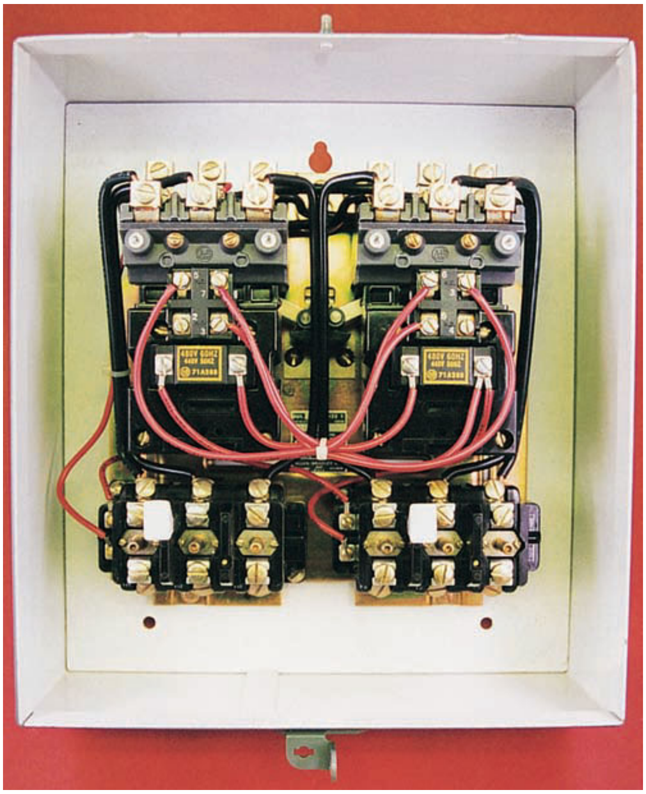


Figure 41–11 Two-speed, two-winding motor controller mounted in cabinet. (Source: Delmar/Cengage Learning.)

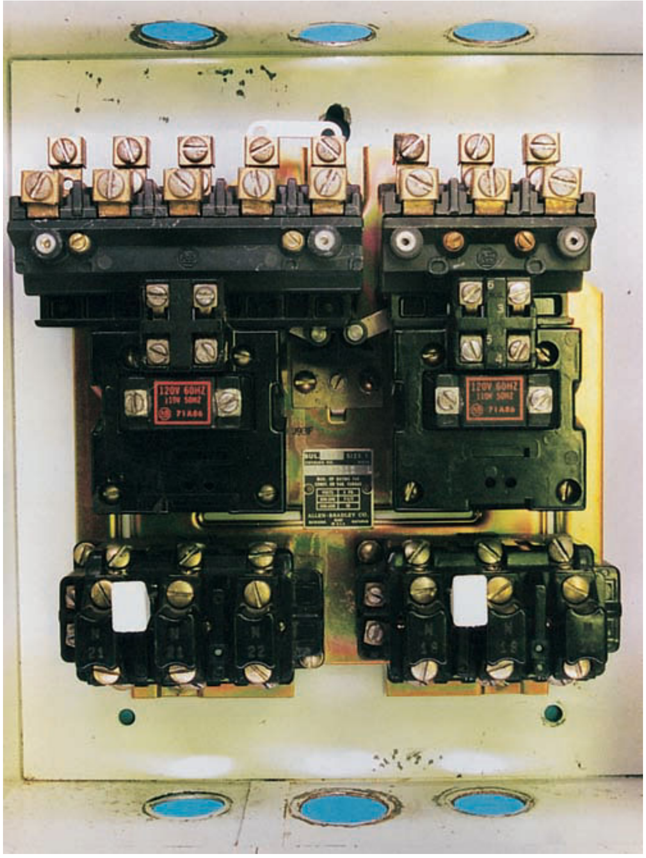


Figure 41–12 Two-speed, one-winding motor controller mounted in cabinet. (Source: Delmar/Cengage Learning.)

Review Questions

1. Name two factors that determine the synchronous speed of a motor.
2. How many speeds can be obtained from a consequent pole motor that contains only one stator winding?
3. What is the advantage of consequent pole motors over some other types of variable speed motors?
4. A consequent pole motor has synchronous speeds of 1800, 1200, and 900 RPM. How many stator windings does this motor have?
5. Refer to the circuit shown in Figure 41–6. You are to install this control system. How many auxiliary contacts should starter 1L contain? List how many are normally open and how many are normally closed.
6. Refer to the circuit shown in Figure 41–6. What is the function of contactor 2L?
7. Refer to the circuit shown in Figure 41–7. When the low speed push button is pressed, the motor begins to run in low speed. When the high push button is pressed the motor stops running. Which of the following could cause this problem?
   a. 1L contactor coil is open.
   b. H contactor coil is open.
   c. PR relay coil is open.
   d. 2L contactor coil is open.
8. Refer to the circuit shown in Figure 41–10. Assume that coil 2CR is shorted. Would it be possible to run the motor in third speed?
9. Refer to the circuit shown in Figure 41–10. Explain the action of the circuit if coil 2CR is shorted and the 2ND speed push button is pressed.
10. Refer to the circuit shown in Figure 41–10. You are to construct this circuit on the job. Would it be possible to use an eleven-pin control relay for 4CR?

CHAPTER 42

VARIABLE VOLTAGE AND MAGNETIC CLUTCHES

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the types of motors that can be controlled with variable voltage.
- Discuss requirements for motors that are controlled with variable voltage.
- Discuss the operation of a magnetic clutch.

Chapter 41 discussed the operation of consequent pole motors that change speed by changing the number of stator poles per phase. Although this is one method of controlling the speed of a motor, it is not the only method. Many small single-phase motors change speed by varying the amount of voltage applied to the motor. This method does not change the speed of the rotating magnetic field of the motor, but it does cause the field to become weaker. As a result, the rotor slip becomes greater, causing a decrease of motor speed.

Variable voltage control is used with small fractional horsepower motors that operate light loads such as fans and blowers. Motors that are intended to operate with variable voltage are designed with high impedance stators. The high impedance of the stator prevents the current flow from becoming excessive as the rotor slows down. The disadvantage of motors that contain high impedance stator windings is that they are very limited in the amount of torque they can produce. When load is added to a motor of this type, its speed will decrease rapidly.

Single-phase motors that use a centrifugal switch to disconnect the start windings cannot be used with variable voltage control. This limits the type of induction motors to capacitor start capacitor run and shaded pole motors. Capacitor start capacitor run motors are employed in applications where it is desirable to reverse the direction of rotation of the motor, such as ceiling fans.

Another type of alternating current motor that can use variable voltage for speed control is the universal or AC series motor. These motors are commonly used in devices such as power drills, skill saws, vacuum cleaners, household mixers, and many other appliances. They can generally be recognized by the fact that they contain a commutator and brushes similar to a direct current motor. Universal motors are so named because they can operate on AC or DC voltage. These motors

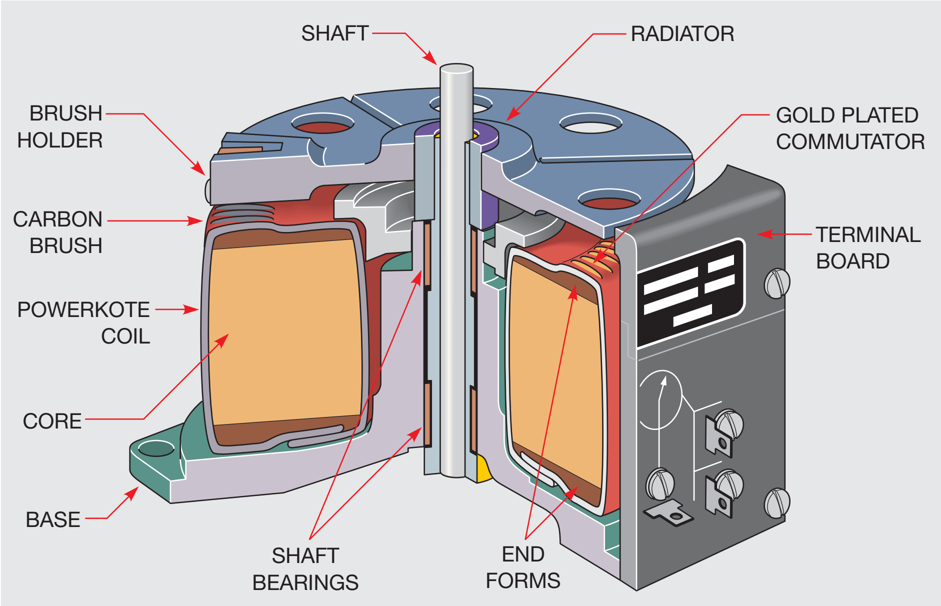


Figure 42–1 Cutaway view of a variable autotransformer. (Source: Delmar/Cengage Learning.)

are used with solid-state speed control devices to operate electric drills, routers, reciprocating saws, and other variable speed tools.

Voltage Control Methods

There are different methods of obtaining a variable AC voltage. One method is with the use of an autotransformer with a sliding tap (Figure 42–1). The sliding tap causes a change in the turns ratio of the transformer (Figure 42–2). An autotransformer is probably the most efficient and reliable method of supplying variable AC voltage, but they are expensive and require a large amount of space for mounting.

Another method involves the use of a solid-state device called a *triac*. A triac is a solid-state device similar to a silicon controlled rectifier (SCR), except that it will conduct both the positive and negative portions of a waveform. Triacs are commonly used in dimmers employed to control incandescent lighting. Triac light dimmers have a characteristic of conducting one half of the waveform before the other half begins conducting. Since only one half of the waveform is conducting, the output voltage is DC, not AC (Figure 42–3). Resistive loads such as incandescent lamps are not harmed when

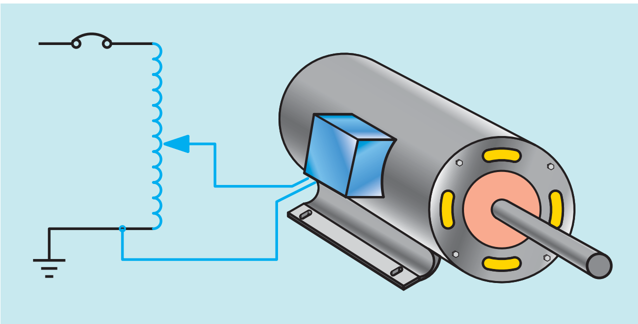


Figure 42–2 An autotransformer supplies variable voltage to a motor. (Source: Delmar/Cengage Learning.)

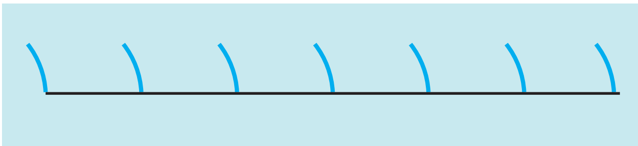


Figure 42–3 Conducting part of a waveform produces pulsating direct current. (Source: Delmar/Cengage Learning.)

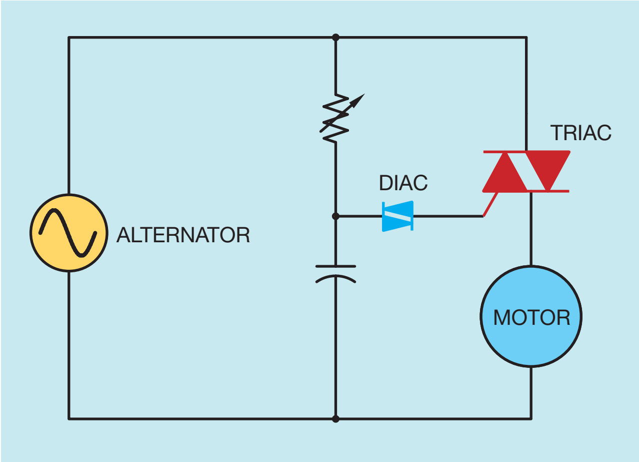


Figure 42–4 Basic triac control circuit. (Source: Delmar/Cengage Learning.)

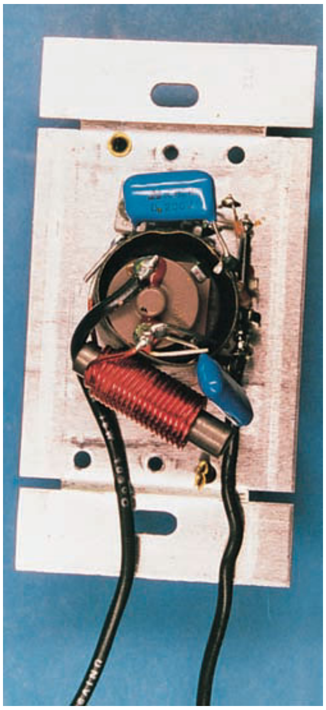


Figure 42–5 Variable speed control using a triac to control the voltage applied to a motor. (Source: Delmar/Cengage Learning.)

direct current is applied to them, but a great deal of harm can occur when DC voltage is applied to in inductive device such as a motor. Only triac controls that are designed for use with inductive loads should be used to control a motor. A basic triac control circuit is shown in Figure 42–4. A triac variable speed control for small AC motors is shown in Figure 42–5.

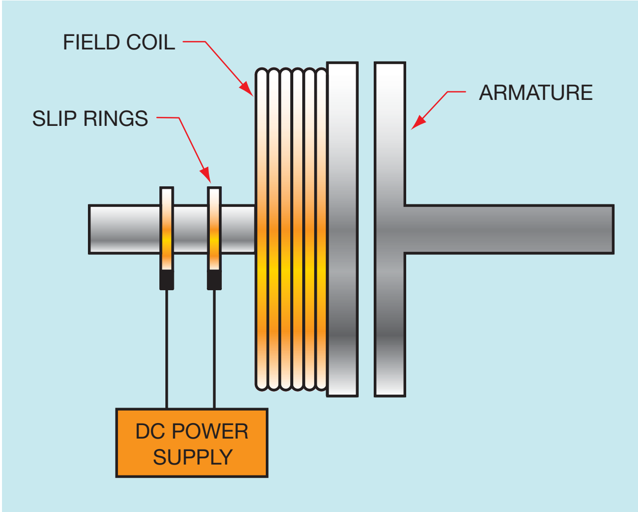


Figure 42–6 Single face magnetic clutch. (Source: Delmar/Cengage Learning.)

Magnetic Clutches

Magnetic clutches are used in applications where it is desirable to permit a motor to reach full speed before load is applied. Clutches can provide a smooth start for loads that can be damaged by sudden starting, or for high inertia loads such as centrifuges or flywheels. Magnetic clutches are divided into two primary sections: the field section, which contains the slip rings and coil winding; and the armature section, which contains the clutch disc (Figure 42–6). When power is applied to the field winding through the slip rings and brushes, the armature is attracted to the field, coupling the motor to the load. The force of coupling can be controlled by adjusting the voltage supplied to the field. This permits control over the degree of slip between the field section and the armature section. The amount of slip will determine how rapidly the motor can accelerate the driven load and the amount of initial torque delivered to the load. When power is removed from the clutch, a spring separates the field and armature. A magnetic clutch is shown in Figure 42–7.

The clutch illustrated in Figure 42–6 is a single face clutch, which means that it contains only one clutch disc. Clutches intended to connect large horsepower motors to heavy loads often contain multiple clutch faces. Double faced clutches have both the armature and field discs mounted on the same hub. A double faced friction lining is sandwiched between

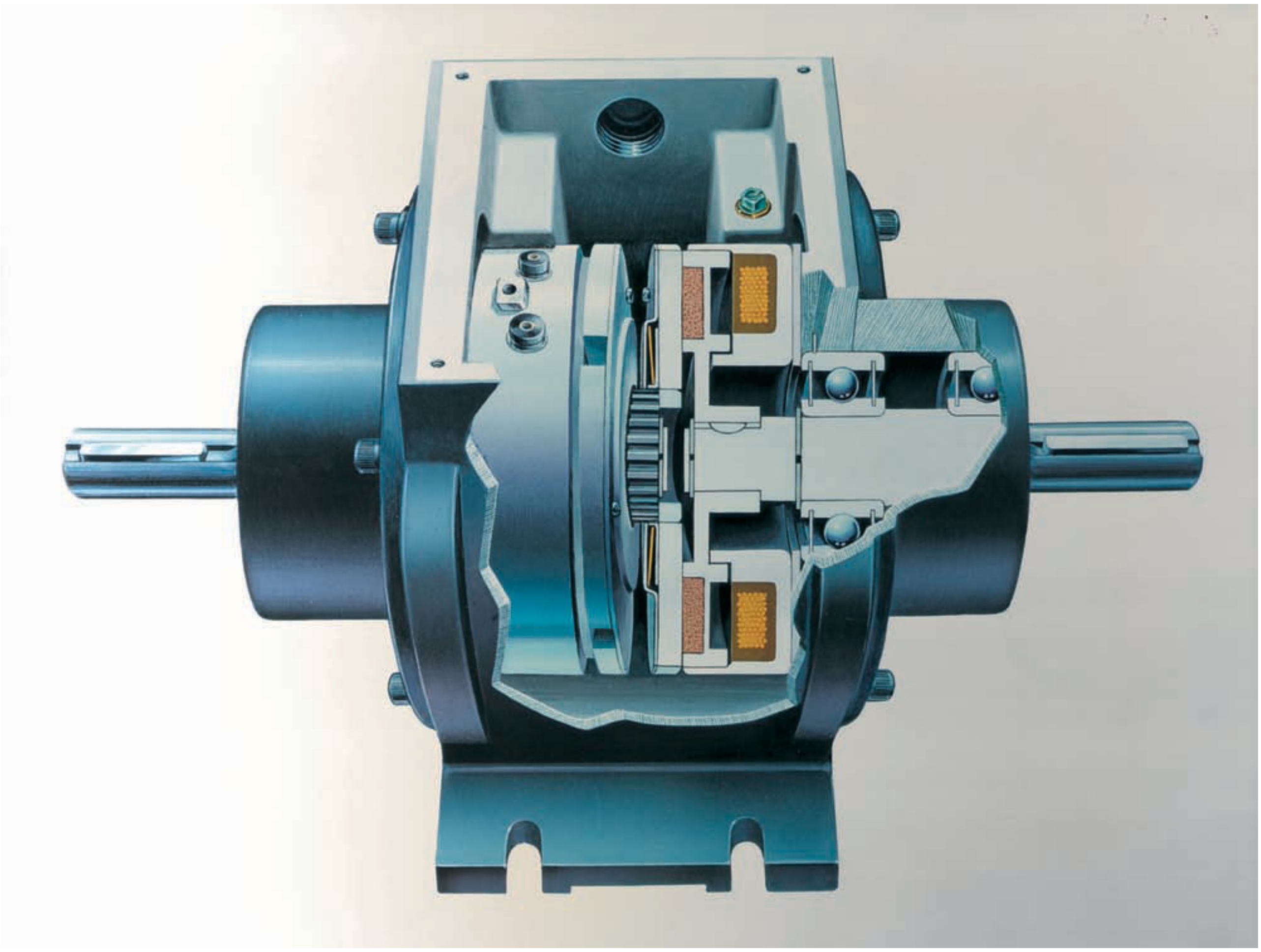


Figure 42–7 Cut-away view of a magnetic clutch. (Courtesy Warner Electric, South Beloit, Illinois.)

them. When the field winding is energized, the field disc and armature disc are drawn together with the double faced friction lining between them. Double faced clutches can be obtained in sizes up to 78 inches in diameter.

Some clutches are intended to provide tension control and are operated with a large amount of slippage between the driving and driven members. These clutches produce an excessive amount of heat because of the friction between clutch discs. Many of these clutches are water cooled to help remove the heat.

Eddy Current Clutches

Eddy current clutches are so named because they induce eddy currents into a metal cylinder or drum. One part of the clutch contains slip rings and a winding (Figure 42–8A). The armature or rotor is constructed so that when the winding is excited with direct current, magnetic pole pieces are formed. The rotor is mounted inside the metal drum that forms the output shaft of the clutch (Figure 42–8B). The rotor is the input of the clutch and is connected to an AC induction motor. The motor provides the turning force for the clutch (Figure 42–9). When direct current is applied to the rotor, the spinning electromagnets induce eddy currents into the metal drum. The induced eddy currents form magnetic poles inside the drum. The magnetic fields of the rotor and drum are attracted to each other, and the clutch turns in the same direction as the motor.

The main advantage of an eddy current clutch is that there is no mechanical connection between the rotor and drum. Since there is no mechanical connection, there is no friction to produce excessive heat and there is no wear as is the case with mechanical clutches.

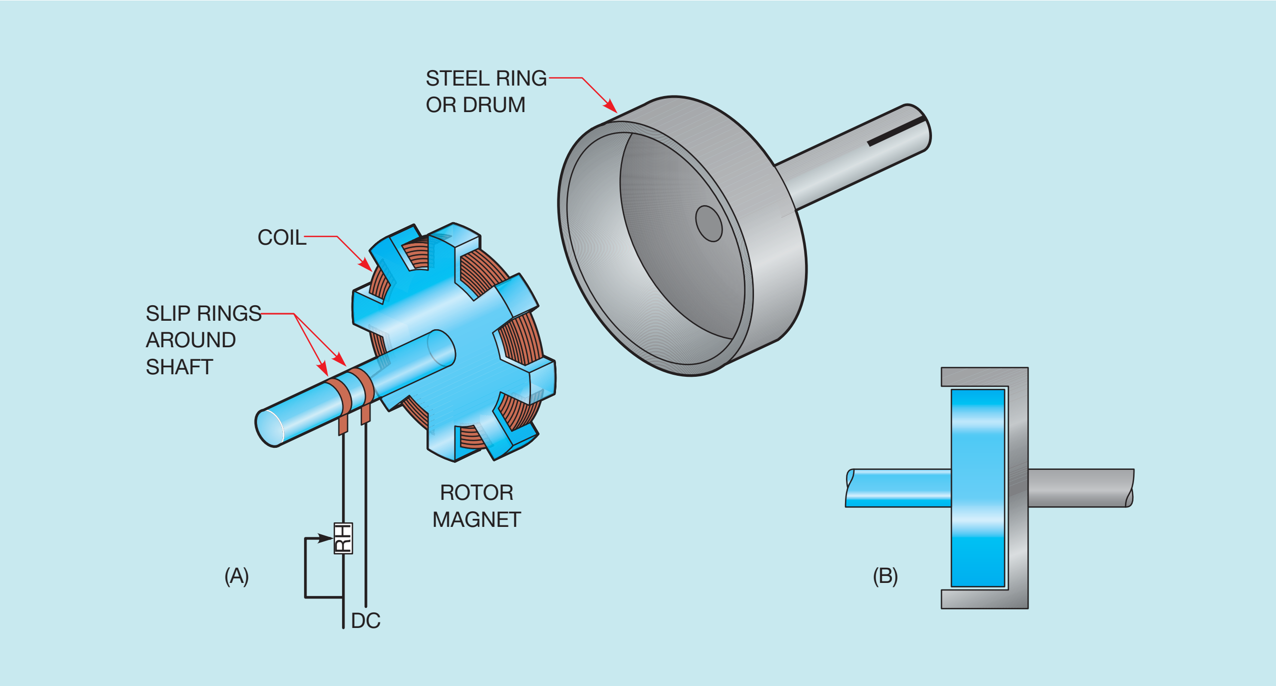


Figure 42–8 Diagram A shows magnetic armature or rotor and drum. Diagram B shows rotor mounted inside the drum. The rotor is the input shaft of the clutch and the drum is the output shaft. (Source: Delmar/Cengage Learning.)

The speed of the clutch can be controlled by varying the amount of direct current applied to the armature or rotor. Since the output speed is determined by the amount of slip between the rotor and drum, when load is added, the slip will become greater, causing a decrease in speed. This can be compensated for by increasing the amount of direct current applied to the rotor. Many eddy current clutch circuits contain a speed sensing device that will automatically increase or decrease the DC excitation current when load is added or removed.

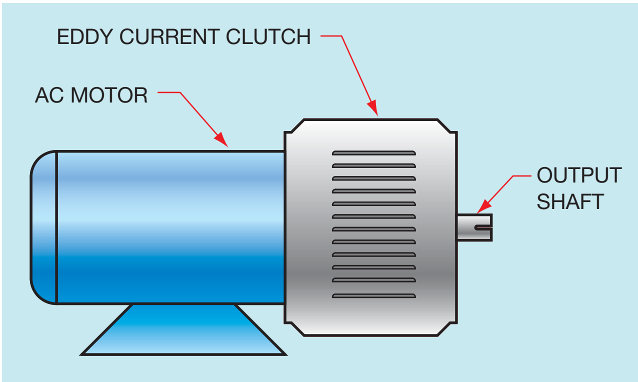


Figure 42–9 An AC motor is coupled to an eddy current clutch. (Source: Delmar/Cengage Learning.)

Review Questions

1. Does varying the voltage to an AC induction motor cause a change in synchronous speed?
2. Why do induction motors that are intended to be controlled by variable voltage contain high impedance stator windings?
3. What is the disadvantage of a motor that contains a high impedance stator winding?
4. What type of AC induction motor is used with variable voltage control when it is desirable for the motor to reverse direction?
5. What type of motor that can be controlled with variable voltage is used to operate power drills, vacuum cleaners, routers, etc.?
6. Why are universal motors so named?

7. What type of solid-state component is generally used to control AC voltage?
8. When using a mechanical clutch, what determines how fast a load can be accelerated and the amount of initial torque applied to the load?
9. What is the primary advantage of an eddy current clutch over a mechanical clutch?
10. How is the speed of an eddy current clutch controlled?

CHAPTER 43
BRAKING

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss mechanical type brakes.
- Connect a mechanical brake circuit.
- Discuss dynamic braking for DC and AC motors.
- Connect a plugging circuit.

Motors are generally permitted to slow to a stop when disconnected from the power line, but there may be instances when that is not an option or not convenient. There are several methods that can be employed to provide braking for a motor. Some of these are:

- Mechanical brakes
- Dynamic braking
- Plugging

Mechanical Brakes

Mechanical brakes are available in two basic types, drum and disk. Drum brakes use brake shoes to apply pressure against a drum (Figure 43–1). A metal cylinder, called the drum, is attached to the motor shaft. Brake shoes are placed around the drum. A spring is used to adjust the amount of pressure the brake shoes exert against the drum to control the amount of braking that takes place when stopping the motor. When the motor is operating, a solenoid is energized to release the pressure of the brake shoes. When the motor is to be stopped, the brakes engage immediately. A circuit of this type is shown in Figure 43–2. Mechanical brakes work by converting the kinetic (moving) energy of the load into thermal (heat) energy when the motor is stopped. Mechanical type brakes have an advantage in that they can hold a suspended load. For this reason, mechanical brakes are often used on cranes.

Disc brakes work in a very similar manner to drum brakes. The only real difference is that brake pads are used to exert force against a spinning disc instead of a cylindrical drum. A combination disc brake and magnetic clutch is shown in Figure 43–3.

Dynamic Braking

Dynamic braking can be used to slow both direct and alternating current motors. Dynamic braking is sometimes referred to as *magnetic braking* because in

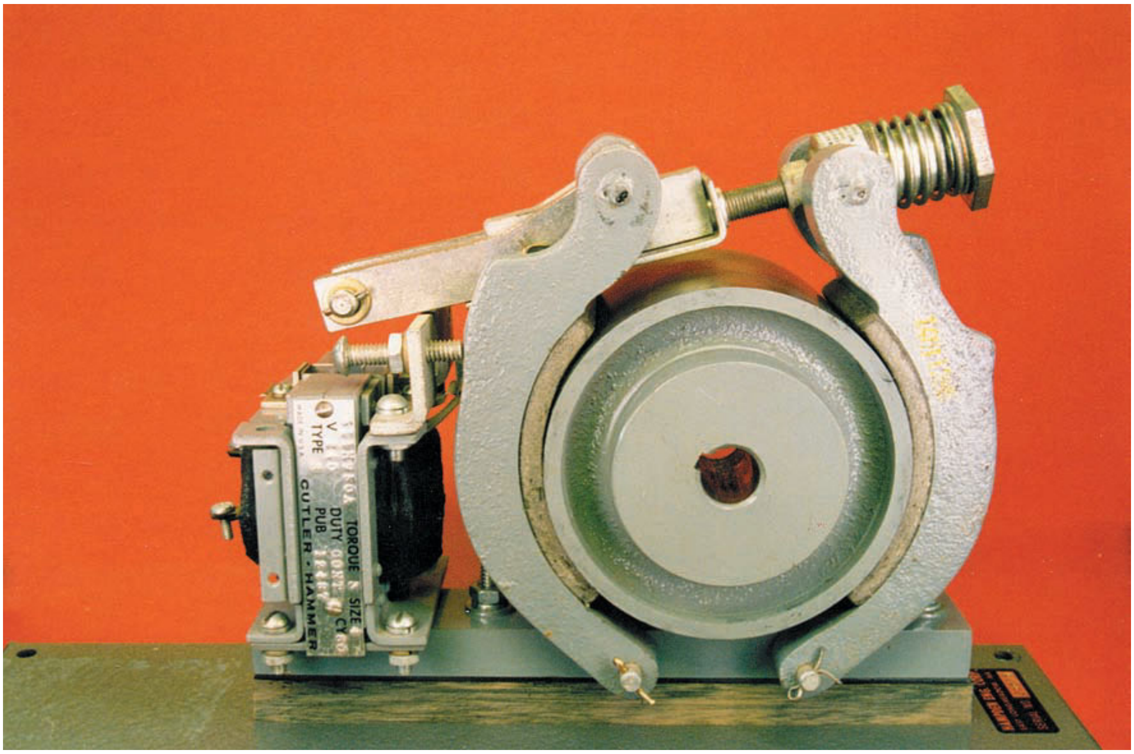


Figure 43–1 Drum brake. (Source: Delmar/Cengage Learning.)

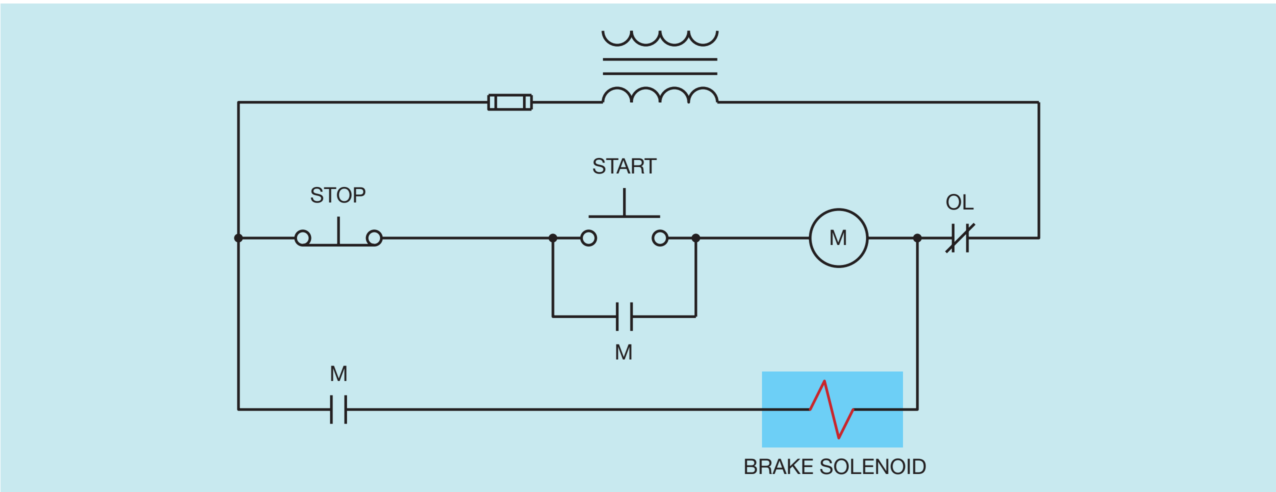


Figure 43–2 The brake is applied automatically when the motor is not operating. (Source: Delmar/Cengage Learning.)

both instances it employs the use of magnetic fields to slow the rotation of a motor. The advantage of dynamic braking is that there are no mechanical brake shoes to wear out. The disadvantage is that dynamic brakes cannot hold a suspended load. Although dynamic braking can be used for both direct and alternating current motors, the principles and methods used for each are very different.

Dynamic Braking for Direct Current Motors

A direct current machine can be used as either a motor or generator. When used as a motor, electrical energy is converted into mechanical energy. When used as a generator, mechanical energy is converted into electrical energy. The principle of dynamic braking for a direct current motor is to change the motor into a generator.

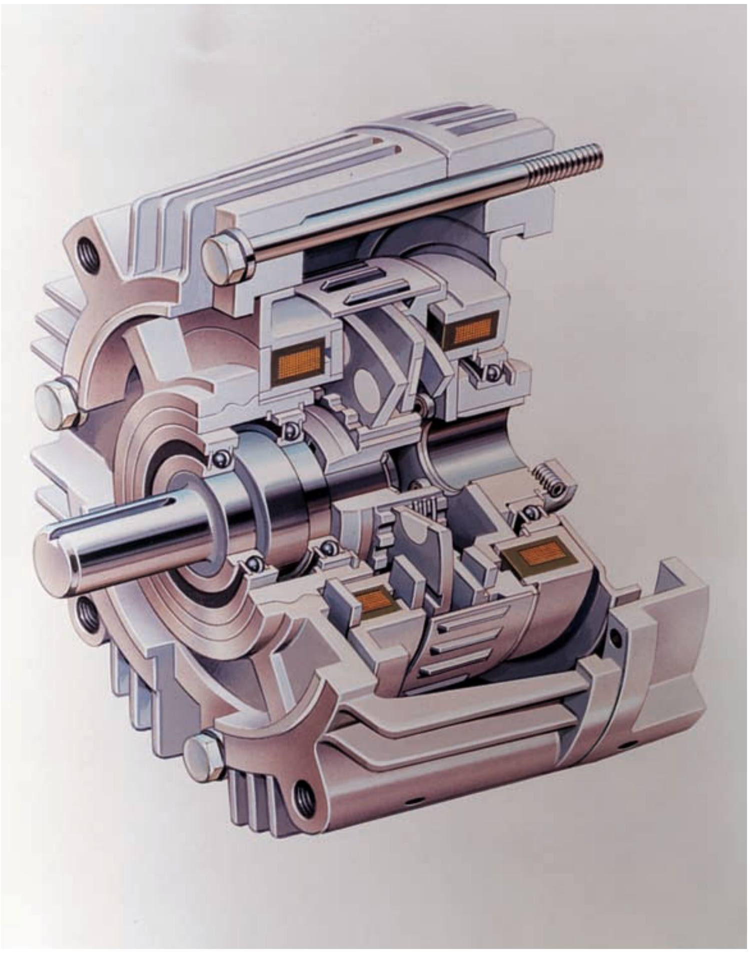


Figure 43–3 Cut-away view of a combination clutch and brake. (Courtesy Warner Electric, South Beloit, Illinois.)

When a generator produces electrical power, it produces *counter torque,* making the armature hard to turn. The amount of counter torque produced by the generator is proportional to the armature current.

Dynamic braking for a DC motor is accomplished by permitting power to remain connected to the shunt field when the motor is stopped, and reconnecting the armature to a high wattage resistor (Figure 43–4). The resistor may actually be more than one resistor depending on motor size, length of braking time, and armature current. High wattage resistors are shown in Figure 43–5. The braking time can be controlled by adjusting the resistance value. If current remains connected to the shunt field, the pole pieces retain their magnetism. Connecting a resistance across the armature terminals causes the motor to become a generator.

Dynamic braking for a DC motor is very effective, but the braking effect becomes weaker as the armature slows down. Counter torque in a generator is proportional to the magnetic field strength of the pole pieces and armature. Although the flux density of the pole pieces will remain constant as long as shunt field current is constant, the armature magnetic field is proportional to armature current. Armature current is proportional to the amount of induced voltage and the resistance of the connected load. There are three factors that determine induced voltage:

- Strength of magnetic field. (In this instance, the flux density of the pole pieces.)
- Length of conductor. (Also stated as number of turns of wire. In this instance, it is the number of turns of wire in the armature winding.)
- Speed of the cutting action. (Armature speed)

As the armature slows, less voltage is induced in the armature windings, causing a decrease of armature current.

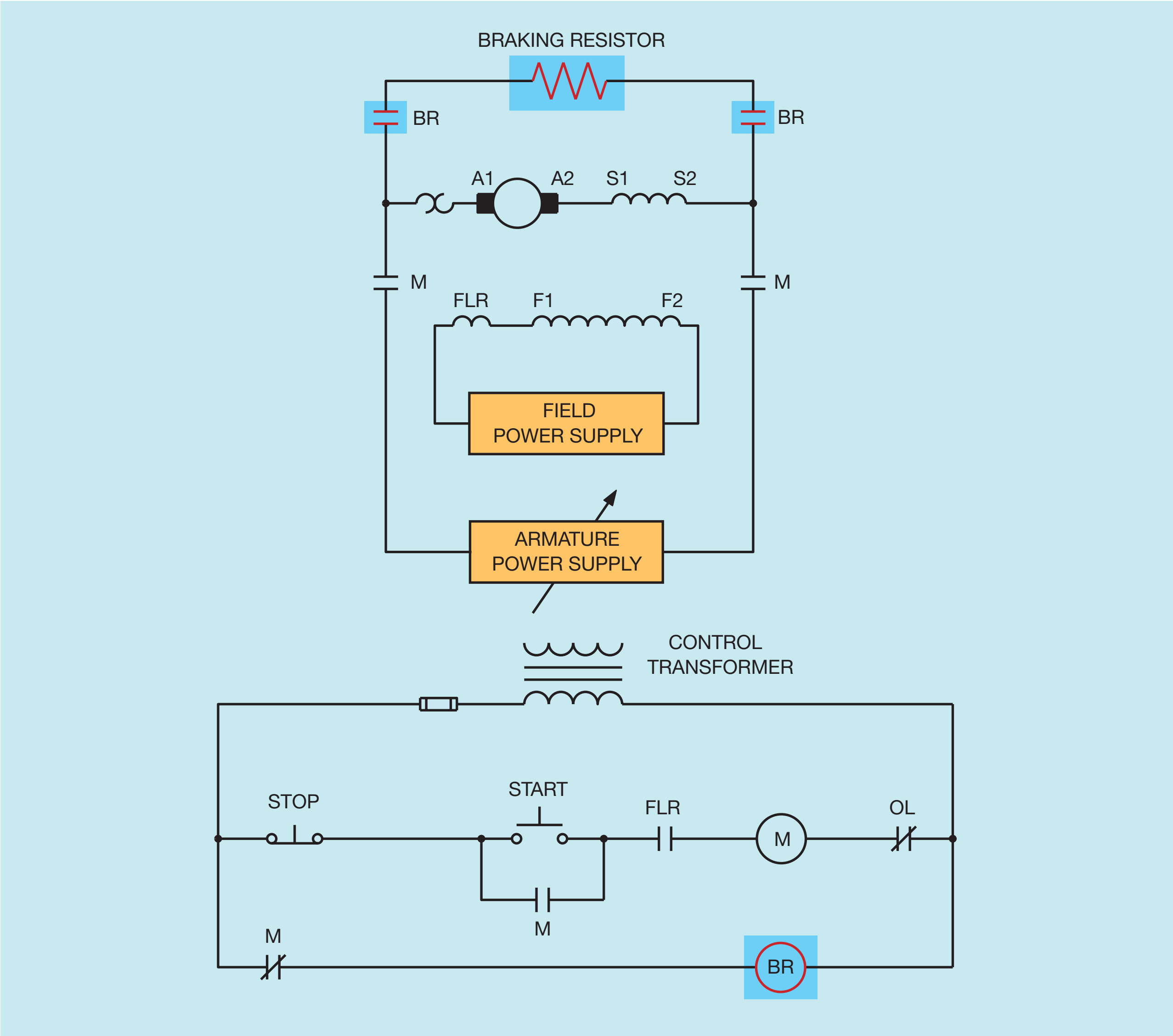


Figure 43–4 Dynamic braking circuit for a direct current motor. (Source: Delmar/Cengage Learning.)

Dynamic Braking for Alternating Current Motors

Dynamic braking for alternating current motors is accomplished in a different way than that described for direct current motors. Dynamic braking for an AC motor can be accomplished by connecting direct current to the stator winding. This causes the stator magnetic field to maintain a constant polarity instead of reversing polarity each time the current changes direction. As the rotor of a squirrel cage motor spins through the stationary magnetic field, a current is induced into the rotor bars. The current flow in the rotor causes a magnetic field to form around the rotor bars. The rotor magnetic field is attracted to the stator field, causing the rotor to slow down. The amount of braking force is proportional to the magnetic field strength of the stator field and the rotor field. The braking force can be controlled by the amount of direct current supplied to the stator.

When direct current is applied to the stator winding, there is no inductive reactance to limit stator current. The only current-limiting effect is the wire resistance of the stator winding. Dynamic braking circuits for alternating current motors generally include a step-down transformer to lower the voltage to the rectifier and often include a series resistor to control the current applied to the stator winding (Figure 43–6).

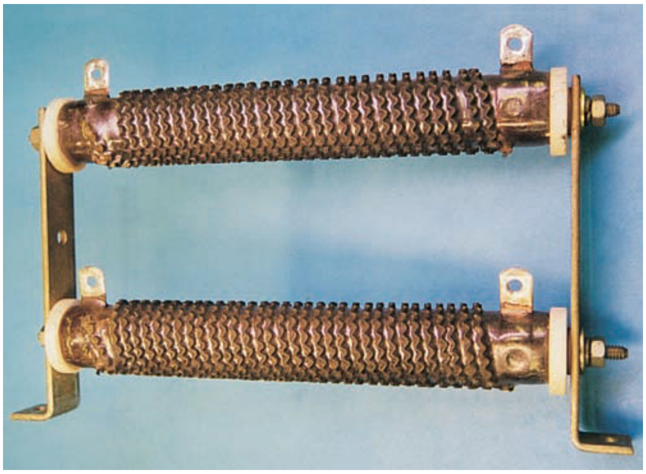


Figure 43–5 High wattage resistors. (Source: Delmar/Cengage Learning.)

In the circuit shown, an off-delay timer is used to determine the length of braking time for the circuit. When the START button is pushed, motor starter M energizes and closes all M load contacts to connect the motor to the line. The M auxiliary contacts change position at the same time. The normally closed M contact opens to prevent power being applied to the dynamic brake relay (DBR). The two normally open M auxiliary contacts close, sealing the circuit and supplying power to the coil of off-delay timer TR. Since TR is an off-delay timer, the TR timed contacts close immediately. The circuit will remain in this position until the STOP button is pressed. At that time, motor starter M de-energizes and disconnects the motor from the line. The normally open M auxiliary contact connected in series with timer coil TR opens, starting the timing sequence. The normally closed M auxiliary contact closes and provides a current path through the now closed TR timed contact to the coil of DBR. This causes the DBR contacts to close and connect the step-down transformer and rectifier to the power line. Direct current is now supplied to the stator winding. Direct current will be supplied to the stator winding until the timed TR contact opens and de-energizes coil DBR.

Plugging

Plugging is defined by NEMA as *a system of braking in which the motor connections are reversed so that the motor develops a counter torque that acts as a retarding force.* Plugging can be used with direct current motors but is more often used with three-phase squirrel cage motors. Plugging is accomplished with three-phase motors by disconnecting the motor from the power line and momentarily reversing the direction of rotation. As a generally rule, the reversing contactor is of a larger size than the forward contactor because of the increased plugging current. There are several methods that can be employed when a plugging control is desired.

Manual Plugging

One type of plugging control depends on an operator to manually perform the operation. A manual plugging control is shown in Figure 43–7. The circuit is basically a forward-reverse control circuit, with the exception that there is no holding contact for the reverse contactor. Also, the PLUGGING push button is a double acting push button with the normally closed section connected in series with the forward contactor. This permits the PLUGGING push button to be used without having to press the STOP button first.

One method of providing plugging control is with the use of an automatic timed circuit (Figure 43–8). This is the same basic control circuit used for time controlling a dynamic braking circuit in Figure 43–6. The dynamic brake relay has been replaced with a reversing contactor. A modification of this circuit is shown in Figure 43–9. This circuit permits an operator to select if a plugging stop is to be used or not. Once the operator has pressed the PLUGGING push button, the timer controls the amount of plugging time.

Although time is used to control plugging, problems can occur due to the length of plugging time. If the timer is not set for a long enough time, the reversing circuit will open before the motor completely stops. If the timer is set

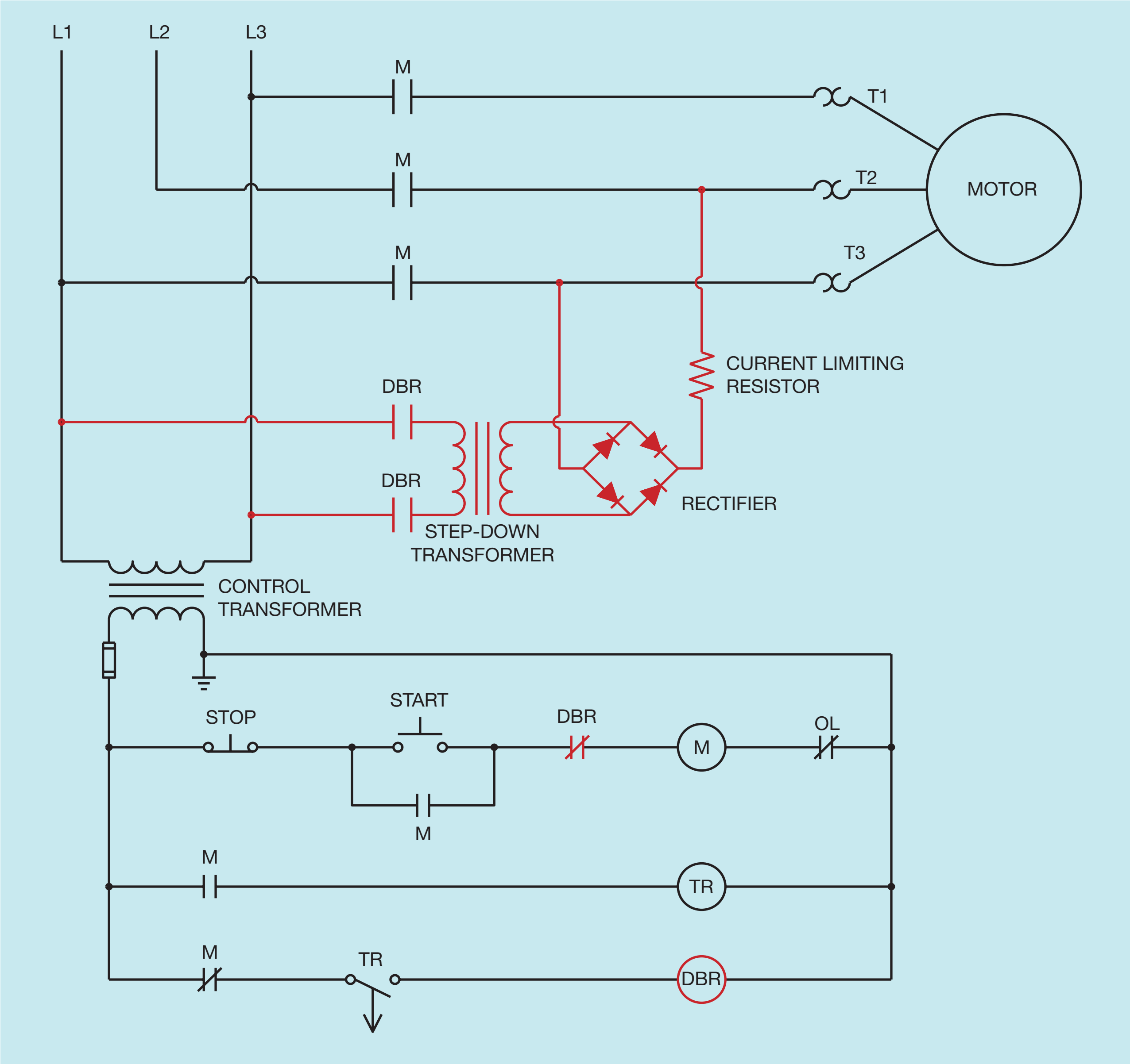


Figure 43–6 Dynamic braking circuit for an alternating current motor. (Source: Delmar/Cengage Learning.)

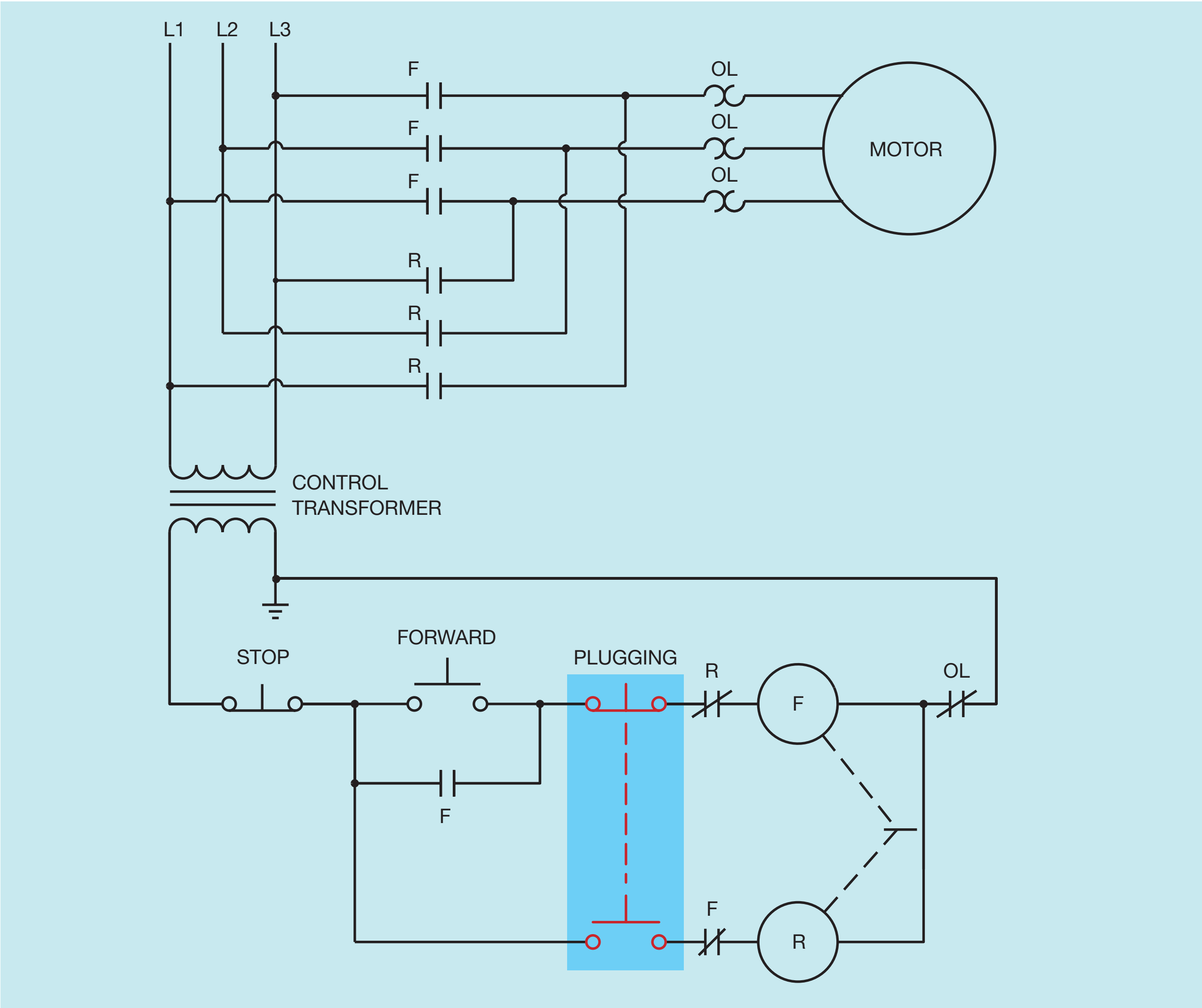


Figure 43–7 Manual plugging control. (Source: Delmar/Cengage Learning.)

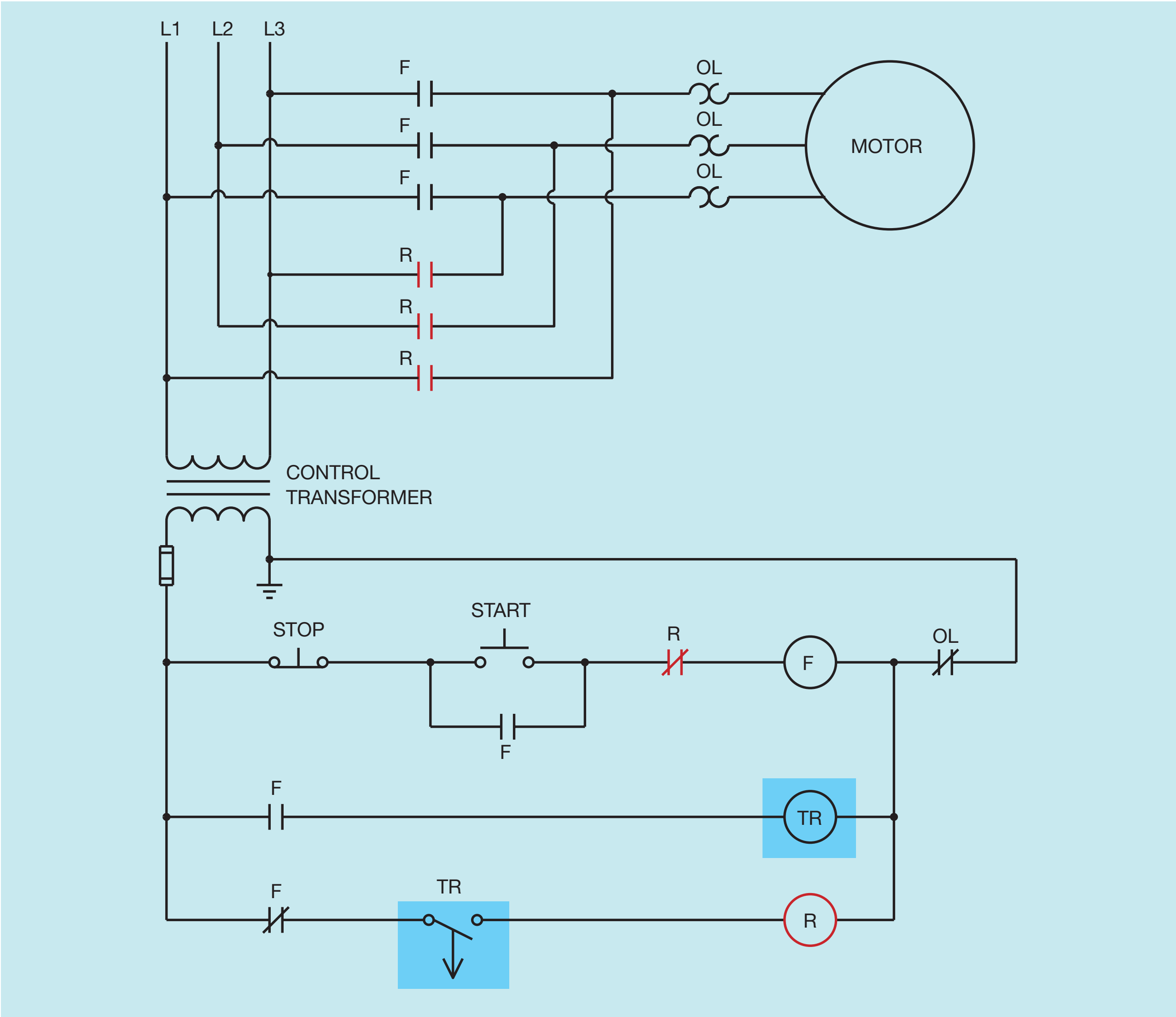


Figure 43–8 Timed controlled plugging circuit. (Source: Delmar/Cengage Learning.)

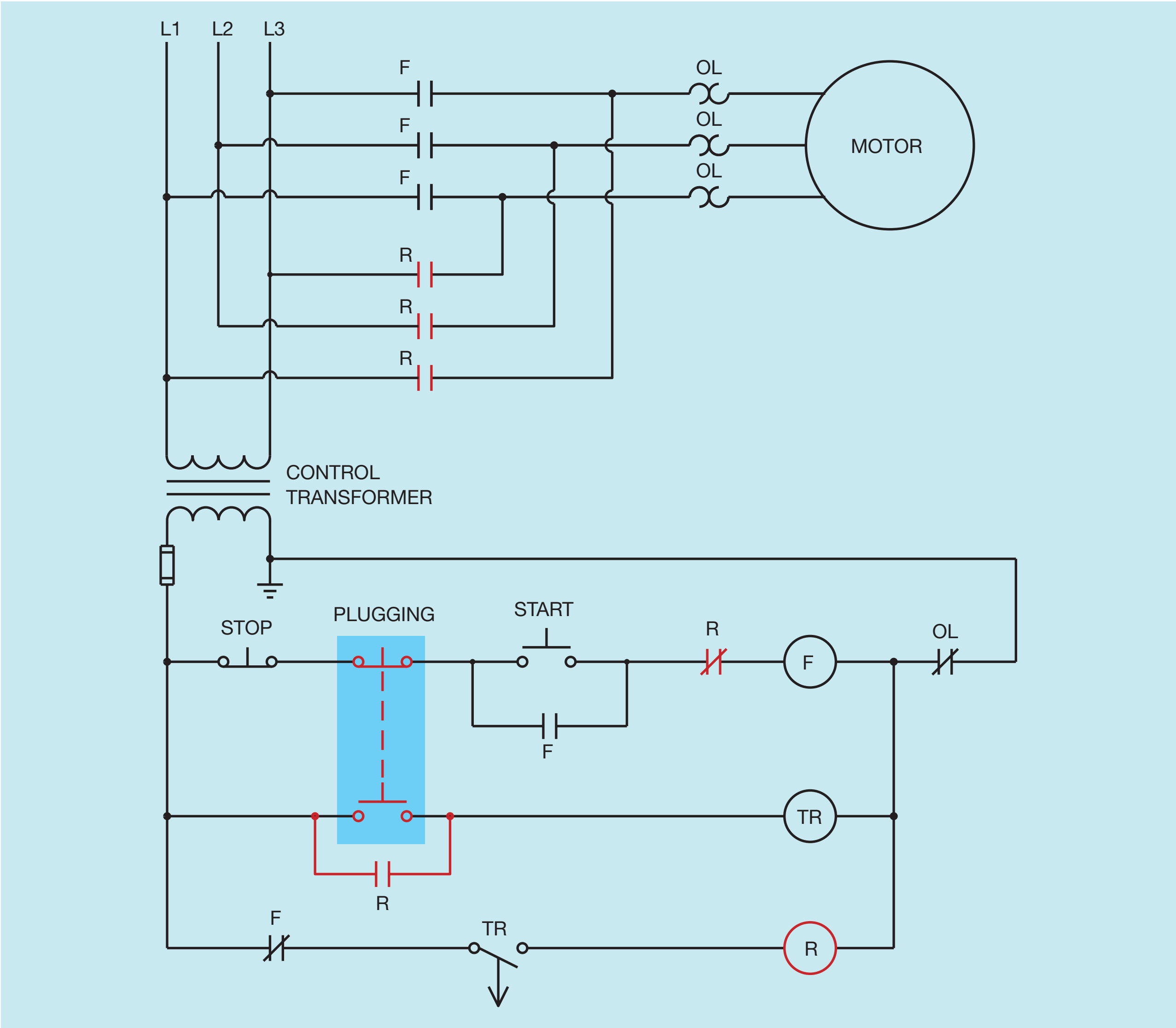


Figure 43–9 An operator controls the plugging stop. (Source: Delmar/Cengage Learning.)

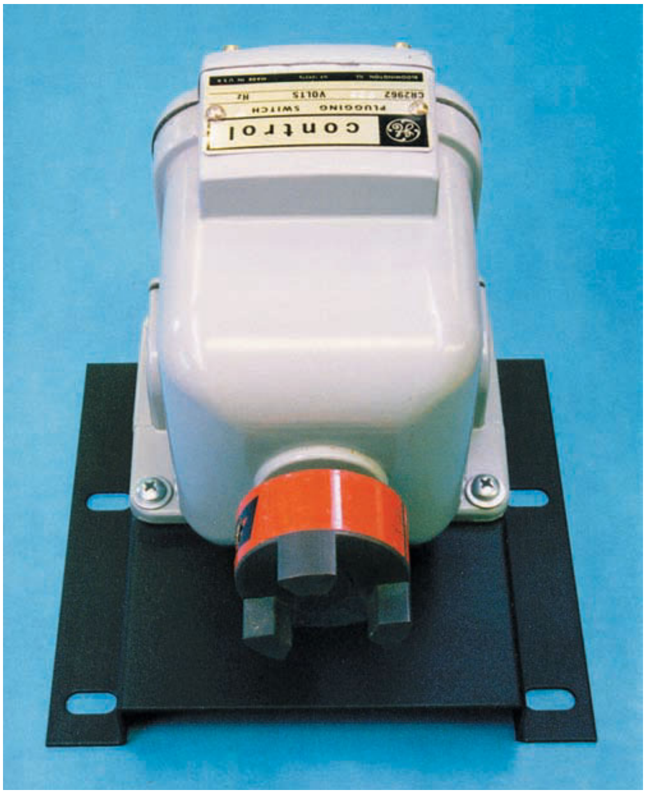


Figure 43–10 Plugging switch or zero speed switch. (Source: Delmar/Cengage Learning.)

too long, the motor will reverse direction before the reversing contactor opens. The most accurate method of plug stopping a motor is with a *plugging switch* or *zero speed switch* (Figure 43–10). The plugging switch is connected to the motor shaft or the shaft of the drive machine. The motion of the rotating shaft is transmitted to the plugging switch either by a centrifugal mechanism or by an eddy current induction disc inside the switch. The plugging switch contact is connected to the coil of the reversing starter (Figure 43–11). When the motor is started, the forward motion of the motor causes the normally open plugging switch contact to close. When the STOP button is pressed, the normally closed F contact connected in series with the reversing contactor will re-close and reverse the direction of rotation of the motor. When the shaft of the motor stops rotating, the plugging switch contact will reopen and disconnect the reversing contactor.

Plugging switches with two normally open contacts can be obtained for use with forward-reverse controls. These switches permit a plugging stop in either direction when the STOP button is pressed (Figure 43–12). The direction of motor rotation will determine which switch closes. The switch symbol indicates the direction of rotation necessary to cause the switch contacts to close.

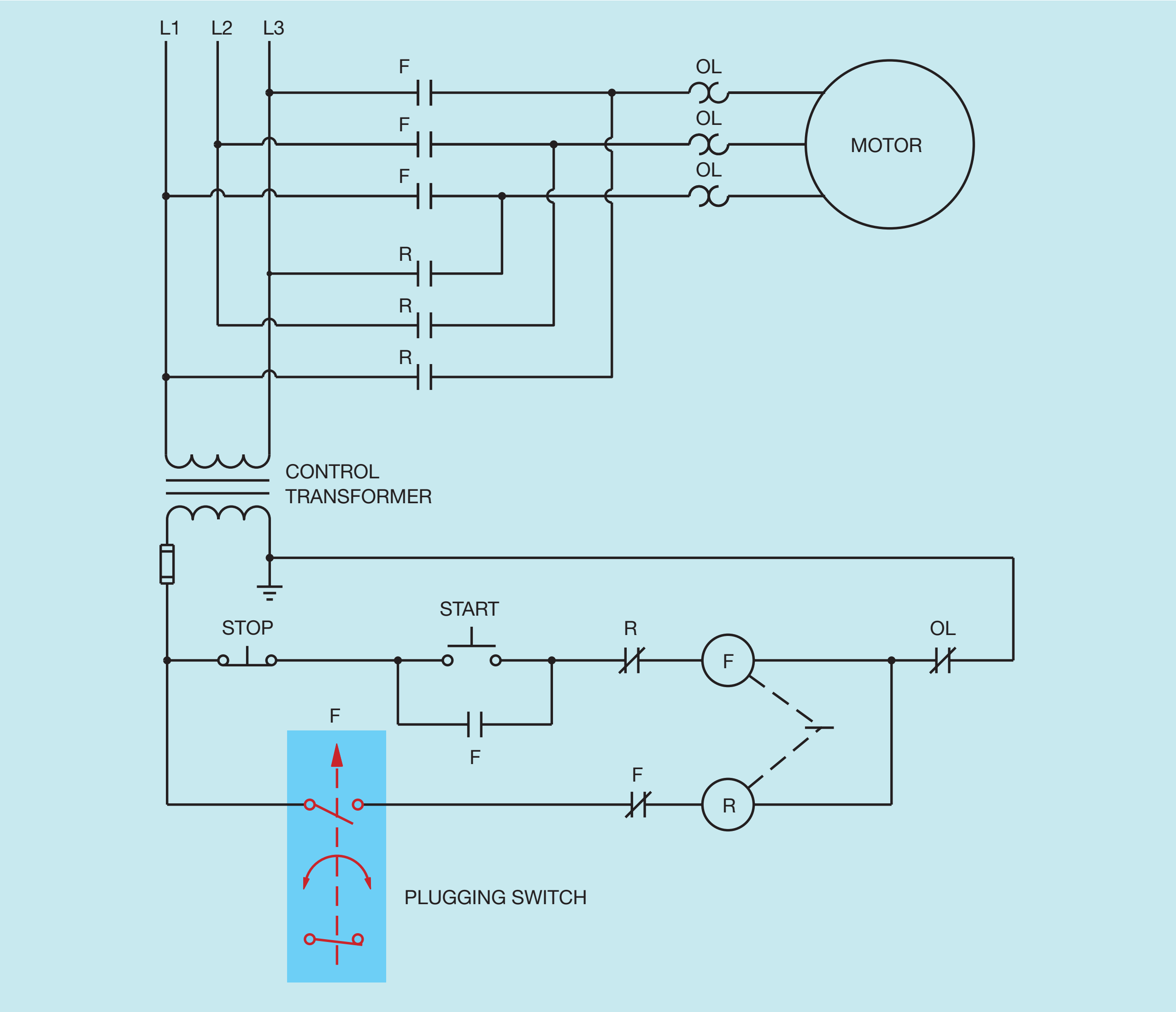


Figure 43–11 Plugging switch controls the operation of the reversing contactor. (Source: Delmar/Cengage Learning.)

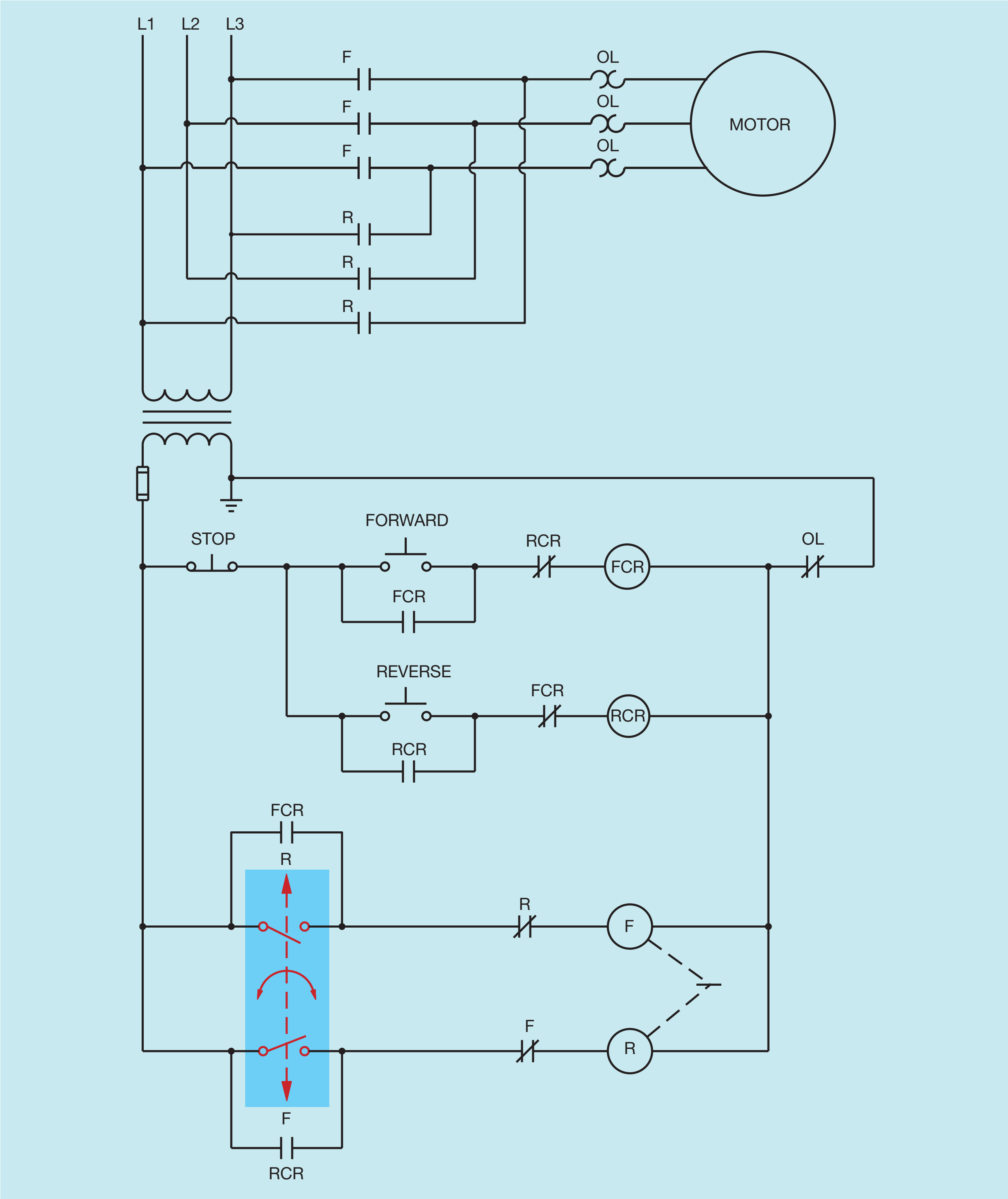


Figure 43–12 Plugging switch used with forward-reverse control. (Source: Delmar/Cengage Learning.)

Review Questions

1. Name three methods of braking a motor.
2. How is the braking force of drum type brakes controlled?
3. Why are mechanical brakes often used on cranes?
4. What is the advantage of dynamic brakes over mechanical brakes?
5. What is the disadvantage of dynamic brakes when compared to mechanical brakes?
6. The amount of counter torque developed by a direct current generator is proportional to what?
7. When using dynamic braking for a direct current motor, how is the braking time controlled?
8. Name three factors that determine the amount of induced voltage.
9. How is dynamic braking for direct current motors accomplished?
10. How is the dynamic braking force of an alternating current motor controlled?
11. How is a plugging stop accomplished?
12. What device is generally used to accurately stop a motor when a plugging stop is used?
13. Refer to the circuit shown in Figure 43–11. When the START button is pushed and the motor starts in the forward direction, the plugging switch will close. What prevents the reversing contactor from energizing when the plugging switch contact closes?

CHAPTER 44

WOUND ROTOR INDUCTION MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Identify the terminal markings of a wound rotor induction motor.
- Discuss the operating characteristics of wound rotor motors.
- Connect a wound rotor motor for operation.
- Discuss speed control of wound rotor motors.

The wound rotor induction motor is one of the three major types of three-phase motors. It is often called the *slip ring* motor because of the three slip rings on the rotor shaft. The stator winding of a wound rotor motor is identical to the squirrel cage motor. The difference between the two motors lies in the construction of the rotor. The rotor of a squirrel cage motor is constructed of bars connected together at each end by shorting rings. The rotor of a wound rotor induction motor is constructed by winding three separate windings in the rotor (Figure 44–1).

The wound rotor motor was the first alternating current motor that permitted speed control. It has a higher starting torque per ampere of starting current than any other type of three-phase motor. It can be started in multiple steps to provide smooth acceleration from 0 RPM to maximum RPM. Wound rotor motors are typically employed to operate conveyors, cranes, mixers, pumps, variable speed fans, and a variety of other devices. They are often used to power gear driven machines because they can be started without supplying a large amount of torque that can damage and even strip the teeth off gears.

The three-phase rotor winding will contain the same number of poles as the stator winding. One end of each rotor winding is connected together inside the rotor to form a wye connection, and the other end of each winding is connected to one of the slip rings mounted on the rotor shaft. The slip rings permit external resistance to be connected to the rotor circuit (Figure 44–2). Placing external resistance in the rotor circuit allows control of the amount of current that can flow through the rotor windings during both the starting and running of the motor. There are three factors that determine the amount of torque developed by a three-phase induction motor:

- Strength of the magnetic field of the stator.
- Strength of the magnetic field of the rotor.
- Phase angle difference between rotor and stator flux.

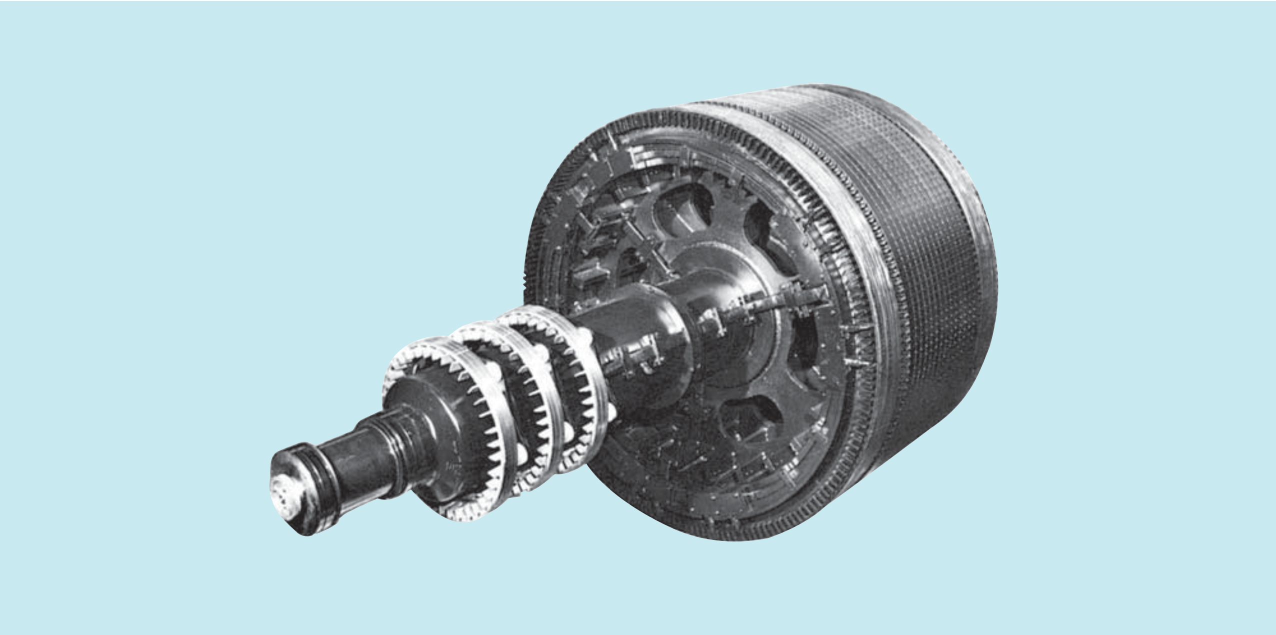


Figure 44–1 Rotor of a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

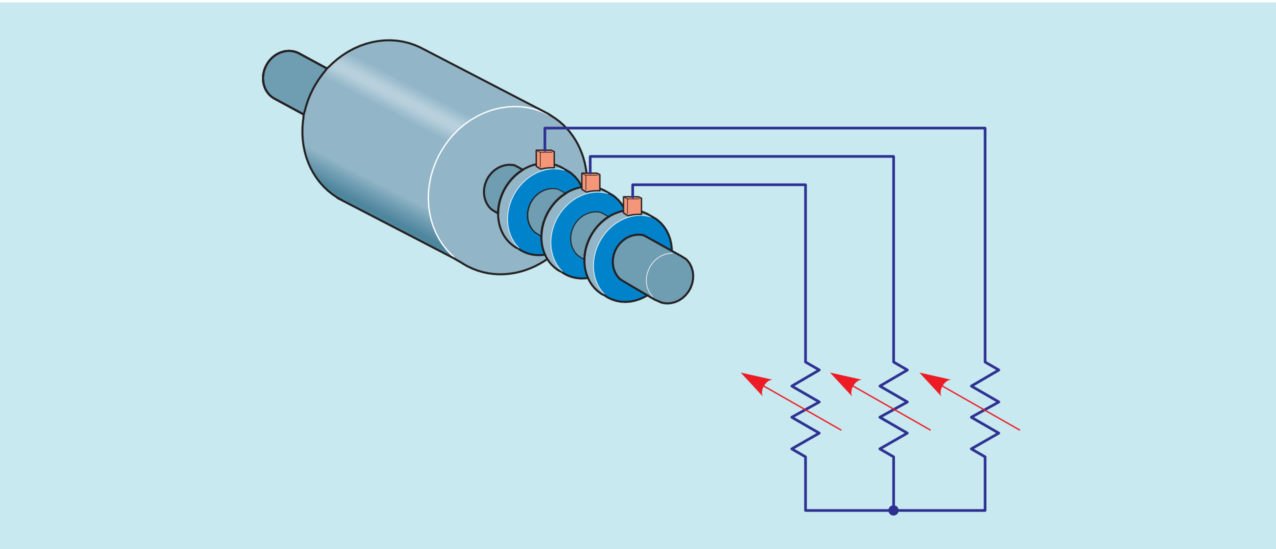


Figure 44–2 The rotor of a wound rotor induction motor is connected to external resistors. (Source: Delmar/Cengage Learning.)

Since an induction motor is basically a transformer, controlling the amount of rotor current also controls the amount of stator current. It is this feature that permits the wound rotor motor to control the in-rush current during the starting period. Limiting the in-rush current also limits the amount of starting torque produced by the motor.

The third factor that determines the amount of torque developed is the phase angle difference between stator and rotor flux. Maximum torque is developed when the magnetic fields of the stator and rotor are in phase with each other. Imagine two bar magnets with their north and south poles connected together. If the magnets are placed so there is no angular difference

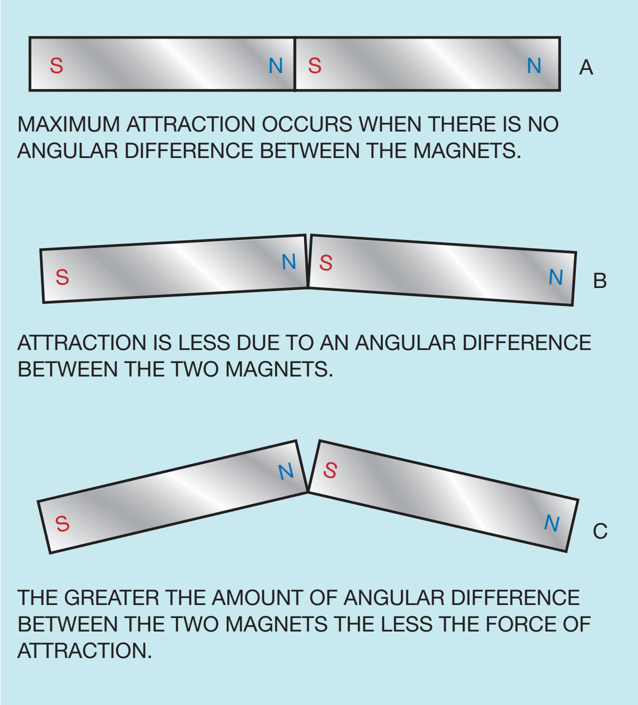


Figure 44–3 The force of attraction is proportional to the flux density of the two magnets and the angle between them. (Source: Delmar/Cengage Learning.)

between them (Figure 44–3A), the attracting force is at maximum. If the magnets are broke apart so there is an angular difference between them, there is still a force of attraction, but it is less than when they are connected together (Figure 44–3B). The greater the angle of separation, the less the force of attraction becomes (Figure 44–3C).

Adding resistance to the rotor circuit causes the induced current in the rotor to be more in phase with the stator current. This produces a very small phase angle difference between the magnetic fields of the rotor and stator. This is the reason that the wound rotor induction motor produces the greatest amount of starting torque per ampere of starting current of any three-phase motor.

The stator windings of a wound rotor motor are marked in the same manner as any other three-phase motor: T1, T2, and T3 for single voltage motors. Dual voltage motors will have nine T leads, like squirrel cage motors. The rotor leads are labeled M1, M2, and M3. The M2 lead is located on the center slip ring and the M3 lead is connected to the slip ring closest to the rotor windings. The schematic symbol for a wound rotor induction motor is shown in Figure 44–4.

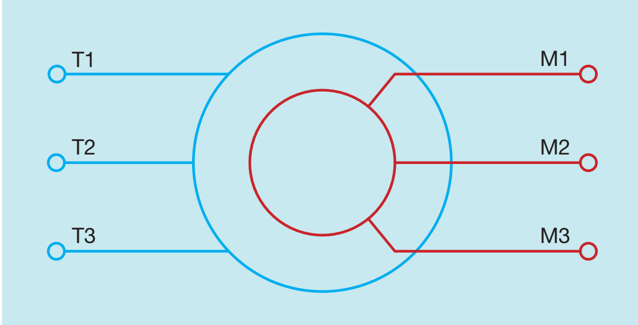


Figure 44–4 Schematic symbol for a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

Manual Control of a Wound Rotor Motor

The starting current and speed of a wound rotor induction motor is controlled by adding or subtracting the amount of resistance connected in the rotor circuit. Small wound rotor motors are often controlled manually by a three-pole make-before-break rotary switch. The switch will contain as many contacts as there are steps of resistance (Figure 44–5). A micro limit switch senses when the controller is set for maximum resistance. Most controllers will not start unless all resistance is in the rotor circuit, forcing the motor to start in its lowest speed. Once the motor has been started, the resistance can then be adjusted out to increase the motor speed. When all the resistance has been removed from the circuit and the M leads are shorted together, the motor will operate at full speed. The operating characteristics of a wound rotor motor with the rotor leads shorted together are very similar to those of a squirrel cage motor. A circuit for use with a manual controller is shown in Figure 44–6.

Timed Controlled Starting

Another method of starting a wound rotor motor is with the use of time delay relays. Any number of steps can be employed, depending on the needs of the driven machine. A circuit with four steps of starting is shown in Figure 44–7. In the circuit shown, when the START button is pressed, motor starter M energizes and closes all M contacts. The load contacts connect the stator winding to the power line. At this point in time, all resistance is connected in the rotor circuit, and the motor starts in its lowest speed. When the M auxiliary

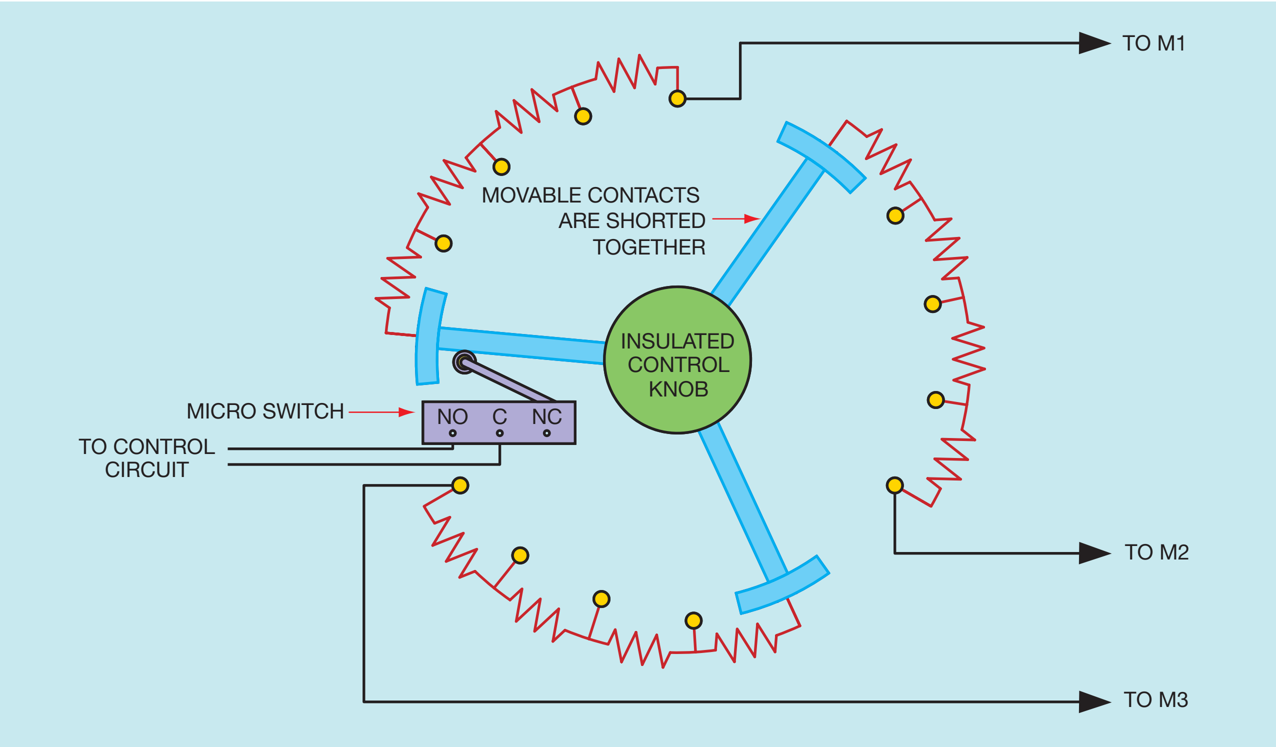


Figure 44–5 Manual controller for a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

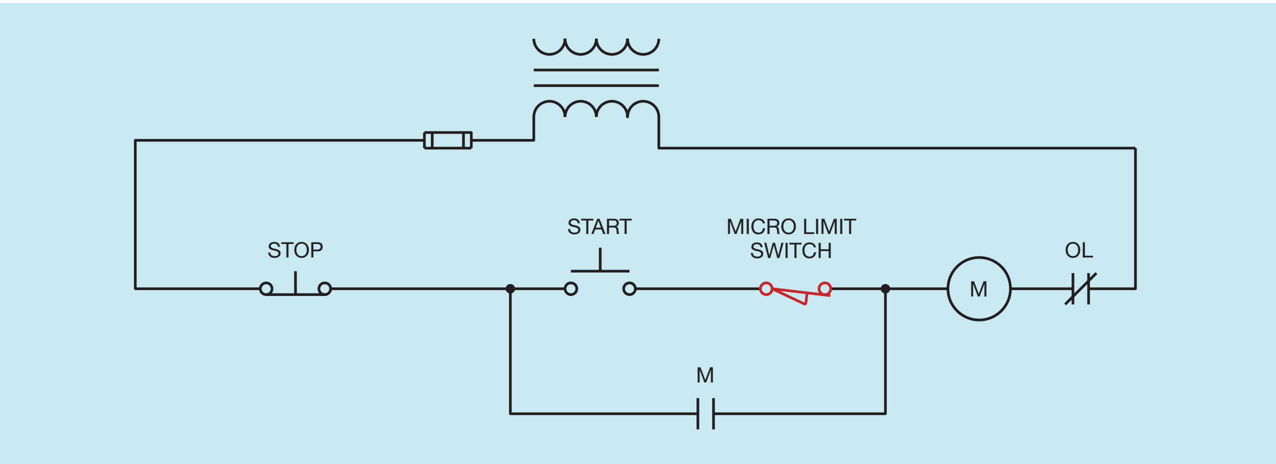


Figure 44–6 Control circuit for a manually controlled wound rotor motor. (Source: Delmar/Cengage Learning.)

contacts close, timer TR1 begins its time sequence. At the end of the time period, timed contact TR1 closes and energizes the coil of contactor S1. This causes the S1 load contacts to close and short out the first bank of resistors in the rotor circuit. The motor now accelerates to the second speed. The S1 auxiliary contact starts the operation of timer TR2. At the end of the time period, timed contact TR2 closes and energizes contactor S2. This causes the S2 load contacts to close and shunt out the second bank of resistors. The motor accelerates to third speed. The process continues until all the resistors have been shorted out of the circuit and the motor operates at the full speed.

The circuit shown in Figure 44–7 is a starter circuit in that the speed of the motor cannot be controlled by permitting resistance to remain in the circuit. Each time the START button is pressed, the motor accelerates through each step of speed until it reaches full speed.

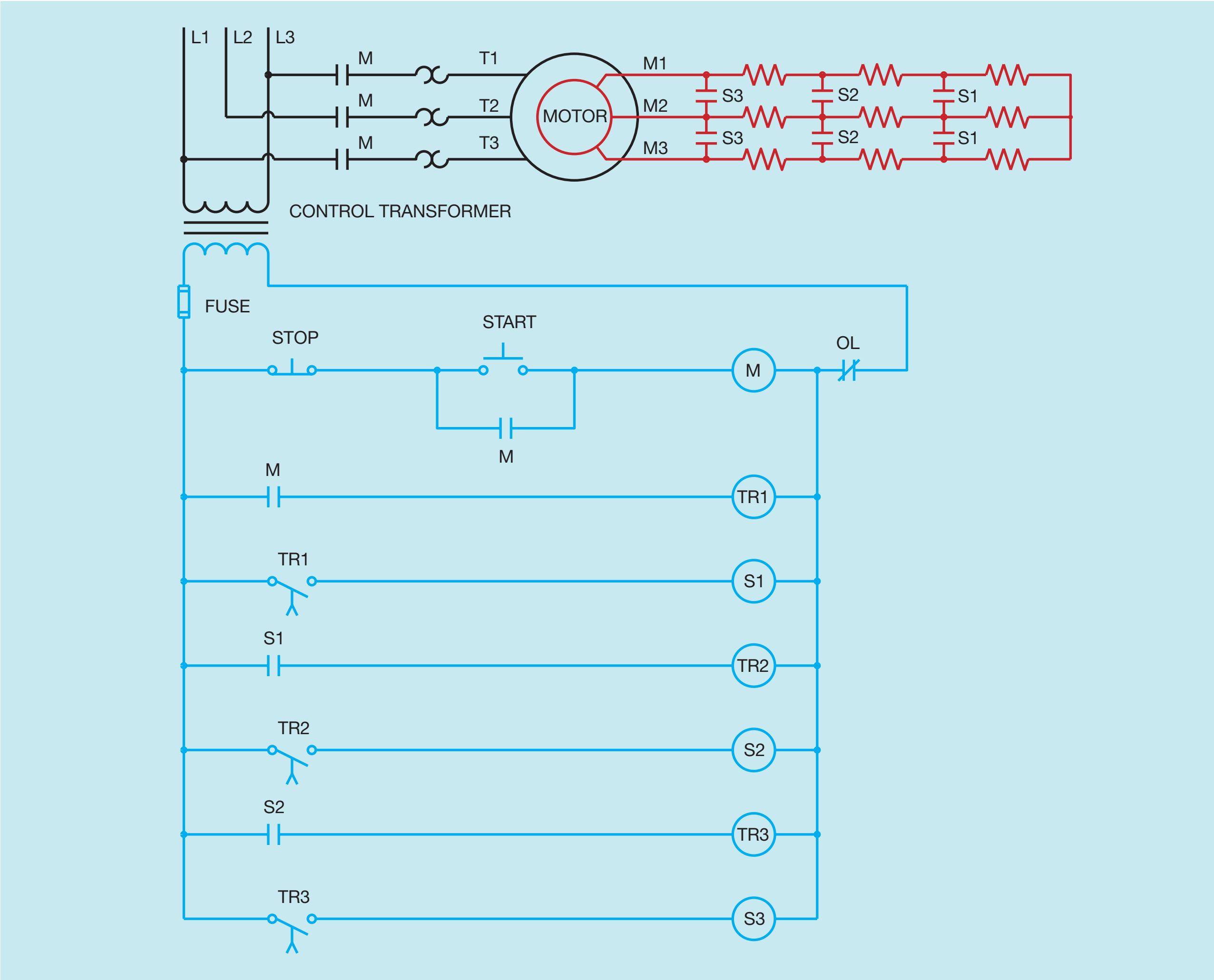


Figure 44–7 Timed starting for a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

Starting circuits generally employ resistors of a lower wattage value than circuits that are intended for speed control, because the resistors are used for only a short period of time when the motor is started. Controllers must employ resistors that have a high enough wattage rating to remain in the circuit at all times.

Wound Rotor Speed Control

A time operated controller circuit is shown in Figure 44–8. In this circuit, four steps of speed control are possible. Four separate push buttons permit selection of the operating speed of the motor. If any speed other than the lowest speed or first speed is selected, the motor will accelerate through each step with a 3 second time delay between each step. If the motor is operating at a low speed and a higher speed is selected, the motor will immediately increase to the next speed if it has been operating in its present speed for more than 3 seconds. Assume for example, that the motor has been operating in the second speed for more than 3 seconds. If the fourth speed is selected, the motor will immediately increase to the third speed and 3 seconds later increase to the fourth speed. If the motor is operating and a lower speed is selected, it will immediately decrease to the lower speed without time delay.

Frequency Control

Frequency control operates on the principle that the frequency of the induced voltage in the motor secondary (rotor) will decrease as the speed of the rotor increases. The rotor windings contain the same number of poles as the stator. When the motor is stopped and

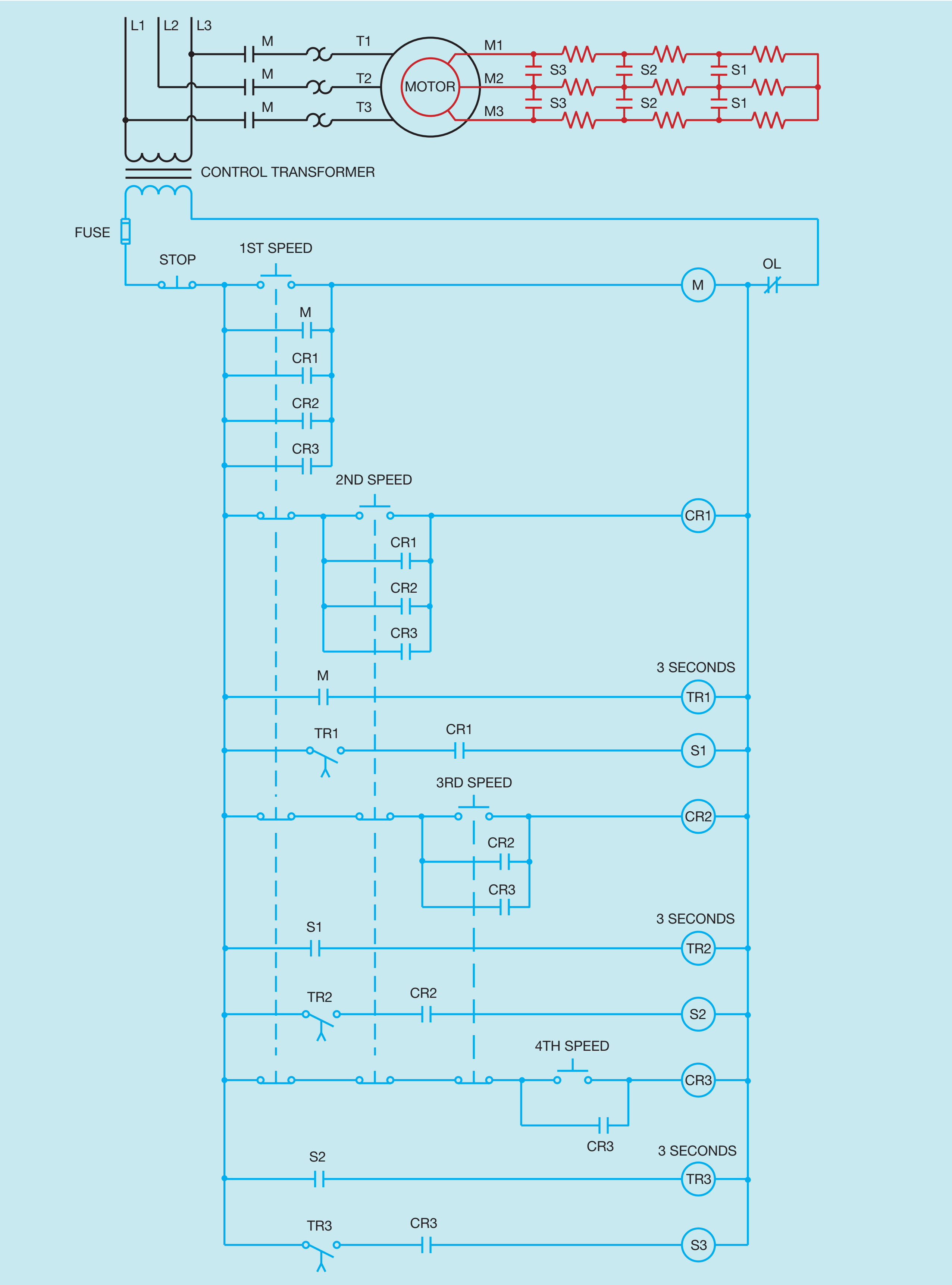


Figure 44–8 Time operated speed control for a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

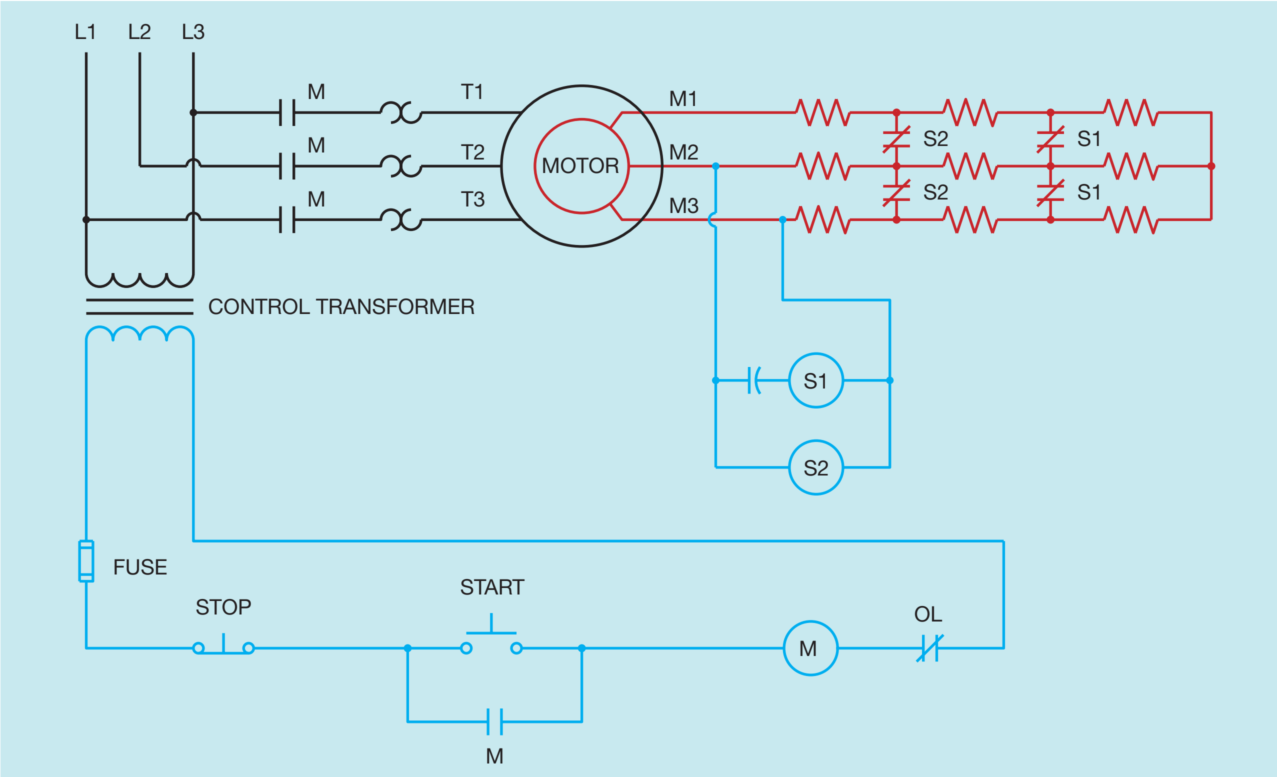


Figure 44–9 Frequency control for a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

power is first applied to the stator windings, the voltage induced into the rotor will have the same frequency as the power line. This will be 60 hertz throughout the United States and Canada. When the rotor begins to turn, there is less cutting action between the rotating magnetic field of the stator and the windings in the rotor. This causes a decrease in both induced voltage and frequency. The greater the rotor speed becomes, the lower the frequency and amount of the induced voltage. The difference between rotor speed and synchronous speed (speed of the rotating magnetic field) is called slip and is measured as a percentage. Assume that the stator winding of a motor has four poles per phase. This would result in a synchronous speed of 1800 rpm when connected to 60 hertz. Now assume that the rotor is turning as a speed of 1710 rpm. This is a difference of 90 rpm. This results in a 5% slip for the motor.

$$Slip = \frac{90}{1800}$$

$$Slip = 0.05$$

$$Slip = 5\%$$

A 5% slip would result in a rotor frequency of 3 hertz.

$$F = 60 \text{ Hz} \times 0.05$$

$$F = 3 \text{ Hz}$$

OR

$$F = \frac{PS}{120}$$

$$F = \frac{4 \times 90}{120}$$

$$F = \frac{360}{120}$$

$$F = 3 \text{ Hz}$$

Where: F = Frequency in Hertz

P = Number of Poles per Phase

S = Speed in RPM

120 = Constant

A diagram of a wound rotor motor starter using frequency relays is shown in Figure 44–9. Note that the frequency relays are connected to the secondary winding of the motor and that the load contacts are connected normally closed instead of normally open. Also note that a capacitor is connected in series with one of the frequency relays. In an alternating current circuit, the current limiting effect of a capacitor is called *capacitive reactance*. Capacitive reactance is inversely proportional to the frequency. A decrease in frequency causes a corresponding increase in capacitive reactance.

When the START button is pressed, M contactor energizes and connects the stator winding to the line. This causes a voltage to be induced into the rotor circuit at a frequency of 60 hertz. The 60 hertz frequency causes both S1 and S2 contactors to energize and open their load contacts. The rotor is now connected to maximum resistance and starts in the lowest speed. As the frequency decreases, capacitive reactance increases, causing contactor S1 to de-energize first and re-close the S1 contacts. The motor now increases in speed, causing a further reduction of both induced voltage and frequency. When contactor S2 de-energizes, the S2 load contacts re-close and short out the second bank of resistors. The motor is now operating at its highest speed.

The main disadvantage of frequency control is that some amount of resistance must remain in the circuit at all times. The load contacts of the frequency relays are closed when power is first applied to the motor. If a set of closed contacts were connected directly across the M leads, no voltage would be generated to operate the coils of the frequency relays and they would never be able to open their normally closed contacts.

Frequency control does have an advantage over other types of control in that it is very responsive to changes in motor load. If the motor is connected to a light load, the rotor will gain speed rapidly, causing the motor to accelerate rapidly. If the load is heavy, the rotor will gain speed at a slower rate, causing a more gradual increase in speed to help the motor overcome the inertia of the load.

Review Questions

1. How many slip rings are on the rotor shaft of a wound rotor motor?
2. What is the purpose of the slip rings located on the rotor shaft of a wound rotor motor?
3. A wound rotor induction motor has a stator that contains six poles per phase. How many poles per phase are in the rotor circuit?
4. Name three factors that determine the amount of torque developed by a wound rotor induction motor.
5. Explain why the wound rotor motor produces the greatest amount of starting torque per ampere of starting current of any three-phase motor.
6. Explain why controlling the rotor current controls the stator current also.
7. What is the function of a micro limit switch when used with a manual controller for a wound rotor motor?
8. Why are the resistors used in the rotor circuit smaller for a starter than for a controller?
9. What is rotor slip?
10. A wound rotor has a synchronous speed of 1200 RPM. The rotor is rotating at a speed of 1075 RPM. What is the percent of rotor slip and what is the frequency of the induced rotor voltage?
11. Refer to the circuit shown in Figure 44–6. Assume that the motor is running at full speed and the STOP button is pressed. The motor stops running. When the manual control knob is returned to the highest resistance setting, the motor immediately starts running in its lowest speed. Which of the following could cause this problem?
    a. The STOP push-button is shorted.
    b. The START push-button is shorted.
    c. M auxiliary contact is shorted.
    d. The micro limit switch contact did not re-close when the control was returned to the highest resistance setting.
12. Refer to the circuit shown in Figure 44–7. Assume that the timers are set for a delay of 3 seconds each. When the START button is pressed, the motor starts in its lowest speed. After 3 seconds, the motor accelerates to second speed, but never reaches third speed. Which of the following **cannot** cause this problem?
    a. TR1 timer coil is open.
    b. S1 contactor coil is open.

c. TR2 timer coil is open.
d. S2 contactor coil is open.

13. Refer to the schematic diagram in Figure 44–8. Assume that the motor is not running. When the 3RD SPEED push-button is pressed, the motor starts in its lowest speed. After a delay of 3 seconds, the motor accelerates to second speed and 3 seconds later to 3 speed. After a period of about 1 minute, the 4TH SPEED push-button is pressed, but the motor does not accelerate to fourth speed. Which of the following could cause this problem?
a. Control relay CR2 coil is open.
b. S2 contactor coil is open.
c. CR3 coil is shorted.
d. S2 contactor coil is open.

CHAPTER 45

SYNCHRONOUS MOTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of a synchronous motor.
- List differences between synchronous motors and squirrel cage motors.
- Explain the purpose of an amortisseur winding.
- Discuss how a synchronous motor can produce a leading power factor.
- Discuss the operation of a brushless exciter.

Synchronous motors are so named because of their ability to operate at synchronous speed. They are able to operate at the speed of the rotating magnetic field because they are **not** induction motors. They exhibit other characteristics that make them different than squirrel cage or wound rotor induction motors. Some of these characteristics are:

- They can operate at synchronous speed.
- They operate at a constant speed from no load to full load. Synchronous motors will either operate at synchronous speed or they will stall and stop running.
- They can produce a leading power factor.
- They are sometimes operated without load to help correct plant power factor. In this mode of operation, they are called synchronous condensers.
- The rotor must be excited with an external source of direct current.
- They contain a special squirrel cage winding called the amortisseur winding that is used to start the motor.

Starting a Synchronous Motor

A special squirrel cage winding, called the amortisseur winding, is used to start a synchronous motor. The rotor of a synchronous motor is shown in Figure 45–1. The amortisseur winding is very similar to a type A squirrel cage winding. It provides good starting torque

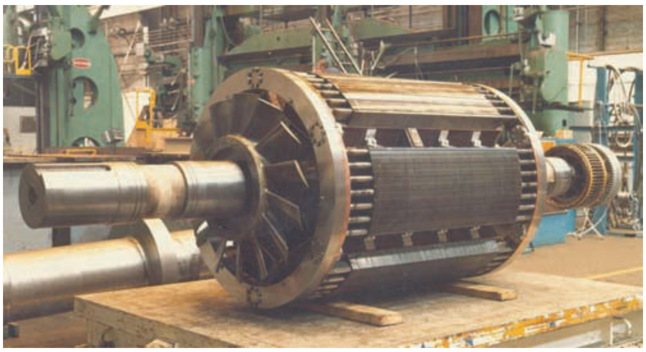


Figure 45–1 Rotor of a synchronous motor. (Courtesy GE Industrial Systems, Fort Wayne, Indiana.)

and a relatively low starting current. Once the synchronous motor has accelerated to a speed close to that of the rotating magnetic field, the rotor is excited by connecting it to a source of direct current. Exciting the rotor causes pole pieces wound in the rotor to become electromagnets. These electromagnets lock with the rotating magnetic field of the stator and the motor runs at synchronous speed. *A synchronous motor should* ***never*** *be started with excitation applied to the rotor.* The magnetic field of the pole pieces will be alternately attracted and repelled by the rotating magnetic field, resulting in no torque being produced in either direction. High induced voltage, however, may damage the rotor windings and other components connected in the rotor circuit. The excitation current should be connected to the rotor only after it has accelerated to a speed that is close to synchronous speed.

Excitation Current

There are several ways in which excitation current can be supplied to the rotor of a synchronous motor, such as slip rings, a brushless exciter, and a DC generator. Small synchronous motors generally contain two slip rings on the rotor shaft. A set of brushes are used to supply direct current to the rotor (Figure 45–2).

If manual starting is employed, an operator will manually excite the rotor after it has accelerated close to synchronous speed. During this acceleration process, a high voltage can be induced into the windings of the rotor. A resistor, called the *field discharge resistor,* is connected in parallel with the rotor winding. Its function is to limit the amount of induced voltage when the motor is started and limit the amount of induced voltage caused by the collapsing magnetic field when the motor is stopped and the excitation current is disconnected. A switch called the *field discharge switch* is used to connect the excitation current to the rotor. The switch is so designed that when it is closed it will make connection to the direct current power supply before it breaks connection with the field discharge resistor. When the switch is opened, it will make connection to the field discharge resistor before it breaks connection with the direct current power supply. This permits the field discharge resistor to always be connected to the rotor when DC excitation is not being applied to the rotor.

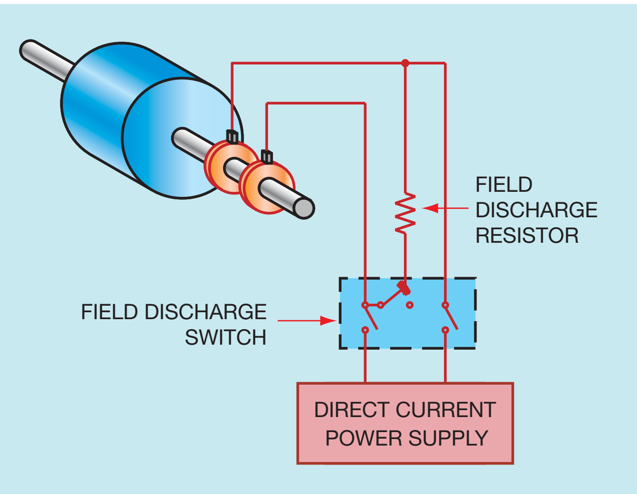


Figure 45–2 A field discharge resistor is connected in parallel with the rotor winding during starting. (Source: Delmar/Cengage Learning.)

The Brushless Exciter

A second method of supplying excitation current to the rotor is with a brushless exciter. The brushless exciter has an advantage in that there are no brushes or slip rings to wear. The brushless exciter is basically a small three-phase alternator winding and three-phase rectifier located on the shaft of the rotor. Refer to the photograph in Figure 45–1. At the back of the rotor a small winding can be seen. This is the winding of the brushless exciter. Electromagnets are placed on either side of the winding (Figure 45–3). A three-phase rectifier and fuses are also located on the rotor shaft. The rectifier converts the three-phase alternating current produced

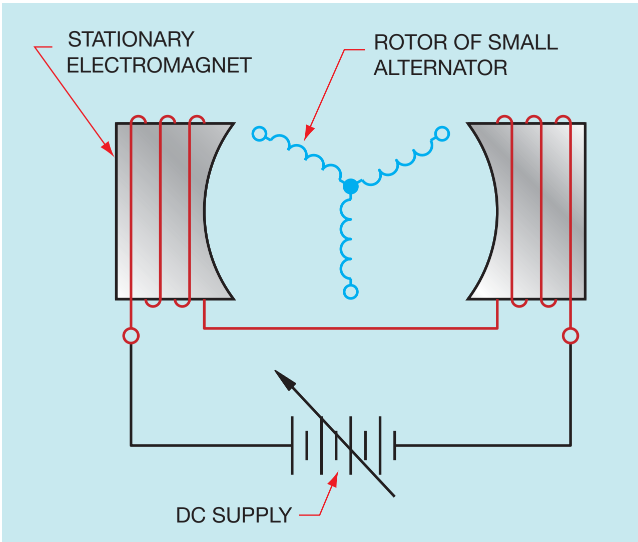


Figure 45–3 The brushless exciter contains stationary electromagnets. (Source: Delmar/Cengage Learning.)

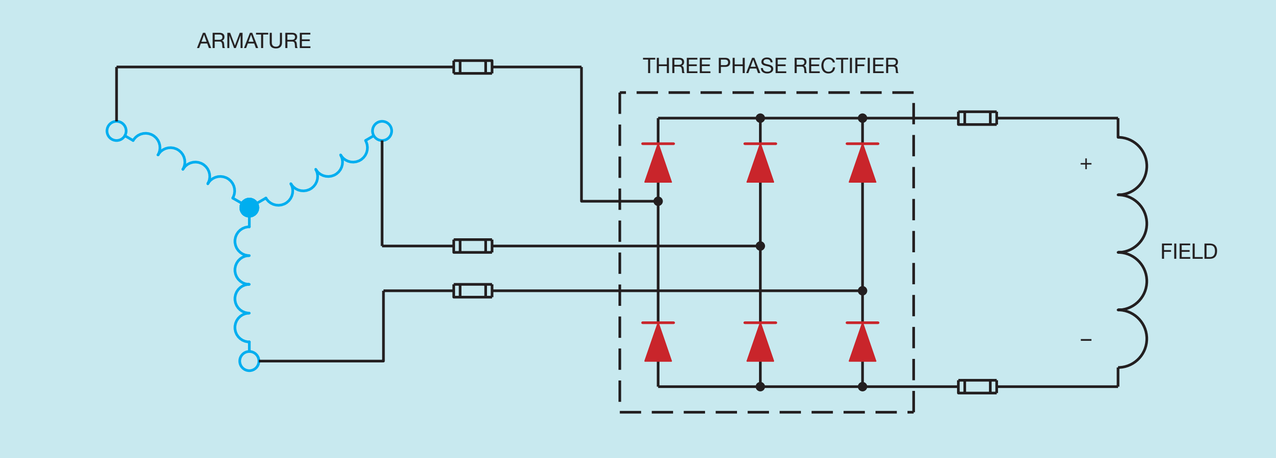


Figure 45–4 Basic brushless exciter circuit. (Source: Delmar/Cengage Learning.)

in the alternator winding into direct current before it is supplied to the rotor winding (Figure 45–4). The amount of excitation current supplied to the rotor winding is controlled by the amount of direct current supplied to the electromagnets. The output voltage of the alternator winding is controlled by the flux density of the pole pieces.

Direct Current Generator

Another method of supplying excitation current is with the use of a self-excited direct current generator mounted on the rotor shaft. The amount of excitation current is adjusted by controlling the field current of the generator. The output of the armature supplies the excitation current for the rotor. Since the generator is self-excited, it does not require an external source of direct current. Although that is an advantage over supplying the excitation current through slip rings or with a brushless exciter, the generator does contain a commutator and brushes. The generator generally requires more maintenance than the other methods.

Automatic Starting for Synchronous Motors

Synchronous motors can be automatically started as well as manually started. One of the advantages of a synchronous motor is that it provides good starting torque with a relatively low starting current. Many large motors are capable of being started directly across the line because of this feature. If the power company will not permit across the line starting, synchronous motors can also employ autotransformer starting, reactor starting, or wye-delta starting. Regardless of the method employed to connect the stator winding to the power line, the main part of automatic control for a synchronous motor lies in connecting excitation current to the rotor at the proper time. The method employed is determined by the manner in which excitation is applied to the rotor. In the case of manual excitation, the field discharge switch is used. Brushless exciter circuits often employ electronic devices for sensing the rotor speed in order to connect DC excitation to the rotor at the proper time. If a direct current generator is employed to provide excitation current, a special field contactor, out-of-step relay, and polarized field frequency relay are generally used.

The Field Contactor

The field contactor looks very similar to a common three-pole contactor (Figure 45–5). This is not a standard contactor, however. The field contactor contains a DC coil and is energized by the excitation current of the rotor. The field contactor serves the same function as the field discharge switch discussed previously. The two outside contacts connect and disconnect the excitation current to the rotor circuit. The middle contact connects and disconnects the field discharge resistor at the proper time.

Out-of-Step Relay

The out-of-step relay is actually a timer that contains a current-operated coil instead of a voltage-operated coil. The coil is connected in series with the field discharge resistor. The timer can be pneumatic, dashpot, or elec-

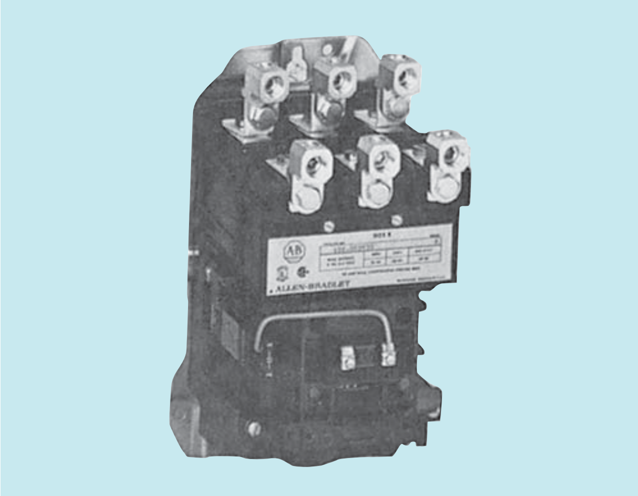


Figure 45–5 Field contactor used in the starting of a synchronous motor. (Courtesy Allen-Bradley Co.)

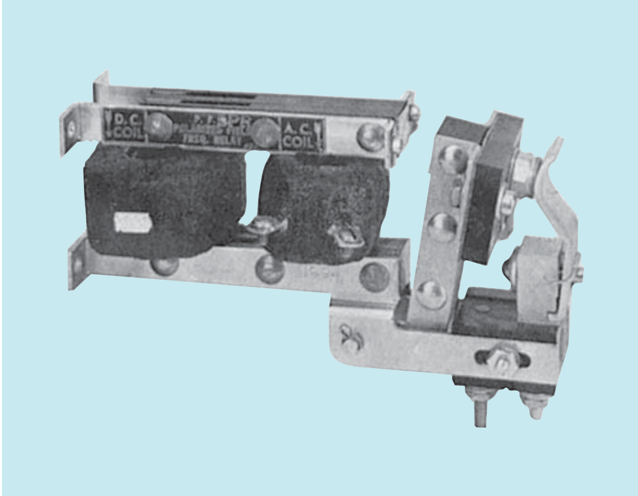


Figure 45–7 Polarized field frequency relay. (Courtesy Allen-Bradley Co.)

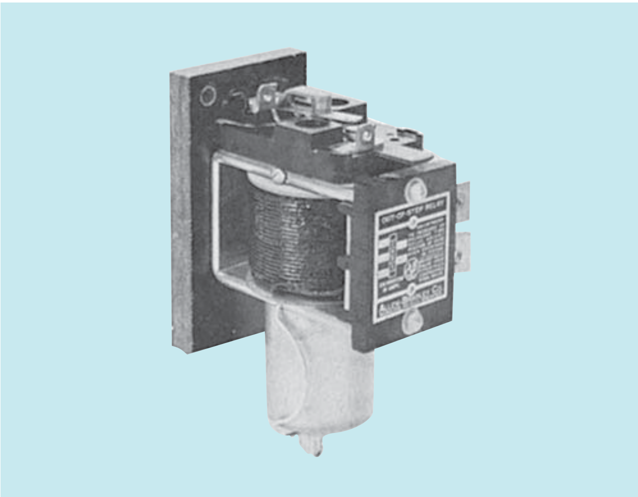


Figure 45–6 Out-of-step relay. (Courtesy of Allen-Bradley Co.)

tronic. A dashpot type of out-of-step relay is shown in Figure 45–6. The function of the out-of-step relay is to disconnect the motor from the power line in the event that the rotor is not excited within a certain length of time. Large synchronous motors can be damaged by excessive starting current if the rotor is not excited within a short time.

The Polarized Field Frequency Relay

The polarized field frequency relay (Figure 45–7) is responsible for sensing the speed of the rotor and controlling the operation of the field contactor. The polarized field frequency relay (PFR) is used in conjunction with a reactor. The reactor is connected in the rotor circuit of the synchronous motor. The polarized field frequency relay contains two separate coils, one DC and one AC (Figure 45–8). Coil A is the DC coil and is connected to the source of direct current excitation. Its function is to polarize the magnetic core material of the relay. Coil B is the AC coil. This coil is connected in parallel with the reactor (Figure 45–9). To understand the operation of the circuit, first consider the path of magnetic flux taken if only the DC coil of the PFR is energized (Figure 45–10). Note that the flux path is through the cross bar, not the ends, of the relay. Since the flux does not reach the ends of the pole piece, the armature is not attracted and the contact remains closed.

When the synchronous motor is started, however, the rotating magnetic field of the stator induces an AC voltage into the rotor winding. A current path exists through the reactor, field discharge resistor, and coil of the out-of-step relay. Since the induced voltage is 60 hertz at the instant of starting, the inductive reactance of the reactor causes a major part of the rotor current to flow through the AC coil of the polarized field frequency relay. Since alternating current is flowing through the AC coil of the PFR, each half cycle the flux produced in the AC coil opposes the flux produced by the DC coil. This causes the DC flux to be diverted to the ends of the pole pieces where it is combined with the AC flux, resulting in a strong enough flux to attract the armature, opening the normally closed contact (Figure 45–11).

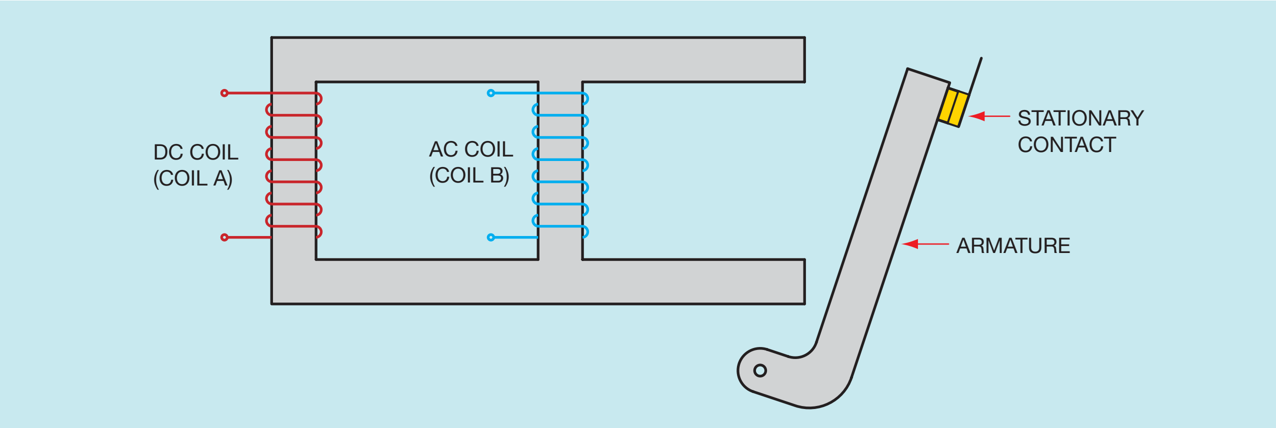


Figure 45–8 The polarized field frequency relay contains both a DC and AC coil. (Source: Delmar/Cengage Learning.)

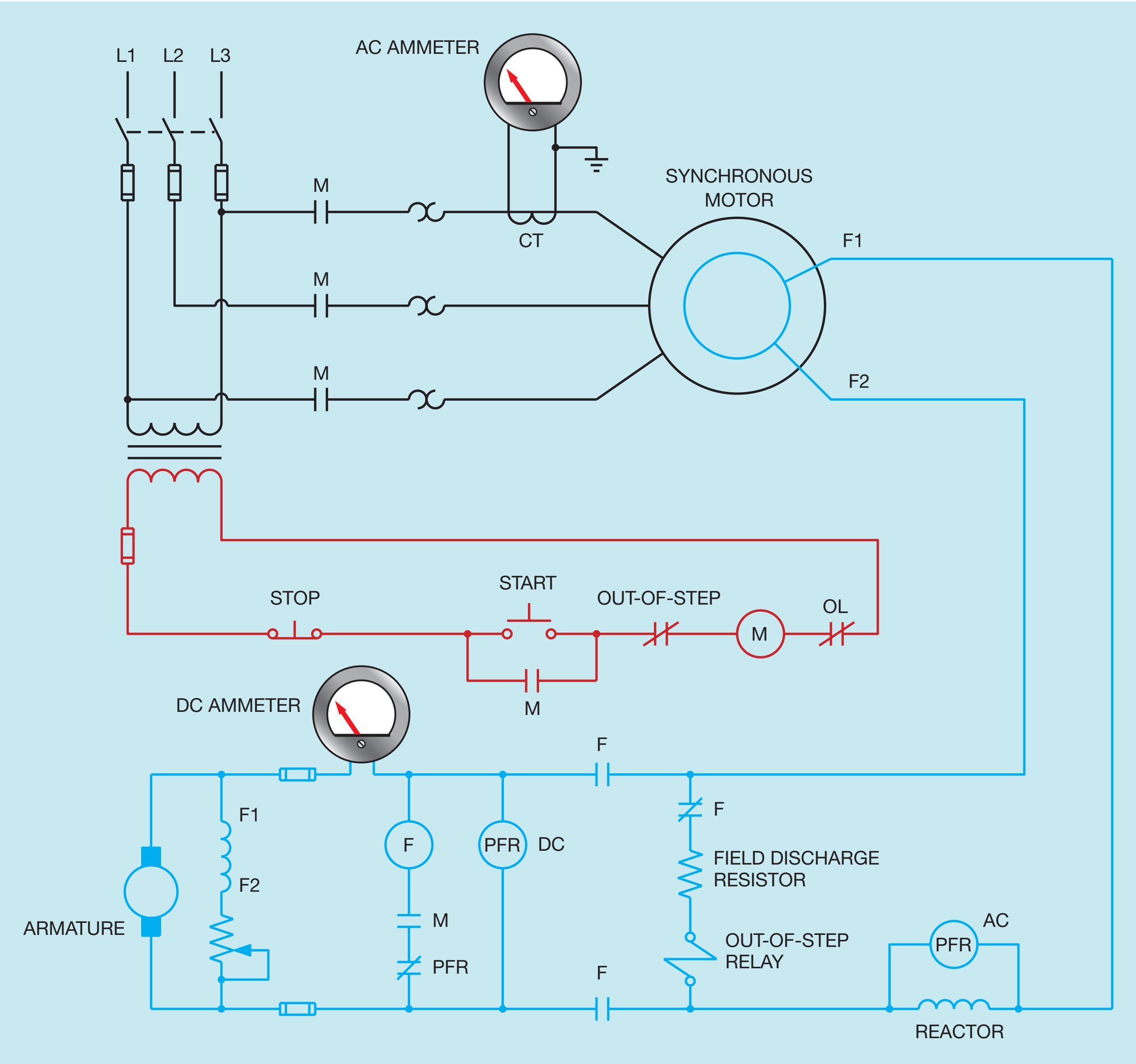


Figure 45–9 Control circuit for a synchronous motor. (Source: Delmar/Cengage Learning.)

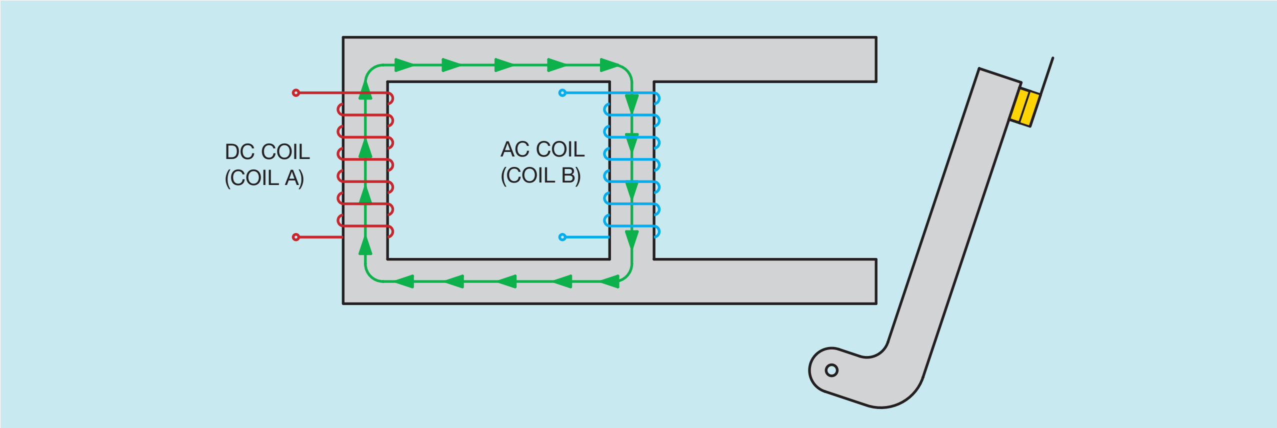


Figure 45–10 Path of magnetic flux produced by the DC coil only. (Source: Delmar/Cengage Learning.)

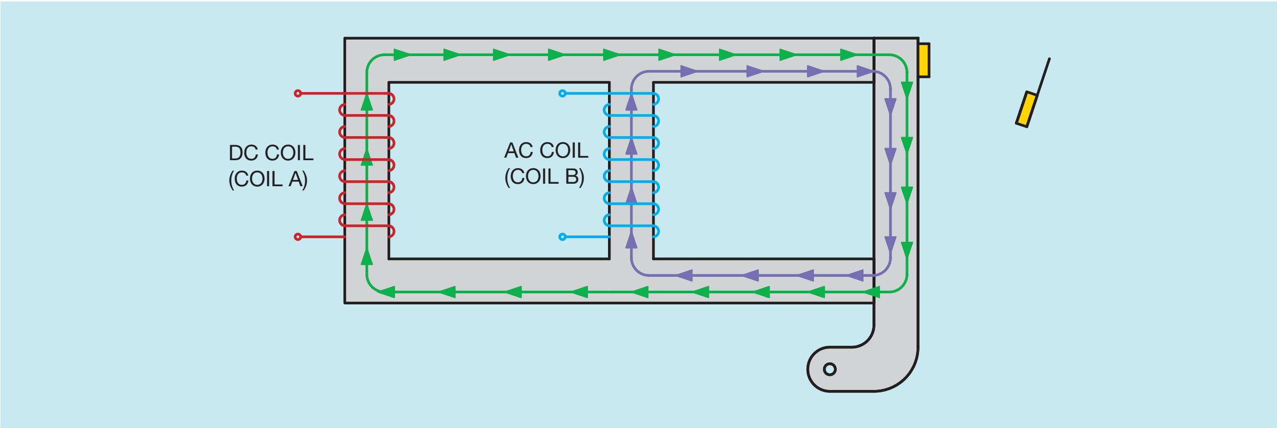


Figure 45–11 Flux of AC and DC coils combine to attract the armature. (Source: Delmar/Cengage Learning.)

In this type of control, a direct current generator is used to supply the excitation current for the rotor. When power is first applied to the stator winding, the rotor is not turning and the DC generator is not producing an output voltage. The rotating magnetic field, however, induces a high voltage into the rotor windings, supplying a large amount of current for the AC coil of the polarized field frequency relay. As the rotor begins to turn, the DC generator begins to produce a voltage, supplying power for the DC coil of the PFR. The combined flux of the two coils will cause the normally closed PFR contact to open before the field relay can energize. As the rotor speed increases, less AC voltage is induced in the rotor circuit, and the frequency decreases in proportion to rotor speed. As the frequency decreases, the inductive reactance of the reactor becomes less, causing more current to flow through the reactor and less to the AC coil. The AC coil of the PFR produces less and less flux as rotor speed increases. When the rotor reaches about 90% of the synchronous speed, the AC flux can no longer maintain the current path through the PFR armature, and the DC flux returns to the path, as shown in Figure 45–10. When the armature drops away, it recloses the PFR contact and connects the coil of the field relay to the line. When the field relay energizes, direct current is connected to the rotor circuit and the field discharge resistor and out-of-step relay are disconnected from the line.

Power Factor Correction

As stated previously, synchronous motors can be made to produce a leading power factor. A synchronous motor can be made to produce a leading power factor by over-exciting the rotor. If the rotor is under-excited, the

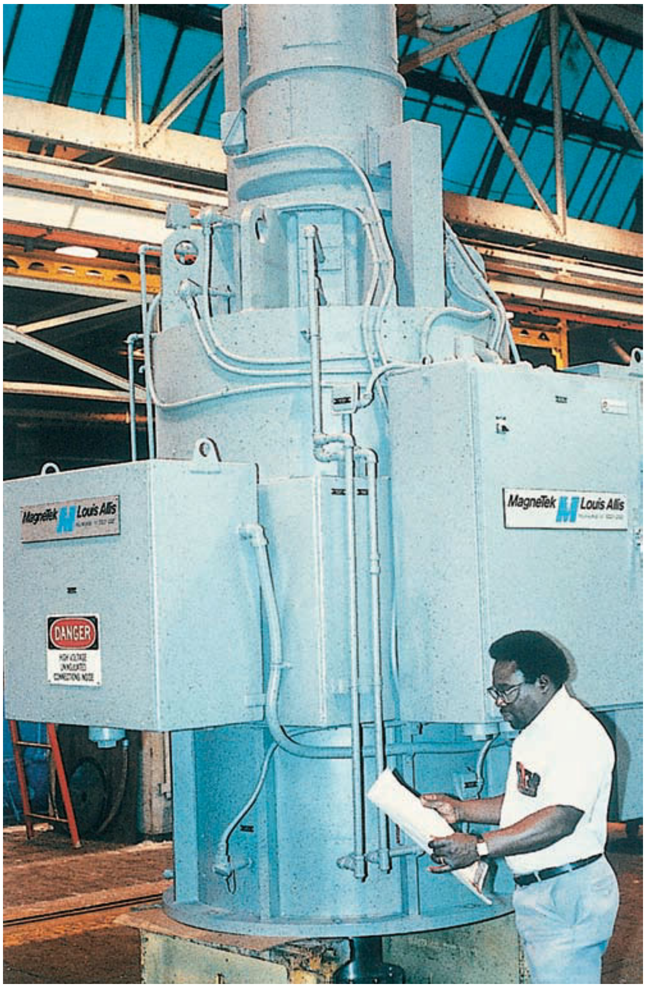


Figure 45–12 A 2500 Hp synchronous motor driving a water circulating pump. (Courtesy MagneTek Louis Allis.)

motor will have a lagging power factor similar to a squirrel cage or wound rotor induction motor. The reason for this is that when the DC excitation current is too low, part of the AC current supplied to the stator winding is used to magnetize the iron in the motor.

Normal excitation is achieved when the amount of excitation current is sufficient to magnetize the iron core of the motor and no alternating current is required. There are two conditions that will indicate when normal excitation has been achieved:

1. The current supplied to the motor will drop to its lowest level.
2. The power factor will be 100% or unity.

If more than normal excitation current is supplied, over-excitation occurs. In this condition, the DC excitation current over-magnetizes the iron of the motor, and part of the AC line current is used to de-magnetize the iron. The de-magnetizing process causes the AC line current to lead the voltage in the same manner as a capacitor.

Applications

Due to their starting characteristics and ability to correct power factor, synchronous motors are generally employed where large horsepower motors are needed. They often provide the power for pumps, compressors, centrifuges, and large grinders. A 2500 horsepower synchronous motor used to drive a water circulating pump is shown in Figure 45–12.

Review Questions

1. What is a synchronous motor called when it is operated without load and used for power factor correction?
2. What is an amortisseur winding and what function does it serve?
3. Should the excitation current be applied to the rotor of a synchronous motor before it is started?
4. What is the function of a field discharge resistor?
5. What controls the output voltage of the alternator when a brushless exciter is used to supply the excitation current of the rotor?
6. What is the purpose of the DC coil on a polarized field frequency relay?
7. What is the purpose of an out-of-step relay?
8. Why is it possible for a synchronous motor to operate at the speed of the rotating magnetic field?
9. Name two factors that indicate when normal excitation current is being applied to the motor.
10. How can a synchronous motor be made to produce a leading power factor?

CHAPTER 46

VARIABLE FREQUENCY CONTROL

OBJECTIVES

After studying this chapter, the student will be able to:

- Explain how the speed of an induction motor can be changed with a change of frequency.
- Discuss different methods of controlling frequency.
- Discuss precautions that must be taken when the frequency is lowered.
- Define the terms ramping and volts per hertz.

The speed of a three-phase induction motor can be controlled by either changing the number of stator poles per phase, as is the case with consequent pole motors, or by changing the frequency of the applied voltage. Both methods will produce a change in the synchronous speed of the rotating magnetic field. The chart shown in Figure 46–1 indicates that when the frequency is changed, a corresponding change in synchronous speed results.

POLES PER PHASE	SYNCHRONOUS SPEED IN RPM					
	60 HZ	50 HZ	40 HZ	30 HZ	20 HZ	10 HZ
2	3,600	3,000	2,400	1,800	1,200	600
4	1,800	1,500	1,200	900	600	300
6	1,200	1,000	800	600	400	200
8	900	750	600	450	300	150

Figure 46–1 Synchronous speed is determined by the number of stator poles per phase and the frequency. (Source: Delmar/Cengage Learning.)

Changing frequency, however, causes a corresponding change in the inductive reactance of the windings ($X_L = 2\pi fL$). Since a decrease in frequency produces a decrease in inductive reactance, the amount of voltage applied to the motor must be reduced in proportion to the decrease of frequency in order to prevent overheating the windings due to excessive current. Any type of variable frequency control must also adjust the output voltage with a change in frequency. There are two basic methods of achieving variable frequency control: alternator and solid state.

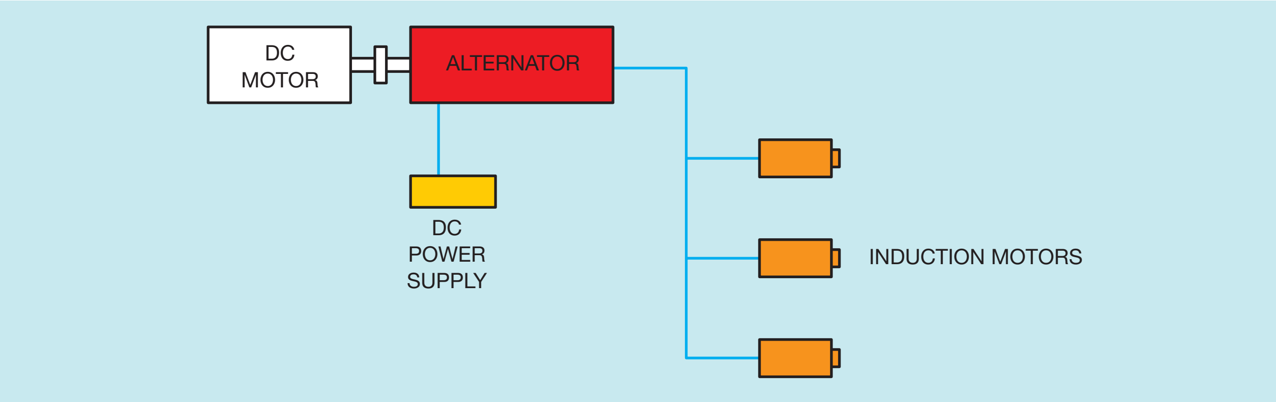


Figure 46–2 An alternator controls the speed of several induction motors. (Source: Delmar/Cengage Learning.)

Alternator Control

Alternators are often used to control the speed of several induction motors that require the same change in speed, such as motors on a conveyer line (Figure 46–2). The alternator is turned by a direct current motor or an AC motor coupled to an eddy current clutch. The output frequency of the alternator is determined by the speed of the rotor. The output voltage of the alternator is determined by the amount of DC excitation current applied to the rotor. Since the output voltage must change with a change of frequency, a variable voltage DC supply is used to provide excitation current. Most controls of this type employ some method of sensing alternator speed and make automatic adjustments to the excitation current.

Solid-State Control

Most variable frequency drives operate by first changing the AC voltage into DC and then changing it back to AC at the desired frequency. A couple of variable frequency drives are shown in Figure 46–3A and Figure 46–3B. There are several methods used to change the DC voltage back into AC. The method employed is generally determined by the manufacturer, age of the equipment, and the size motor the drive must control. Variable frequency drives intended to control the speed of motors up to 500 horsepower generally use transistors. In the circuit shown in Figure 46–4, a three-phase bridge rectifier changes the alternating current into direct current. The bridge rectifier uses six SCRs (Silicon Controlled Rectifiers). The SCRs permit the output voltage of the rectifier to be controlled. As the frequency decreases, the SCRs fire later in the cycle and lower the output voltage to the transistors. A choke coil and capacitor bank are used to filter the output voltage before transistors Q1 through Q6 change the DC voltage back into AC. An electronic control unit is connected to the bases of transistors Q1 through Q6. The control unit converts the DC voltage back into three-phase alternating current by turning transistors on or off at the proper time and in the proper sequence. Assume, for example, that transistors Q1 and Q4 are switched on at the same time. This permits stator winding T1 to be connected to a positive voltage and T2 to be connected to a negative voltage. Current can flow through Q4 to T2, through the motor stator winding and through T1 to Q1.

Now assume that transistors Q1 and Q4 are switched off and transistors Q3 and Q6 are switched on. Current will now flow through Q6 to stator winding T3, through the motor to T2, and through Q3 to the positive of the power supply.

Since the transistors are turned completely on or completely off, the waveform produced is a square wave instead of a sine wave (Figure 46–5). Induction motors will operate on a square wave without a great deal of problem. Some manufacturers design units that will produce a stepped waveform as shown in Figure 46–6. The stepped waveform is used because it more closely approximates a sine wave.

Some Related Problems

The circuit illustrated in Figure 46–4 employs the use of SCRs in the power supply and junction transistors in the output stage. SCR power supplies control the output voltage by chopping the incoming waveform.

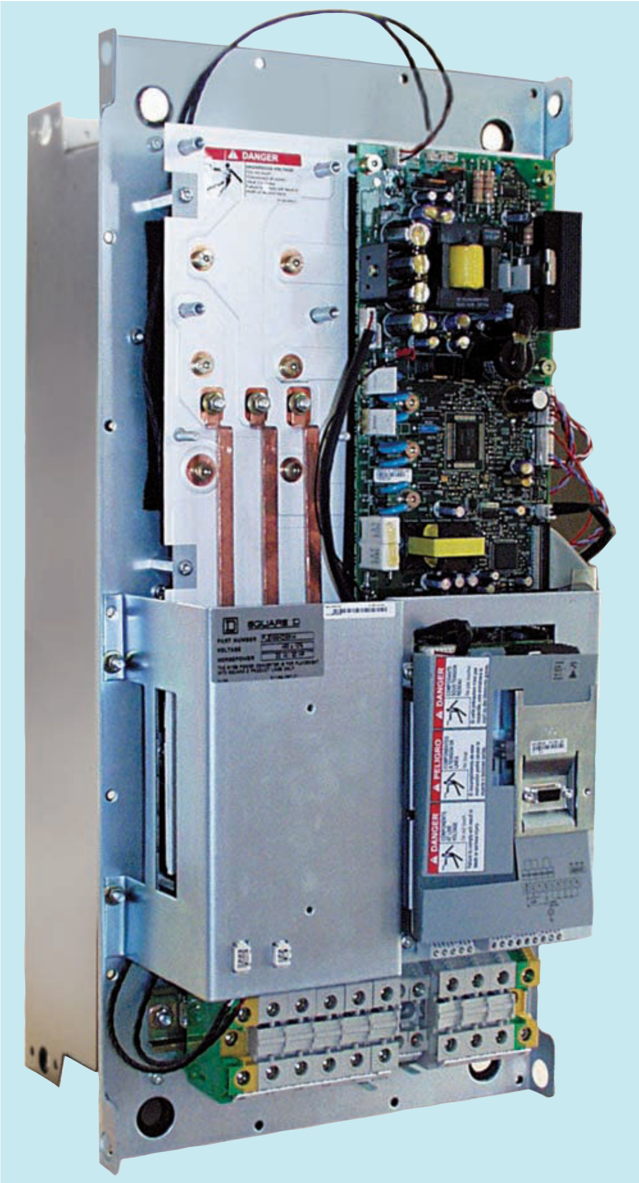


Figure 46–3A Inside of a variable frequency AC motor drive. (Courtesy Square D Company.)

This can cause harmonics on the line that cause overheating of transformers and motors, and can cause fuses to blow and circuit breakers to trip. When bipolar junction transistors are employed as switches, they are generally driven into saturation by supplying them with an excessive amount of base-emitter current. Saturating the transistor causes the collector-emitter voltage to drop to between 0.04 and 0.03 volts. This small voltage drop allows the transistor to control large amounts of current without being destroyed. When a junction transistor is driven into saturation, however, it cannot re-

Figure 46–3B 2 Hp. variable frequencydrive. (Courtesy Toshiba International Corp.)

cover or turn off as quickly as normal. This greatly limits the frequency response of the transistor.

IGBTs

Many transistor controlled variable frequency drives now employ a special type of transistor called an Insulated Gate Bipolar Transistor (IGBT). IGBTs have an insulated gate very similar to some types of field effect transistors (FETs). Since the gate is insulated, it has very high impedance. The IGBT is a voltage controlled device, not a current controlled device. This gives it the ability to turn off very quickly. IGBTs can be driven into saturation to provide a very low voltage drop between emitter and collector, but they do not suffer from the slow recovery time of common junction transistors. The schematic symbol for an IGBT is shown in Figure 46–7.

Drives using IGBTs generally use diodes, not SCRs, to rectify the AC voltage into DC (Figure 46–8).

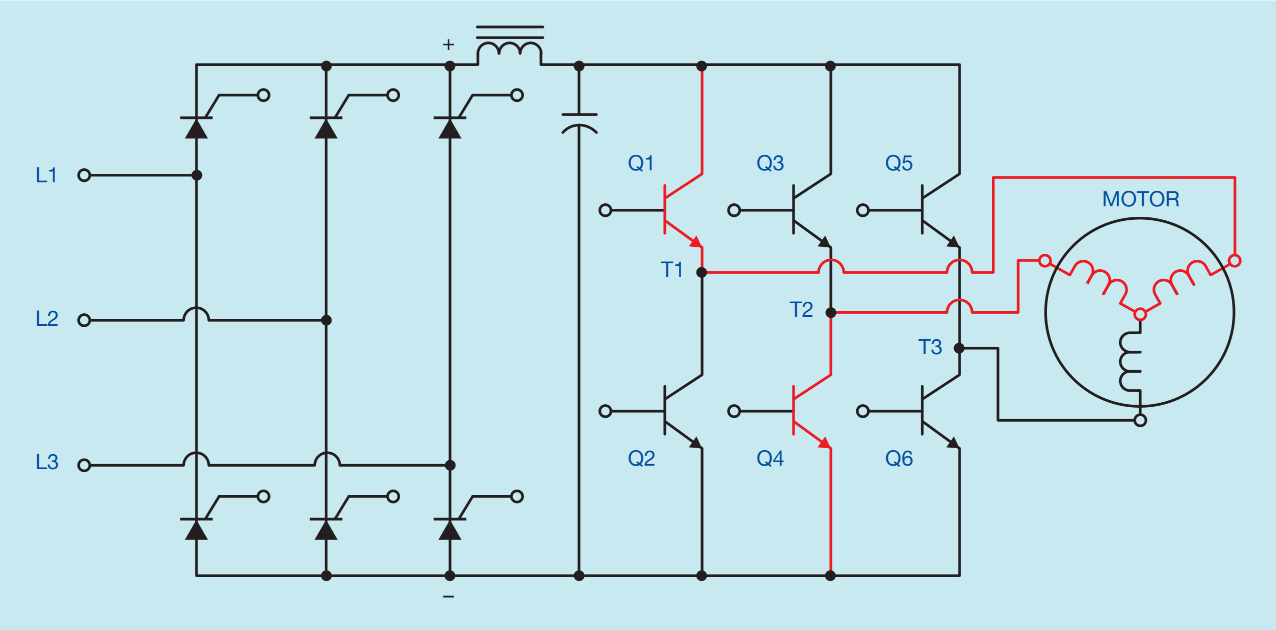


Figure 46–4 Solid-state variable frequency control using junction transistors. (Source: Delmar/Cengage Learning.)

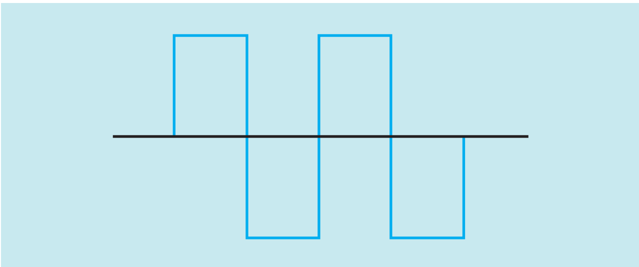


Figure 46–5 Square wave. (Source: Delmar/Cengage Learning.)

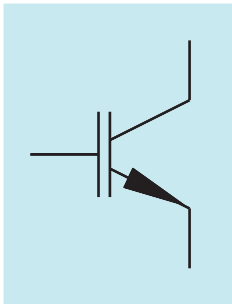


Figure 46–7 Schematic symbol for an Insulated Gate Bipolar Transistor. (Source: Delmar/Cengage Learning.)

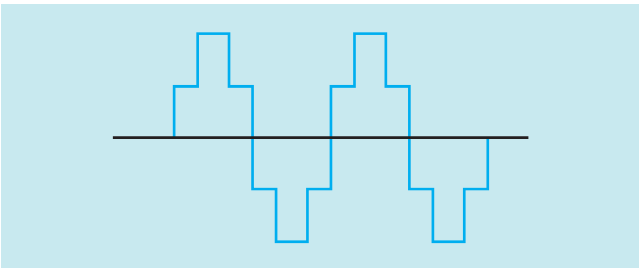


Figure 46–6 Stepped wave. (Source: Delmar/Cengage Learning.)

The three-phase rectifier supplies a constant DC voltage to the transistors. The output voltage to the motor is controlled by pulse width modulation (PWM). PWM is accomplished by turning the transistor on and off several times during each half cycle (Figure 46–9). The output voltage is an average of the peak or maximum voltage and the amount of time the transistor is turned on or off. Assume that 480 volts three-phase AC is rectified to DC and filtered. The DC voltage applied to the IGBTs is approximately 630 volts. The output voltage to the motor is controlled by the switching rate of the transistors. Assume that the transistor is on for 10 microseconds and off for 20 microseconds. In this example, the transistor is on for one-third of the time and off for two-thirds of the time. The voltage applied to the motor would be 210 volts (630/3). The speed at which IGBTs can operate permits pulse width modulation to produce

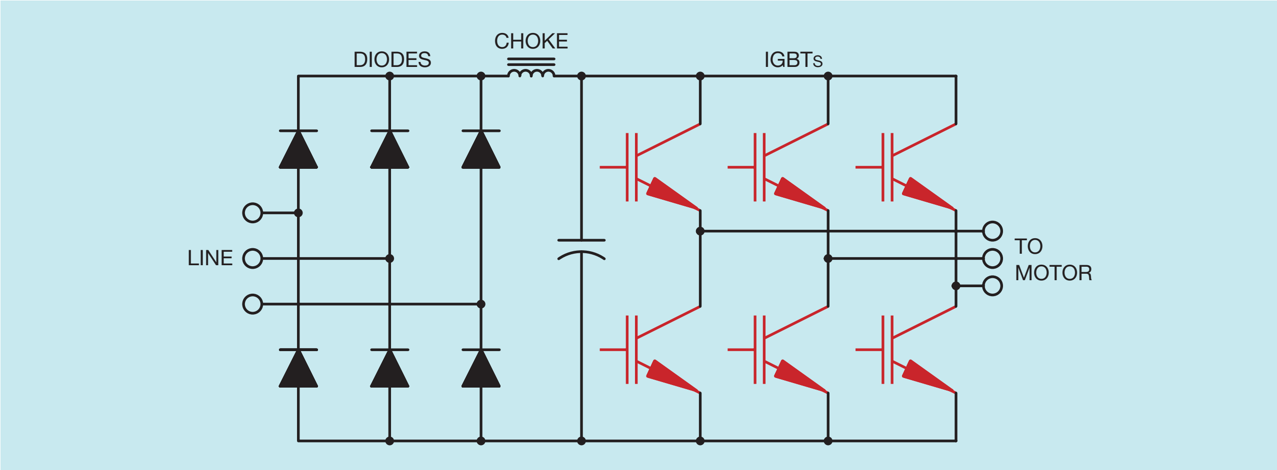


Figure 46–8 Variable frequency drives using IGBTs generally use diodes in the rectifier instead of SCRs. (Source: Delmar/Cengage Learning.)

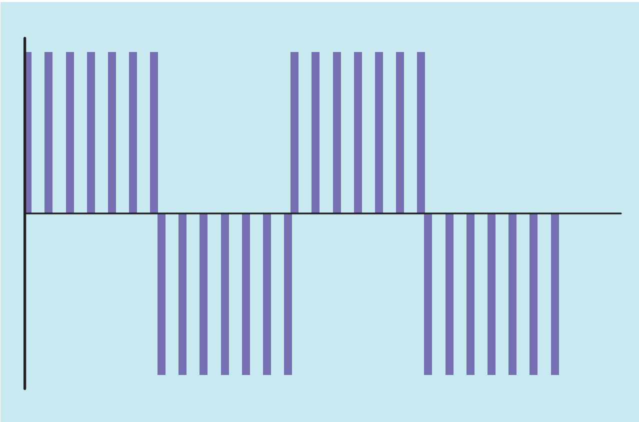


Figure 46–9 Pulse width modulation is accomplished by turning the voltage on and off several times during each half cycle. (Source: Delmar/Cengage Learning.)

a stepped wave that is very similar to a standard sine wave (Figure 46–10).

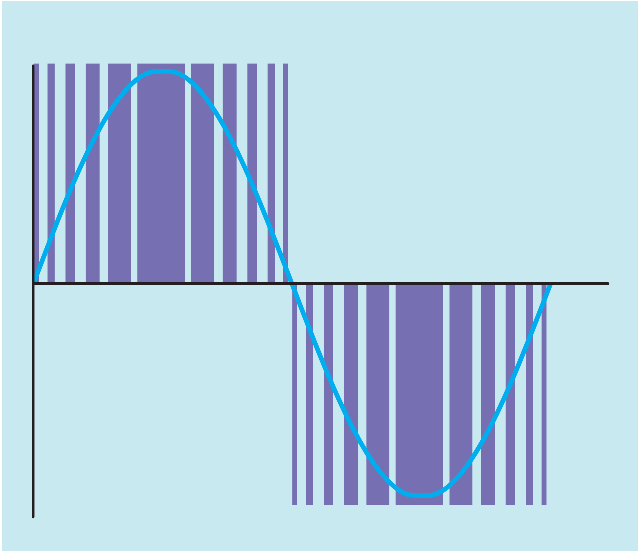


Figure 46–10 The speed of the IGBTs can produce a stepped wave that is similar to a sine wave. (Source: Delmar/Cengage Learning.)

Advantages and Disadvantages of IGBT Drives

A great advantage of drives using IGBTs is the fact that SCRs are generally not used in the power supply and this greatly reduces problems with line harmonics. The greatest disadvantage is that the fast switching rate of the transistors can cause voltage spikes in the range of 1600 volts to be applied to the motor. These voltage spikes can destroy some motors. Line length from the drive to the motor is of great concern with drives using IGBTs. Short line lengths are preferred.

Inverter Rated Motors

Due to the problem of excessive voltage spikes caused by IGBT drives, some manufacturers produce a motor that is *inverter rated*. These motors are specifically designed to be operated by variable frequency drives. They differ from standard motors in several ways:

1. Many inverter rater motors contain a separate blower to provide continuous cooling for the motor regardless of the speed. Many motors use a fan connected to

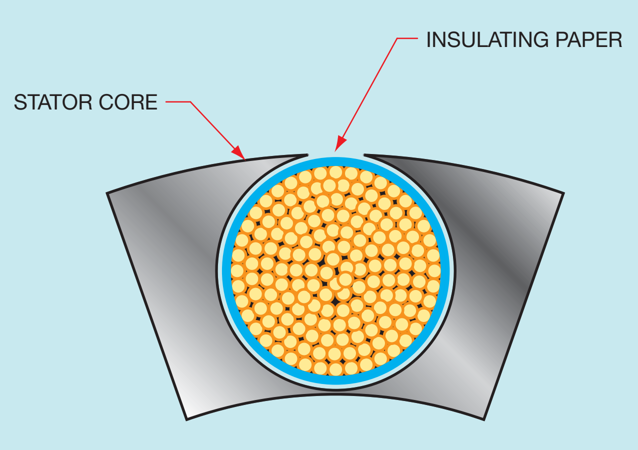


Figure 46–11 Insulating paper is between the windings and the stator frame. (Source: Delmar/Cengage Learning.)

the motor shaft to help draw air though the motor. When the motor speed is reduced, the fan cannot maintain sufficient air flow to cool the motor.

2. Inverter rated motors generally have insulating paper between the windings and the stator core (Figure 46–11). The high voltage spikes produce high currents that produce a strong magnetic field. This increased magnetic field causes the motor windings to move, because like magnetic fields repel each other. This movement can eventually cause the insulation to wear off the wire and produce a grounded motor winding.
3. Inverter rated motors generally have phase paper added to the terminal leads. Phase paper is insulating paper added to the terminal leads that exit the motor. The high voltage spikes affect the beginning lead of a coil much more than the wire inside the coil. The coil is an inductor that naturally opposes a change of current. Most of the insulation stress caused by high voltage spikes occurs at the beginning of a winding.
4. The magnet wire used in the construction of the motor windings has a higher rated insulation than other motors.
5. The case size is larger than most three-phase motors. The case size is larger because of the added insulating paper between the windings and the stator core. Also, a larger case size helps cool the motor by providing a larger surface area for the dissipation of heat.

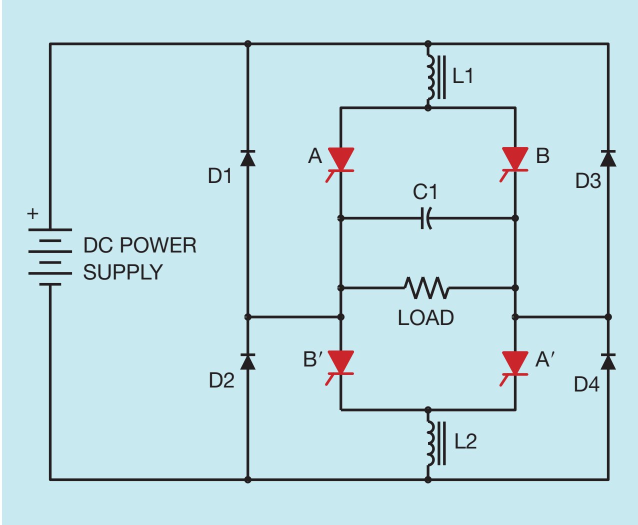


Figure 46–12 Changing DC into AC using SCRs. (Source: Delmar/Cengage Learning.)

Variable Frequency Drives Using SCRs and GTOs

Variable frequency drives intended to control motors over 500 horsepower generally use SCRs or GTOs (gate turn off device). GTOs are similar to SCRs except that conduction through the GTO can be stopped by applying a negative voltage—negative with respect to the cathode—to the gate. SCRs and GTOs are thyristors and have the ability to handle a greater amount of current than transistors. Thyristors are solid-state devices that exhibit only two states of operation: completely turned on or completely turned off. An example of a single-phase circuit used to convert DC voltage to AC voltage with SCRs is shown in Figure 46–12. In this circuit, the SCRs are connected to a phase shift unit that controls the sequence and rate at which the SCRs are gated on. The circuit is constructed so that SCRs A and A′ are gated on at the same time and SCRs B and B′ are gated on at the same time. Inductors L1 and L2 are used for filtering and wave shaping. Diodes D1 through D4 are clamping diodes and are used to prevent the output voltage from becoming excessive. Capacitor C1 is used to turn one set of SCRs off when the other set is gated on. This capacitor must be a true AC capacitor because it will be charged to the alternate polarity each half cycle. In a converter intended to handle large amounts of power, capacitor C1 will be a bank of capacitors. To understand the operation of the circuit, assume that SCRs

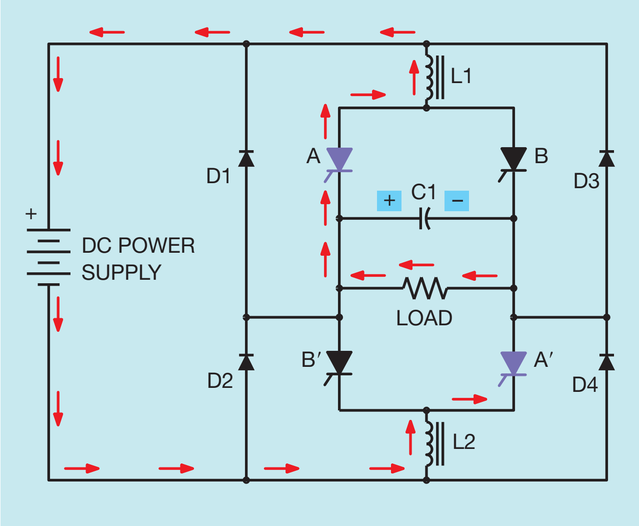


Figure 46–13 Current flows through SCRs A and A′. (Source: Delmar/Cengage Learning.)

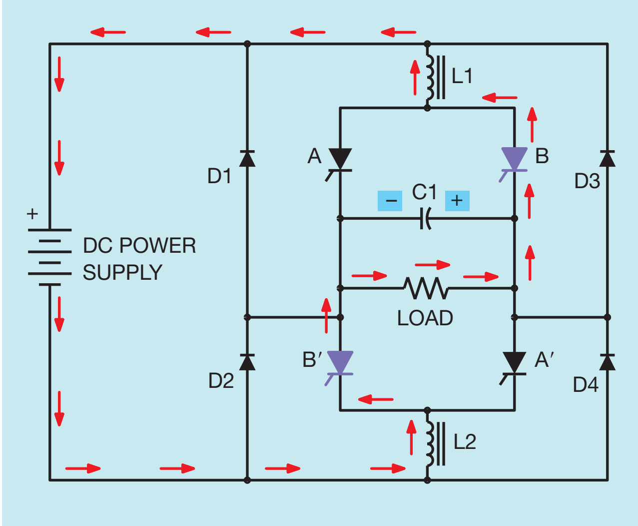


Figure 46–14 Current flows through SCRs B and B′. (Source: Delmar/Cengage Learning.)

A and A′ are gated on at the same time. Current will flow through the circuit as shown in Figure 46–13. Notice the direction of current flow through the load, and that capacitor C1 has been charged to the polarity shown. When an SCR is gated on, it can only be turned off by permitting the current flow through the anode-cathode section to drop below a certain level, called the holding current level. As long as the current continues to flow through the anode-cathode, the SCR will not turn off.

Now assume that SCRs B and B′ are turned on. Because SCRs A and A′ are still turned on, two current paths now exist through the circuit. The positive charge on capacitor C1, however, causes the negative electrons to see an easier path. The current will rush to charge the capacitor to the opposite polarity, stopping the current flowing through SCRs A and A′, permitting them to turn off. The current now flows through SCRs B and B′ and charges the capacitor to the opposite polarity (Figure 46–14). Notice that the current now flows through the load in the opposite direction, which produces alternating current across the load.

To produce the next half cycle of AC current, SCRs A and A′ are gated on again. The positively charged side of the capacitor will now cause the current to stop flowing through SCRs B and B′, permitting them to turn off. The current again flows through the load in the direction indicated in Figure 46–13. The frequency of the circuit is determined by the rate at which the SCRs are gated on. A variable frequency drive rated at 125 horsepower is shown in Figure 46–15.

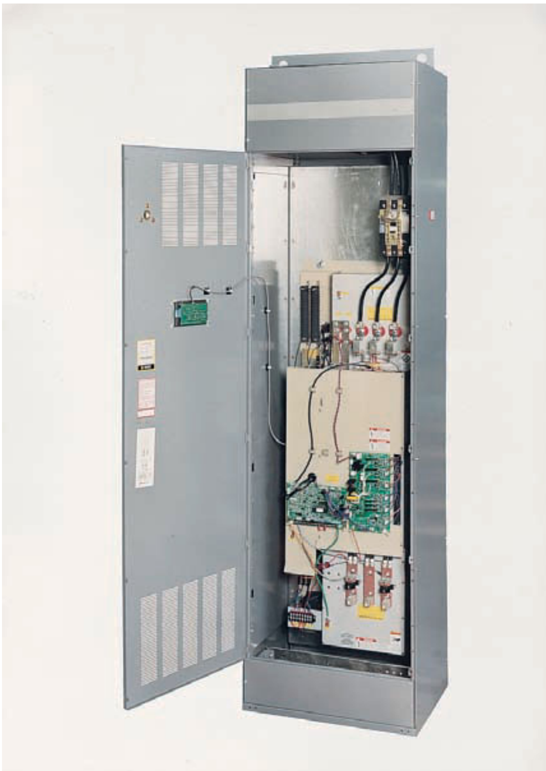


Figure 46–15 A 125 Hp. variable frequency AC motor Controller. (Courtesy Toshiba International Corp.)

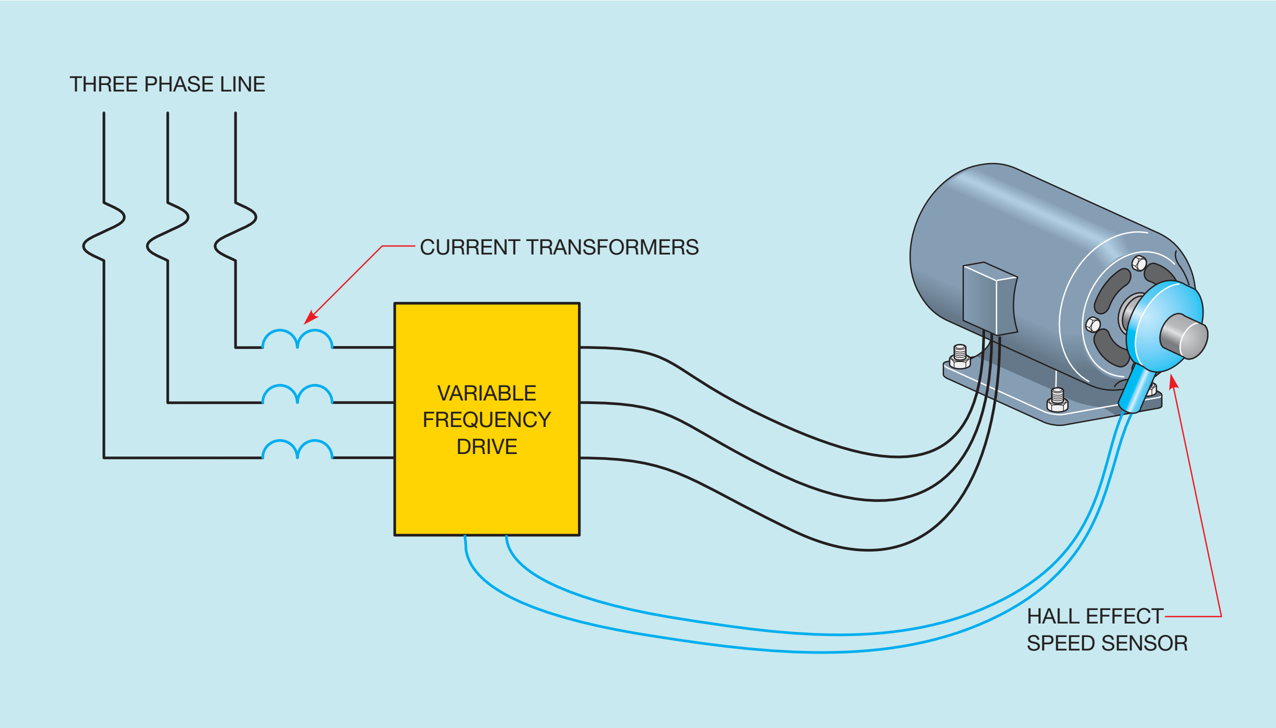


Figure 46–16 Most variable frequency drives provide current limit and speed regulation. (Source: Delmar/Cengage Learning.)

Features of Variable Frequency Control

Although the primary purpose of a variable frequency drive is to provide speed control for an AC motor, most drives provide functions that other types of controls do not. Many variable frequency drives can provide the low speed torque characteristic that is so desirable in DC motors. It is this feature that permits AC squirrel cage motors to replace DC motors for many applications.

Many variable frequency drives also provide current limit and automatic speed regulation for the motor. Current limit is generally accomplished by connecting current transformers to the input of the drive and sensing the increase in current as load is added. Speed regulation is accomplished by sensing the speed of the motor and feeding this information back to the drive (Figure 46–16).

Another feature of variable frequency drives is acceleration and deceleration control, sometimes called *ramping*. Ramping is used to accelerate or decelerate a motor over some period of time. Ramping permits the motor to bring the load up to speed slowly as opposed to simply connecting the motor directly to the line. Even if the speed control is set in the maximum position when the start button is pressed, ramping forces the motor to accelerate the load from zero to its maximum RPM over several seconds. This feature can be a real advantage for some types of loads, especially gear drive loads. In some controllers, the amount of acceleration and deceleration time can be adjusted by setting potentiometers on the main control board (Figure 46–17). Other controllers are completely digitally controlled and the acceleration and deceleration times are programmed into the computer memory.

Some other adjustments that can usually be set by changing potentiometers or programming the unit are as follows:

Current Limit: This control sets the maximum amount of current the drive is permitted to deliver to the motor.

Volts per Hertz: This sets the ratio by which the voltage increases as frequency increases or decreases as frequency decreases.

Maximum Hertz: This control sets the maximum speed of the motor. Most motors are intended to operate between 0 and 60 hertz, but some drives permit the output frequency to be set above 60 hertz,

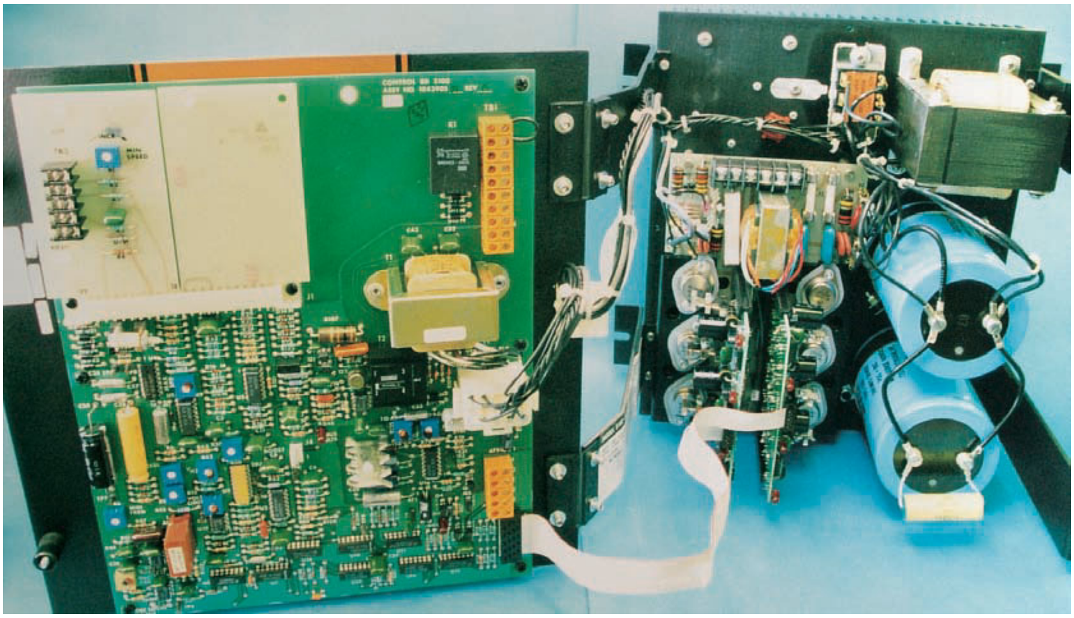


Figure 46–17 Some variable frequency drives permit setting to be made by making adjustments on a main control board. (Source: Delmar/Cengage Learning.)

which would permit the motor to operate at higher than normal speed. The maximum hertz control can also be set to limit the output frequency to a value less than 60 hertz, which would limit the motor speed to a value less than normal.

Minimum Hertz: This sets the minimum speed the motor is permitted to run.

Some variable frequency drives permit adjustment of current limit, maximum and minimum speed, ramping time, and so on, by adjustment of trim resistors located on the main control board. Other drives employ a microprocessor as the controller. The values of current limit, speed, ramping time, and so on, for these drives are programmed into the unit and are much easier to make and are generally more accurate than adjusting trim resistors. A programmable variable frequency drive is shown in Figure 46–18.

Review Questions

1. What is the synchronous speed of a six-pole motor operated with an applied voltage of 20 hertz?
2. Why is it necessary to reduce the voltage to a motor when the frequency is reduced?
3. If an alternator is used to provide variable frequency, how is the output voltage of the alternator controlled?
4. What solid-state device is generally used to produce variable frequency in drives designed to control motors up to 500 horsepower?
5. Why are SCRs used to construct a bridge rectifier in many solid-state variable frequency drives?
6. What is the main disadvantage of using SCRs in a variable frequency drive?
7. How are junction transistors driven into saturation, and what is the advantage of driving a transistor into saturation?
8. What is the disadvantage of driving a junction transistor into saturation?
9. What is the advantage of an IGBT over a junction transistor?
10. In variable frequency drives that employ IGBTs, how is the output voltage to the motor controlled?

Figure 46–18 Programmable variable frequency drives permit setting such as current limit, volts per Hz., max. and min. Hz., acceleration and deceleration to be programmed into the unit. (Courtesy Toshiba International Corp.)

11. What type of motor is generally used with IGBT drives?
12. What is the primary difference between a GTO and an SCR?
13. What is a thyristor?
14. After an SCR has been turned on, what must be done to permit it to turn off again?
15. What is meant by "ramping" and why is it used?

CHAPTER 47
MOTOR INSTALLATION

OBJECTIVES

After studying this chapter, the student will be able to:

- Determine the full load current rating of different types of motors using the *National Electrical Code (NEC)®*.
- Determine the conductor size for installing motors.
- Determine the overload size for different types of motors.
- Determine the size of the short circuit protective device for individual motors and multi-motor connections.
- Select the proper size starter for a particular motor.

Determining Motor Current

There are different types of motors, such as direct current, single-phase AC, two-phase AC, and three-phase AC. Different tables from the *National Electrical Code (NEC)®* are used to determine the running current for these different types of motors. *Table 430.247* (Figure 47–1) is used to determine the full load running current for a direct current motor. *Table 430.248* (Figure 47–2) is used to determine the full load running current for single-phase motors; *Table 430.249* (Figure 47–3) is used to determine the running current for two-phase motors; and *Table 430.250* (Figure 47–4) is used to determine the full load running current for three-phase motors. Note that the tables list the amount of current that the motor is expected to draw under a full load condition. The motor will exhibit less current draw if it is not under full load. These tables list the ampere rating of the motors according to horsepower and connected voltage. It should also be noted that *NEC Section 430.6(A)(1)* states these tables are to be used to in determining *conductor size, short circuit protection size,* and *ground fault protection size* instead of the nameplate rating of the motor. The motor overload size, however, is to be determined by the nameplate rating of the motor.

Direct Current Motors

Table 430.247 lists the full load running currents for direct current motors. The horsepower rating of the motor is given in the far left-hand column. Rated voltages are listed across the top of the table. The table

Table 430.247 Full-Load Current in Amperes, Direct-Current Motors
The following values of full-load currents* are for motors running at base speed.

	Armature Voltage Rating*					
Horsepower	**90 Volts**	**120 Volts**	**180 Volts**	**240 Volts**	**500 Volts**	**550 Volts**
¼	4.0	3.1	2.0	1.6	—	—
⅓	5.2	4.1	2.6	2.0	—	—
½	6.8	5.4	3.4	2.7	—	—
¾	9.6	7.6	4.8	3.8	—	—
1	12.2	9.5	6.1	4.7	—	—
1½	—	13.2	8.3	6.6	—	—
2	—	17	10.8	8.5	—	—
3	—	25	16	12.2	—	—
5	—	40	27	20	—	—
7½	—	58	—	29	13.6	12.2
10	—	76	—	38	18	16
15	—	—	—	55	27	24
20	—	—	—	72	34	31
25	—	—	—	89	43	38
30	—	—	—	106	51	46
40	—	—	—	140	67	61
50	—	—	—	173	83	75
60	—	—	—	206	99	90
75	—	—	—	255	123	111
100	—	—	—	341	164	148
125	—	—	—	425	205	185
150	—	—	—	506	246	222
200	—	—	—	675	330	294

*These are average dc quantities.

Figure 47–1 Table 430.247 is used to determine the full load current for direct current motors. (Reprinted with permission from NFPA 70™, *National Electrical Code®*, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

shows that a 1 horsepower motor will have a full-load current of 12.2 amperes when connected to 90 volts DC. If a 1 horsepower motor is designed to be connected to 240 volts, it will have a current draw of 4.7 amperes.

Single-Phase AC Motors

The current ratings for single-phase AC motors are given in *Table 430.248.* Particular attention should be paid to the statement preceding the table. The statement asserts that the values listed in this table are for motors that operate under normal speeds and torques. Motors especially designed for low speed and high torque, or multispeed motors, should have their running current determined from the nameplate rating of the motor.

The voltages listed in the table are 115, 200, 208, and 230. The last sentence of the preceding statement says that the currents listed shall be permitted for voltages of 110 to 120 volts and 220 to 240 volts. This means that if the motor is connected to a 120 volt line, it is permissible to use the currents listed in the 115 volt column. If the motor is connected to a 220 volt line, the 230 volt column can be used.

EXAMPLE:

A 3 horsepower single-phase AC motor is connected to a 208 volt line. What will be the full load running current of this motor?

Locate 3 horsepower in the far left-hand column. Follow across to the 208 volt column. The full load current will be 18.7 amperes.

Table 430.248 Full-Load Currents in Amperes, Single-Phase Alternating-Current Motors
The following values of full-load currents are for motors running at usual speeds and motors with normal torque characteristics. The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120 and 220 to 240 volts.

Horsepower	115 Volts	200 Volts	208 Volts	230 Volts
1/6	4.4	2.5	2.4	2.2
1/4	5.8	3.3	3.2	2.9
1/3	7.2	4.1	4.0	3.6
1/2	9.8	5.6	5.4	4.9
3/4	13.8	7.9	7.6	6.9
1	16	9.2	8.8	8.0
1½	20	11.5	11.0	10
2	24	13.8	13.2	12
3	34	19.6	18.7	17
5	56	32.2	30.8	28
7½	80	46.0	44.0	40
10	100	57.5	55.0	50

Figure 47–2 Table 430.248 is used to determine the full load current for single-phase motors. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

Two-Phase Motors

Although two-phase motors are seldom used, *Table 430.249* lists the full load running currents for these motors. Like single-phase motors, two-phase motors that are especially designed for low speed, high torque applications and multispeed motors, use the nameplate rating instead of the values shown in the table. When using a two-phase, three-wire system, the size of the neutral conductor must be increased by the square root of 2, or 1.41. The reason for this is that the voltages of a two-phase system are 90 degrees out-of-phase with each other, as shown in Figure 47–5. The principle of two-phase power generation is shown in Figure 47–6. In a two-phase alternator, the phase windings are arranged 90 degrees apart. The magnet is the rotor of the alternator. When the rotor turns, it induces voltage into the phase windings, which are 90 degrees apart. When one end of each phase winding is joined to form a common terminal, or neutral, the current in the neutral conductor will be greater than the current in either of the two phase conductors. An example of this is shown in Figure 47–7. In this example, a two-phase alternator is connected to a two-phase motor. The current draw on each of the phase windings is 10 amperes. The current flow in the neutral, however, is 1.41 times greater than the current flow in the phase windings, or 14.1 amperes.

Table 430.249 Full-Load Current, Two-Phase Alternating-Current Motors (4-Wire)
The following values of full-load current are for motors running at speeds usual for belted motors and motors with normal torque characteristics. Current in the common conductor of a 2-phase, 3-wire system will be 1.41 times the value given. The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)				
Horsepower	115 Volts	230 Volts	460 Volts	575 Volts	2300 Volts
1/2	4.0	2.0	1.0	0.8	—
3/4	4.8	2.4	1.2	1.0	—
1	6.4	3.2	1.6	1.3	—
1½	9.0	4.5	2.3	1.8	—
2	11.8	5.9	3.0	2.4	—
3	—	8.3	4.2	3.3	—
5	—	13.2	6.6	5.3	—
7½	—	19	9.0	8.0	—
10	—	24	12	10	—
15	—	36	18	14	—
20	—	47	23	19	—
25	—	59	29	24	—
30	—	69	35	28	—
40	—	90	45	36	—
50	—	113	56	45	—
60	—	133	67	53	14
75	—	166	83	66	18
100	—	218	109	87	23
125	—	270	135	108	28
150	—	312	156	125	32
200	—	416	208	167	43

Figure 47–3 Table 430.249 is used to determine the full load current for two-phase motors. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

Table 430.250 Full-Load Current, Three-Phase Alternating-Current Motors
The following values of full-load currents are typical for motors running at speeds usual for belted motors and motors with normal torque characteristics.

The voltages listed are rated motor voltages. The currents listed shall be permitted for system voltage ranges of 110 to 120, 220 to 240, 440 to 480, and 550 to 600 volts.

	Induction-Type Squirrel Cage and Wound Rotor (Amperes)							Synchronous-Type Unity Power Factor* (Amperes)			
Horsepower	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts	2300 Volts	230 Volts	460 Volts	575 Volts	2300 Volts
½	4.4	2.5	2.4	2.2	1.1	0.9	—	—	—	—	—
¾	6.4	3.7	3.5	3.2	1.6	1.3	—	—	—	—	—
1	8.4	4.8	4.6	4.2	2.1	1.7	—	—	—	—	—
1½	12.0	6.9	6.6	6.0	3.0	2.4	—	—	—	—	—
2	13.6	7.8	7.5	6.8	3.4	2.7	—	—	—	—	—
3	—	11.0	10.6	9.6	4.8	3.9	—	—	—	—	—
5	—	17.5	16.7	15.2	7.6	6.1	—	—	—	—	—
7½	—	25.3	24.2	22	11	9	—	—	—	—	—
10	—	32.2	30.8	28	14	11	—	—	—	—	—
15	—	48.3	46.2	42	21	17	—	—	—	—	—
20	—	62.1	59.4	54	27	22	—	—	—	—	—
25	—	78.2	74.8	68	34	27	—	53	26	21	—
30	—	92	88	80	40	32	—	63	32	26	—
40	—	120	114	104	52	41	—	83	41	33	—
50	—	150	143	130	65	52	—	104	52	42	—
60	—	177	169	154	77	62	16	123	61	49	12
75	—	221	211	192	96	77	20	155	78	62	15
100	—	285	273	248	124	99	26	202	101	81	20
125	—	359	343	312	156	125	31	253	126	101	25
150	—	414	396	360	180	144	37	302	151	121	30
200	—	552	528	480	240	192	49	400	201	161	40
250	—	—	—	—	302	242	60	—	—	—	—
300	—	—	—	—	361	289	72	—	—	—	—
350	—	—	—	—	414	336	83	—	—	—	—
400	—	—	—	—	477	382	95	—	—	—	—
450	—	—	—	—	515	412	103	—	—	—	—
500	—	—	—	—	590	472	118	—	—	—	—

*For 90 and 80 percent power factor, the figures shall be multiplied by 1.1 and 1.25, respectively.

Figure 47–4 Table 430.250 is used to determine the full load current for three-phase motors. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

EXAMPLE:

Compute the phase current and neutral current for a 60 horsepower, 460 volt two-phase motor.

The phase current can be taken from *Table 430.249.*

Phase current = 67 amperes

The neutral current will be 1.41 times higher than the phase current.

Neutral current = 67 × 1.41

Neutral current = 94.5 amperes

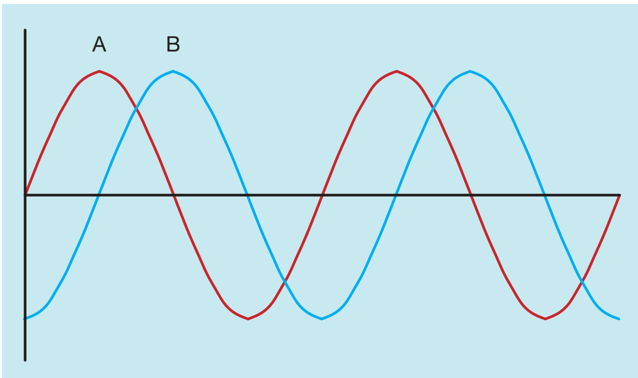


Figure 47–5 The voltages of a two-phase system are 90° out of phase with each other. (Source: Delmar/Cengage Learning.)

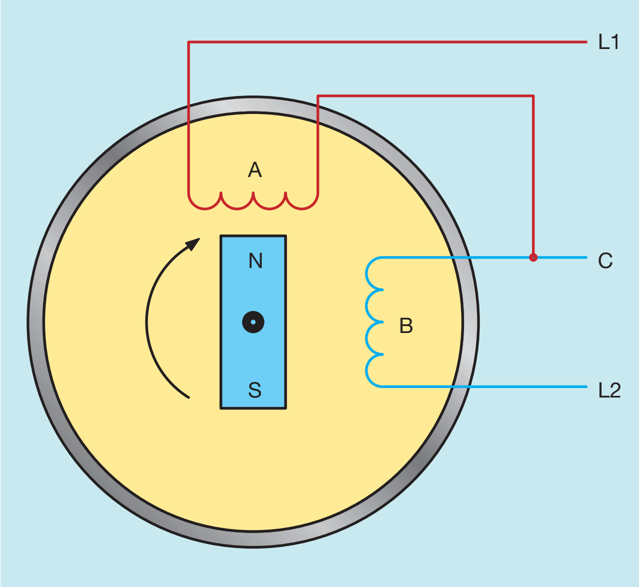


Figure 47–6 A two-phase alternator produces voltages that are 90° out of phase with each other. (Source: Delmar/Cengage Learning.)

Three-Phase Motors

Table 430.250 is used to determine the full load current of three-phase motors. The notes at the top of the table are very similar to the notes of *Tables 430.248* and *430.249*. The full load current of low speed, high torque and multispeed motors is to be determined from the nameplate rating instead of from the values listed in the table. *Table 430.250* has an extra note that deals with synchronous motors. Notice that the right-hand side of *Table 430.250* is devoted to the full load currents of synchronous type motors. The currents listed are for synchronous type motors that are to be operated at unity, or 100%, power factor. Since synchronous motors are often made to have a leading power factor by over excitation of the rotor current, the full load current rating must be increased when this is done. If the motor is to be operated at 90% power factor, the rated full load current in the table must be increased by 10%. If the motor is to be operated at 80% power factor, the full load current is to be increased by 25%.

EXAMPLE:

A 150 horsepower, 460 volt synchronous motor is to be operated at 80% power factor. What will be the full load current rating of the motor?

The table indicates a current value of 151 amperes for this motor. To determine the running current at 80% power factor, multiply this current by 125%, or 1.25. (Multiplying by 1.25 results in the same answer that would be obtained by dividing by 0.80.)

$$151 \times 1.25 = 188.75 \text{ or } 189 \text{ amperes}$$

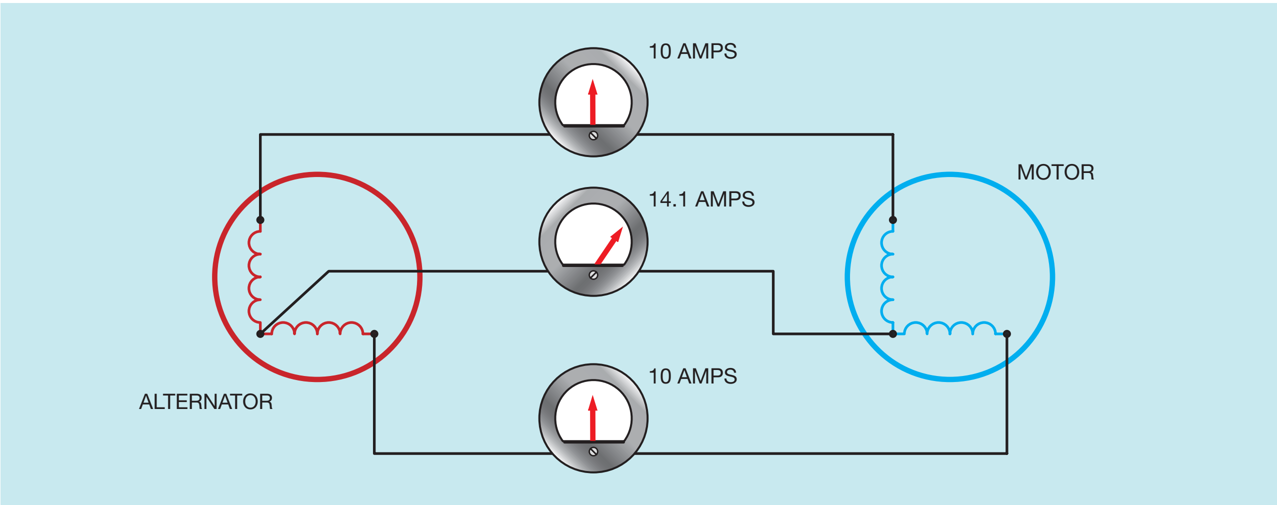


Figure 47–7 The neutral conductor of a two-phase system has a greater current than the other two conductors. (Source: Delmar/Cengage Learning.)

EXAMPLE:

A 200 horsepower, 2300 volt synchronous motor is to be operated at 90% power factor. What will be the full load current rating of this motor?

Locate 200 horsepower in the far left-hand column. Follow across to the 2300 volt column listed under synchronous type motors. Increase this value by 10%:

$$40 \times 1.10 = 44 \text{ amperes}$$

Determining Conductor Size for a Single Motor

NEC Section 430.6(A)(1) states that the conductor for a motor connection shall be based on the values from *Tables 430.247, 430.248, 430.249,* and *430.250* instead of the motor nameplate current. *Section 430.22(A)* states that conductors supplying a single motor shall have an ampacity of not less than 125% of the motor full load current. *NEC Section 310* is used to select the conductor size after the ampacity has been determined. The exact table employed will be determined by the wiring conditions. Probably the most frequently used table is *310.16* (Figure 47–8).

Termination Temperature

Another factor that must be taken into consideration when determining the conductor size is the temperature rating of the devices and terminals as specified in *NEC Section 110.14(C).* This section states that the conductor is to be selected and coordinated as to not exceed the lowest temperature rating of any connected termination, any connected conductor, or any connected device. This means that, regardless of the temperature rating of the conductor, the ampacity must be selected from a column that does not exceed the temperature rating of the termination. The conductors listed in the first column of *Table 310.16* have a temperature rating of 60°C, the conductors in the second column have a rating of 75°C, and the conductors in the third column have a rating of 90°C. The temperature ratings of devices such as circuit breakers, fuses, and terminals are often found in the UL (Underwriters Laboratories) product directories. Occasionally, the temperature rating may be found on the piece of equipment, but this is the exception and not the rule. As a general rule, the temperature rating of most devices will not exceed 75°C.

When the termination temperature rating is not listed or known, *NEC Section 110.14(C)(1)(a)* states that for circuits rated at 100 amperes or less, or for #14 AWG through #1 AWG conductors, the ampacity of the wire, regardless of the temperature rating, will be selected from the 60°C column. This does not mean that only those types of insulations listed in the 60°C column can be used, but that the *ampacities* listed in the 60°C column must be used to select the conductor size. For example, assume that a copper conductor with type XHHW insulation is to be connected to a 50 ampere circuit breaker that does not have a listed temperature rating. According to *NEC Table 310.16,* a #8 AWG copper conductor with XHHW insulation is rated to carry 55 amperes of current. Type XHHW insulation is located in the 90°C column, but the temperature rating of the circuit breaker is not known. Therefore, the wire size must be selected from the ampacity ratings in the 60°C column. A #6 AWG copper conductor with type XHHW insulation would be used.

NEC Section 110.14(C)(1)(a)(4) has a special provision for motors with marked NEMA design codes

EXAMPLE:

A 30 horsepower three-phase squirrel cage induction motor is connected to a 480 volt line. The conductors are run in conduit to the motor. The motor does not have a NEMA design code listed on the nameplate. The termination temperature rating of the devices is not known. Copper conductors with THWN insulation are to be used for this motor connection. What size conductors should be used?

The first step is to determine the full load current of the motor. This is determined from *Table 430.250.* The table indicates a current of 40 amperes for this motor. The current must be increased by 25% according to *Section 430.22(A).*

$$40 \times 1.25 = 50 \text{ amperes}$$

Table 310.16 is used to determine the conductor size. Locate the column that contains THWN insulation in the copper section of the table. THWN is located in the 75°C column. Since this circuit is less than 100 amperes and the termination temperature is not known, and the motor does not contain a NEMA design code letter, the conductor size must be selected from the ampacities listed in the 60°C column. A #6 AWG copper conductor with type THWN insulation will be used.

Table 310.16 Allowable Ampacities of Insulated Conductors Rated 0 Through 2000 Volts, 60°C Through 90°C (140°F Through 194°F), Not More Than Three Current-Carrying Conductors in Raceway, Cable, or Earth (Directly Buried), Based on Ambient Temperature of 30°C (86°F)

	Temperature Rating of Conductor [See Table 310.13(A).]						
	60°C (140°F)	75°C (167°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	90°C (194°F)	
Size AWG or kcmil	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE, ZW	Types TBS, SA, SIS, FEP, FEPB, MI, RHH, RHW-2, THHN, THHW, THW-2, THWN-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Types TW, UF	Types RHW, THHW, THW, THWN, XHHW, USE	Types TBS, SA, SIS, THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2, ZW-2	Size AWG or kcmil
	COPPER			ALUMINUM OR COPPER-CLAD ALUMINUM			
18	—	—	14	—	—	—	—
16	—	—	18	—	—	—	—
14*	20	20	25	—	—	—	—
12*	25	25	30	20	20	25	12*
10*	30	35	40	25	30	35	10*
8	40	50	55	30	40	45	8
6	55	65	75	40	50	60	6
4	70	85	95	55	65	75	4
3	85	100	110	65	75	85	3
2	95	115	130	75	90	100	2
1	110	130	150	85	100	115	1
1/0	125	150	170	100	120	135	1/0
2/0	145	175	195	115	135	150	2/0
3/0	165	200	225	130	155	175	3/0
4/0	195	230	260	150	180	205	4/0
250	215	255	290	170	205	230	250
300	240	285	320	190	230	255	300
350	260	310	350	210	250	280	350
400	280	335	380	225	270	305	400
500	320	380	430	260	310	350	500
600	355	420	475	285	340	385	600
700	385	460	520	310	375	420	700
750	400	475	535	320	385	435	750
800	410	490	555	330	395	450	800
900	435	520	585	355	425	480	900
1000	455	545	615	375	445	500	1000
1250	495	590	665	405	485	545	1250
1500	520	625	705	435	520	585	1500
1750	545	650	735	455	545	615	1750
2000	560	665	750	470	560	630	2000
	CORRECTION FACTORS						
Ambient Temp. (°C)	For ambient temperatures other than 30°C (86°F), multiply the allowable ampacities shown above by the appropriate factor shown below.						Ambient Temp. (°F)
21–25	1.08	1.05	1.04	1.08	1.05	1.04	70–77
26–30	1.00	1.00	1.00	1.00	1.00	1.00	78–86
31–35	0.91	0.94	0.96	0.91	0.94	0.96	87–95
36–40	0.82	0.88	0.91	0.82	0.88	0.91	96–104
41–45	0.71	0.82	0.87	0.71	0.82	0.87	105–113
46–50	0.58	0.75	0.82	0.58	0.75	0.82	114–122
51–55	0.41	0.67	0.76	0.41	0.67	0.76	123–131
56–60	—	0.58	0.71	—	0.58	0.71	132–140
61–70	—	0.33	0.58	—	0.33	0.58	141–158
71–80	—	—	0.41	—	—	0.41	159–176

* See 240.4(D).

Figure 47–8 Table 310.16 is used to determine the ampacity of conductors. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

B, C, or D. This section states that conductors rated at 75°C or higher may be selected from the 75°C column even if the ampacity is 100 amperes or less. This code will not apply to motors that do not have a NEMA design code marked on their nameplate. Most motors manufactured before 1996 will not have a NEMA design code. The NEMA design code letter should not be confused with the code letter that indicates the type squirrel cage rotor used in the motor.

For circuits rated over 100 amperes, or for conductor sizes larger than #1 AWG, *Section 110.14(C)(1)(b)* states that the ampacity ratings listed in the 75°C column may be used to select wire sizes unless conductors with a 60°C temperature rating have been selected for use. For example, types TW and UF insulation are listed in the 60°C column. If one of these two insulation types has been specified, the wire size must be chosen from the 60°C column regardless of the ampere rating of the circuit.

Overload Size

When determining the overload size for a motor, the *nameplate* current rating of the motor is used instead of the current values listed in the tables *(NEC Section 430.6(A)(1))*. Other factors such as the service factor (SF) or temperature rise (°C) of the motor are also to be considered when determining the overload size for a motor. The temperature rise of the motor is an indication of the amount of temperature increase the motor should experience under a full load conditon and should not be confused with termination temperature discussed in *Section 110.14(C)*. *NEC Section 430.32* (Figure 47–9) is used to determine the overload size for motors of 1 horsepower or more. The overload size is based on a percentage of the full load current of the motor listed on the motor nameplate.

EXAMPLE:

A 25 horsepower three-phase induction motor has a nameplate rating of 32 amperes. The nameplate also shows a temperature rise of 30°C. Determine the ampere rating of the overload for this motor.

NEC Section 430.32(A)(1) indicates the overload size is 125% of the full load current rating of the motor.

$$32 \times 1.25 = 40 \text{ amperes}$$

If for some reason this overload size does not permit the motor to start without tripping out, *Section 430.32(C)* permits the overload size to be increased to a maximum of 140% for this motor. If this increase in overload size does not solve the starting problem, the overload may be shunted out of the circuit during the starting period in accordance with *Section 430.35(A)&(B)*.

Determining Locked Rotor Current

There are two basic methods for determining the locked rotor current (starting current) of a squirrel cage induction motor, depending on the information available. If the motor nameplate lists code letters that range from A to V, they indicate the type of rotor bars used when the rotor was made. Different types of bars are used to make motors with different operating characteristics. The type of rotor bars largely determines the maximum starting current of the motor. *NEC Table 430.7(B)* (Figure 47–10) lists the different code letters and gives the locked-rotor kilovolt-amperes per horsepower. The starting current can be determined by multiplying the kilovolt-ampere rating by the horsepower rating and then dividing by the applied voltage.

EXAMPLE:

A 15 horsepower, three-phase squirrel cage motor with a code letter of K is connected to a 240 volt line. Determine the locked-rotor current.

The table lists 8.0 to 8.99 kilovolt-amperes per horsepower for a motor with a code letter of K. An average value of 8.5 will be used.

$$8.5 \times 15 = 127.5 \text{ kVA or } 127{,}500 \text{ VA}$$

$$\frac{127{,}500}{240 \times \sqrt{3}} = 306.7 \text{ amperes}$$

The second method of determining locked rotor current is to use *Tables 430.251(A)&(B)* (Figure 47–11) if the motor nameplate lists NEMA design codes. *Table 430.251(A)* lists the locked rotor currents for single-phase motors and *Table 430.251(B)* lists the locked rotor currents for poly-phase motors.

430.32 Continuous-Duty Motors.

(A) More Than 1 Horsepower. Each motor used in a continuous duty application and rated more than 1 hp shall be protected against overload by one of the means in 430.32(A)(1) through (A)(4).

(1) Separate Overload Device. A separate overload device that is responsive to motor current. This device shall be selected to trip or shall be rated at no more than the following percent of the motor nameplate full-load current rating:

Motors with a marked service factor 1.15 or greater	125%
Motors with a marked temperature rise 40°C or less	125%
All other motors	115%

Modification of this value shall be permitted as provided in 430.32(C). For a multispeed motor, each winding connection shall be considered separately.

Where a separate motor overload device is connected so that it does not carry the total current designated on the motor nameplate, such as for wye-delta starting, the proper percentage of nameplate current applying to the selection or setting of the overload device shall be clearly designated on the equipment, or the manufacturer's selection table shall take this into account.

FPN: Where power factor correction capacitors are installed on the load side of the motor overload device, see 460.9.

(2) Thermal Protector. A thermal protector integral with the motor, approved for use with the motor it protects on the basis that it will prevent dangerous overheating of the motor due to overload and failure to start. The ultimate trip current of a thermally protected motor shall not exceed the following percentage of motor full-load current give in Table 430.248, Table 430.249, and Table 430.250:

Motor full-load current 9 amperes or less	170%
Motor full-load current from 9.1 to, and including, 20 amperes	156%
Motor full-load current greater than 20 amperes	140%

If the motor current-interrupting device is separate from the motor and its control circuit is operated by a protective device integral with the motor, it shall be arranged so that the opening of the control circuit will result in interruption of current to the motor.

(3) Integral with Motor. A protective device integral with a motor that will protect the motor against damage due to failure to start shall be permitted if the motor is part of an approved assembly that does not normally subject the motor to overloads.

(4) Larger Than 1500 Horsepower. For motors larger than 1500 hp, a protective device having embedded temperature detectors that cause current to the motor to be interrupted when the motor attains a temperature rise greater than marked on the nameplate in an ambient temperature of 40°C.

(B) One Horsepower or Less, Automatically Started. Any motor of 1 hp or less that is started automatically shall be protected against overload by one of the following means.

(1) Separate Overload Device. By a separate overload device following the requirements of 430.32(A)(1).

For a multispeed motor, each winding connection shall be considered separately. Modification of this value shall be permitted as provided in 430.32(C).

(2) Thermal Protector. A thermal protector integral with the motor, approved for use with the motor that it protects on the basis that it will prevent dangerous overheating of the motor due to overload and failure to start. Where the motor current-interrupting device is separate from the motor and its control circuit is operated by a protective device integral with the motor, it shall be arranged so that the opening of the control circuit results in interruption of current to the motor.

(3) Integral with Motor. A protective device integral with a motor that protects the motor against damage due to failure to start shall be permitted (1) if the motor is part of an approved assembly that does not subject the motor to overloads, or (2) if the assembly is also equipped with other safety controls (such as the safety combustion controls on a domestic oil burner) that protect the motor against damage due to failure to start. Where the assembly has safety controls that protect the motor, it shall be so indicated on the nameplate of the assembly where it will be visible after installation.

(4) Impedance-Protected. If the impedance of the motor windings is sufficient to prevent overheating due to failure to start, the motor shall be permitted to be protected as specified in 430.32(D)(2)(a) for manually started motors if the motor is part of an approved assembly in which the motor will limit itself so that it will not be dangerously overheated.

FPN: Many ac motors of less than 1⁄20 hp, such as clock motors, series motors, and so forth, and also some larger motors such as torque motors, come within this classification. It does not include split-phase motors having automatic switches that disconnect the starting windings.

(C) Selection of Overload Device. Where the sensing element or setting or sizing of the overload device selected in accordance with 430.32(A)(1) and 430.32(B)(1) is not sufficient to start the motor or to carry the load, higher size sensing elements or incremental settings or sizing shall be permitted to be used, provided the trip current of the overload device does not exceed the following percentage of motor nameplate full-load current rating:

Motors with marked service factor 1.15 or greater	140%
Motors with a marked temperature rise 40°C or less	140%
All other motors	130%

If not shunted during the starting period of the motor as provided in 430.35, the overload device shall have sufficient time delay to permit the motor to start and accelerate its load.

FPN: A Class 20 or Class 30 overload relay will provide a longer motor acceleration time than a Class 10 or Class 20, respectively. Use of a higher class overload relay may preclude the need for selection of a higher trip current.

(D) One Horsepower or Less, Nonautomatically Started.

(1) Permanently Installed. Overload protection shall be in accordance with 430.32(B).

(2) Not Permanently Installed.

(a) *Within Sight from Controller.* Overload protection shall be permitted to be furnished by the branch-circuit short-circuit and ground-fault protective device; such device, however, shall not be larger than that specified in Part IV of Article 430.

Exception: Any such motor shall be permitted on a nominal 120-volt branch circuit protected at not over 20 amperes.

(b) *Not Within Sight from Controller.* Overload protection shall be in accordance with 430.32(B).

(E) Wound-Rotor Secondaries. The secondary circuits of wound-rotor ac motors, including conductors, controllers, resistors, and so forth, shall be permitted to be protected against overload by the motor-overload device.

Figure 47–9 Table 430.32 is used to determine overload size for motors. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

Table 430.7(B) Locked-Rotor Indicating Code Letters

Code Letter	Kilovolt-Amperes per Horsepower with Locked Rotor
A	0–3.14
B	3.15–3.54
C	3.55–3.99
D	4.0–4.49
E	4.5–4.99
F	5.0–5.59
G	5.6–6.29
H	6.3–7.09
J	7.1–7.99
K	8.0–8.99
L	9.0–9.99
M	10.0–11.19
N	11.2–12.49
P	12.5–13.99
R	14.0–15.99
S	16.0–17.99
T	18.0–19.99
U	20.0–22.39
V	22.4 and up

Figure 47–10 Table 430.7(B) is used to determine locked rotor current for motors that do not contain a NEMA code letter. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

Short-Circuit Protection

The rating of the short-circuit protective device is determined by *NEC Table 430.52* (Figure 47–12). The far left-hand column lists the type of motor that is to be protected. To the right of this are four columns that list different types of short-circuit protective devices; non-time delay fuses, dual-element time delay fuses, instantaneous trip circuit breakers and inverse time circuit breakers. Although it is permissible to use non-time delay fuses and instantaneous trip circuit breakers, most motor circuits are protected by dual-element time delay fuses or inverse time circuit breakers.

Each of these columns lists the percentage of motor current that is to be used in determining the ampere rating of the short-circuit protective device. The current listed in the appropriate motor table is to be used instead of the nameplate current. *NEC Section 430.52(C)(1)* states that the protective device is to have a rating or setting not exceeding the value calculated in accord with *Table 430.52. Exception No. 1* of this section, however, states that if the calculated value does not correspond to a standard size or rating of a fuse or circuit breaker, it shall be permissible to use the next higher standard size. The standard sizes of fuses and circuit breakers are listed in *NEC Section 240.6* (Figure 47–13).

Starting in 1996, *Table 430.52* has listed squirrel cage motor types by NEMA design letters instead of code letters. *Section 430.7(A)(9)* requires that motor nameplates be marked with design letters B, C, or D. Motors manufactured before this requirement, however, do not list design letters on the nameplate. Most common squirrel cage motors used in industry actually fall in the design B classification and for purposes of selecting the short-circuit protective device are considered to be design B unless otherwise listed.

EXAMPLE:

A 100 horsepower three-phase squirrel cage induction motor is connected to a 240 volt line. The motor does not contain a NEMA design code. A dual-element time delay fuse is to be used as the short-circuit protective device. Determine the size needed.

Table 340.250 lists a full load current of 248 amperes for this motor. *Table 430.52* indicates that a dual-element time delay fuse is to be calculated at 175% of the full load current rating for an AC polyphase (more than one phase) squirrel cage motor, other than design code E. Since the motor does not list a NEMA design code on the nameplate, it will be assumed that the motor is design B.

$$248 \times 1.75 = 434 \text{ amperes}$$

The nearest standard fuse size above the computed value listed in *Section 240.6* is 450 amperes, so 450 ampere fuses will be used to protect this motor.

If for some reason this fuse will not permit the motor to start without blowing, *NEC Section 430.52(C)(1) Exception 2(b)* states that the rating of a dual-element time delay fuse may be increased to a maximum of 225% of the full load motor current.

Table 430.251(A) Conversion Table of Single-Phase Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating
For use only with 430.110, 440.12, 440.41, and 455.8(C).

Rated Horsepower	Maximum Locked-Rotor Current in Amperes, Single Phase 115 Volts	208 Volts	230 Volts
½	58.8	32.5	29.4
¾	82.8	45.8	41.4
1	96	53	48
1½	120	66	60
2	144	80	72
3	204	113	102
5	336	186	168
7½	480	265	240
10	600	332	300

Table 430.251(B) Conversion Table of Polyphase Design B, C, and D Maximum Locked-Rotor Currents for Selection of Disconnecting Means and Controllers as Determined from Horsepower and Voltage Rating and Design Letter
For use only with 430.110, 440.12, 440.41, and 455.8(C).

Rated Horsepower	Maximum Motor Locked-Rotor Current in Amperes, Two- and Three-Phase, Design B, C, and D*					
	115 Volts	200 Volts	208 Volts	230 Volts	460 Volts	575 Volts
	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D	B, C, D
½	40	23	22.1	20	10	8
¾	50	28.8	27.6	25	12.5	10
1	60	34.5	33	30	15	12
1½	80	46	44	40	20	16
2	100	57.5	55	50	25	20
3	—	73.6	71	64	32	25.6
5	—	105.8	102	92	46	36.8
7½	—	146	140	127	63.5	50.8
10	—	186.3	179	162	81	64.8
15	—	267	257	232	116	93
20	—	334	321	290	145	116
25	—	420	404	365	183	146
30	—	500	481	435	218	174
40	—	667	641	580	290	232
50	—	834	802	725	363	290
60	—	1001	962	870	435	348
75	—	1248	1200	1085	543	434
100	—	1668	1603	1450	725	580
125	—	2087	2007	1815	908	726
150	—	2496	2400	2170	1085	868
200	—	3335	3207	2900	1450	1160
250	—	—	—	—	1825	1460
300	—	—	—	—	2200	1760
350	—	—	—	—	2550	2040
400	—	—	—	—	2900	2320
450	—	—	—	—	3250	2600
500	—	—	—	—	3625	2900

*Design A motors are not limited to a maximum starting current or locked rotor current.

Figure 47–11 Table 430.251(A) & (B) are used to locked rotor current for motors that do contain NEMA code letters. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

Table 430.52 Maximum Rating or Setting of Motor Branch-Circuit Short-Circuit and Ground-Fault Protective Devices

	Percentage of Full-Load Current			
Type of Motor	**Nontime Delay Fuse**[1]	**Dual Element (Time-Delay) Fuse**[1]	**Instantaneous Trip Breaker**	**Inverse Time Breaker**[2]
Single-phase motors	300	175	800	250
AC polyphase motors other than wound-rotor	300	175	800	250
Squirrel cage — other than Design B energy-efficient	300	175	800	250
Design B energy-efficient	300	175	1100	250
Synchronous[3]	300	175	800	250
Wound rotor	150	150	800	150
Direct current (constant voltage)	150	150	250	150

Note: For certain exceptions to the values specified, see 430.54.
[1]The values in the Nontime Delay Fuse column apply to Time-Delay Class CC fuses.
[2]The values given in the last column also cover the ratings of nonadjustable inverse time types of circuit breakers that may be modified as in 430.52(C)(1), Exception No. 1 and No. 2.
[3]Synchronous motors of the low-torque, low-speed type (usually 450 rpm or lower), such as are used to drive reciprocating compressors, pumps, and so forth, that start unloaded, do not require a fuse rating or circuit-breaker setting in excess of 200 percent of full-load current.

Figure 47–12 Table 430.52 is used to determine the size of the short circuit protective device for a motor. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

Starter Size

Another factor that must be considered when installing a motor is the size of starter used to connect the motor to the line. Starter sizes are rated by motor type, horsepower, and connected voltage. The two most common ratings are NEMA and IEC. A chart showing common NEMA size starters for alternating current motors is shown in Figure 47–14. A chart showing IEC starters for alternating current motors is shown in Figure 47–15. Each of these charts lists the minimum size starter designed to connect the listed motors to the line. It is not uncommon to employ larger size starters than those listed. This is especially true when using IEC type starters because of their smaller load contact size.

240.6 Standard Ampere Ratings.

(A) Fuses and Fixed-Trip Circuit Breakers. The standard ampere ratings for fuses and inverse time circuit breakers shall be considered 15, 20, 25, 30, 35, 40, 45, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500, 600, 700, 800, 1000, 1200, 1600, 2000, 2500, 3000, 4000, 5000, and 6000 amperes. Additional standard ampere ratings for fuses shall be 1, 3, 6, 10, and 601. The use of fuses and inverse time circuit breakers with nonstandard ampere ratings shall be permitted.

(B) Adjustable-Trip Circuit Breakers. The rating of adjustable-trip circuit breakers having external means for adjusting the current setting (long-time pickup setting), not meeting the requirements of 240.6(C), shall be the maximum setting possible.

(C) Restricted Access Adjustable-Trip Circuit Breakers. A circuit breaker(s) that has restricted access to the adjusting means shall be permitted to have an ampere rating(s) that is equal to the adjusted current setting (long-time pickup setting). Restricted access shall be defined as located behind one of the following:

(1) Removable and sealable covers over the adjusting means
(2) Bolted equipment enclosure doors
(3) Locked doors accessible only to qualified personnel

Figure 47–13 Section 240.6 lists standard fuse and circuit breaker sizes. (Reprinted with permission from NFPA 70™, *National Electrical Code*®, Copyright© 2007, National Fire Protection Association, Quincy, MA 02269. This reprinted material is not the official position of the National Fire Protection Association, which is represented by the standard in its entirety.)

EXAMPLE:

A 40 horsepower three-phase squirrel cage motor is connected to a 208 volt line. What are the minimum size NEMA and IEC starters that should be used to connect this motor to the line?

NEMA: The 200 volt listing is used for motors rated at 208 volts. Locate the NEMA size starter that corresponds to 200 volts and 40 horsepower. Since the motor is three-phase, 40 horsepower will be in the polyphase column. A NEMA size 4 starter is the minimum size for this motor.

IEC: As with the NEMA chart, the IEC chart lists 200 volts instead of 208 volts. A size N starter lists 200 volts and 40 horsepower in the three-phase column.

Motor Starter Sizes and Ratings

NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Poly Phase	NEMA Size	Load Volts	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Single Phase	Maximum Horsepower Rating—Nonplugging and Nonjogging Duty: Poly Phase
	115	½	. . .		115	7½	. . .
	200	. . .	1½		200	. . .	25
	230	1	1½		230	15	30
00	380	. . .	1½	3	380	. . .	50
	460	. . .	2		460	. . .	50
	575	. . .	2		575	. . .	50
	115	1	. . .		200	. . .	40
	200	. . .	3		230	. . .	50
	230	2	3		380	. . .	75
0	380	. . .	5	4	460	. . .	100
	460	. . .	5		575	. . .	100
	575	. . .	5				
	115	2	. . .		200	. . .	75
	200	. . .	7½		230	. . .	100
	230	3	7½		380	. . .	150
1	380	. . .	10	5	460	. . .	200
	460	. . .	10		575	. . .	200
	575	. . .	10				
					200	. . .	150
	115	3	. . .		230	. . .	200
*1P	230	5	. . .	6	380	. . .	300
					460	. . .	400
					575	. . .	400
	115	3	. . .		230	. . .	300
	200	. . .	10	7	460	. . .	600
	230	7½	15		575	. . .	600
2	380	. . .	25		230	. . .	450
	460	. . .	25	8	460	. . .	900
	575	. . .	25		575	. . .	900

Tables are taken from NEMA Standards.
*1¾, 10 hp is available.

Figure 47–14 NEMA table of standard starter sizes. (Source: Delmar/Cengage Learning.)

I.E.C. MOTOR STARTERS (60 Hz)

SIZE	MAX AMPS	MOTOR VOLTAGE	MAX. HORSEPOWER	
			1 θ	3 θ
A	7	115	1/4	
		200		1 1/2
		230	1/2	1 1/2
		460		3
		575		5
B	10	115	1/2	
		200		2
		230	1	2
		460		5
		575		7 1/2
C	12	115	1/2	
		200		3
		230	2	3
		460		7 1/2
		575		10
D	18	115	1	
		200		5
		230	3	5
		460		10
		575		15
E	25	115	2	
		200		5
		230	3	7 1/2
		460		15
		575		20
F	32	115	2	
		200		7 1/2
		230	5	10
		460		20
		575		25
G	37	115	3	
		200		7 1/2
		230	5	10
		460		25
		575		30
H	44	115	3	
		200		10
		230	7 1/2	15
		460		30
		575		40
J	60	115	5	
		200		15
		230	10	20
		460		40
		575		40
K	73	115	5	
		200		20
		230	10	25
		460		50
		575		50
L	85	115	7 1/2	
		200		25
		230	10	30
		460		60
		575		75

SIZE	MAX AMPS	MOTOR VOLTAGE	MAX. HORSEPOWER	
			1 θ	3 θ
M	105	115	10	
		200		30
		230	10	40
		460		75
		575		100
N	140	115	10	
		200		40
		230	10	50
		460		100
		575		125
P	170	115		
		200		50
		230		60
		460		125
		575		125
R	200	115		
		200		60
		230		75
		460		150
		575		150
S	300	115		
		200		75
		230		100
		460		200
		575		200
T	420	115		
		200		125
		230		125
		460		250
		575		250
U	520	115		
		200		150
		230		150
		460		350
		575		250
V	550	115		
		200		150
		230		200
		460		400
		575		400
W	700	115		
		200		200
		230		250
		460		500
		575		500
X	810	115		
		200		250
		230		300
		460		600
		575		600
Z	1215	115		
		200		450
		230		450
		460		900
		575		900

Figure 47–15 IEC motor starters rated by size, horsepower, and voltage for 60 hertz circuits. (Source: Delmar/Cengage Learning.)

Example Problems

Example 1

A 40 horsepower 240 volt DC motor has a nameplate current rating of 132 amperes. The conductors are to be copper with type TW insulation. The short-circuit protective device is to be an instantaneous trip circuit breaker. The termination temperature rating of the connected devices is not known. Determine the conductor size, overload size, and circuit breaker size for this installation. Refer to Figure 47–16.

The conductor size must be determined from the current listed in *Table 430.247*. This value is to be increased by 25%. (NOTE: multiplying by 1.25 has the same effect as multiplying by 0.25 and then adding the product back to the original number (140 × 0.25 = 35) (35 + 140 = 175 amperes)

$$140 \times 1.25 = 175 \text{ amperes}$$

Table 310.16 is used to find the conductor size. Although *Section 110.14(C)* states that for currents of 100 amperes or greater, the ampacity rating of the conductor is to be determined from the 75°C column, in this instance, the insulation type is located in the 60°C column. Therefore, the conductor size must be determined using the 60°C column instead of the 75°C column. A 4/0 AWG copper conductor with type TW insulation will be used.

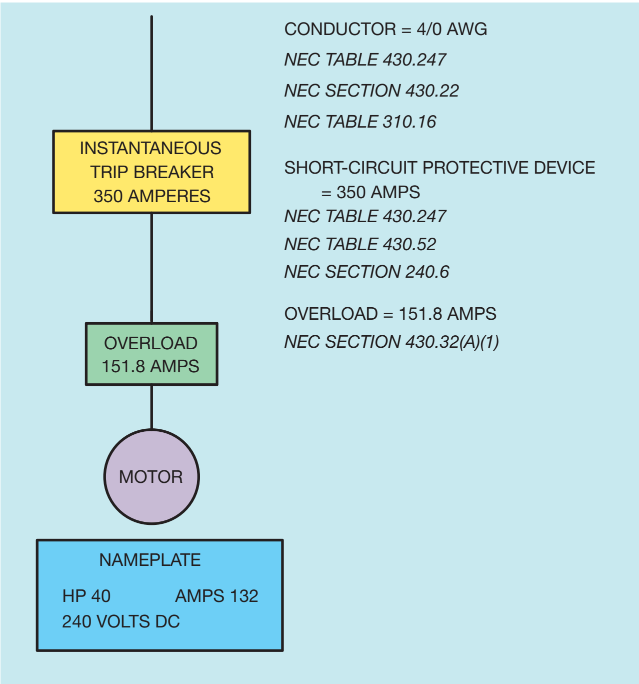


Figure 47–16 Example problem #1. (Source: Delmar/Cengage Learning.)

The overload size is determined from *NEC Section 430.32(A)(1)*. Since there is no service factor or temperature rise listed on the motor nameplate, the heading *ALL OTHER MOTORS* will be used. The motor nameplate current will be increased by 15%.

$$132 \times 1.15 = 151.8 \text{ amperes}$$

The circuit breaker size is determined from *Table 430.52*. The current value listed in *Table 430.247* is used instead of the nameplate current. Under DC motors (constant voltage), the instantaneous trip circuit breaker rating is given at 250%.

$$140 \times 2.50 = 350 \text{ amperes}$$

Since 350 amperes is one of the standard sizes of circuit breakers listed in *NEC Section 240.6,* that size breaker will be employed as the short-circuit protective device.

Example 2

A 150 horsepower three-phase squirrel cage induction motor is connected to a 440 volt line. The motor nameplate lists the following information:

Amps 175 SF 1.25 Code D NEMA code B

The conductors are to be copper with type THHN insulation. The short-circuit protective device is to be an inverse time circuit breaker. The termination temperature rating is not known. Determine the conductor size, overload size, circuit breaker size, minimum NEMA starter size, and IEC starter size. Refer to Figure 47–17.

The conductor size is determined from the current listed in *Table 430.250* and increased by 25%.

$$180 \times 1.25 = 225 \text{ amperes}$$

Table 310.16 is used to determine the conductor size. Type THHN insulation is located in the 90°C column. Since the motor nameplate lists NEMA code B, and the amperage is over 100 amperes, the conductor will be selected from the 75°C column. The conductor size will be 4/0 AWG.

The overload size is determined from the nameplate current and *NEC Section 430.32(A)(1)*. The motor has a marked service factor of 1.25. The motor nameplate current will be increased by 25%.

$$175 \times 1.25 = 218.75 \text{ amperes}$$

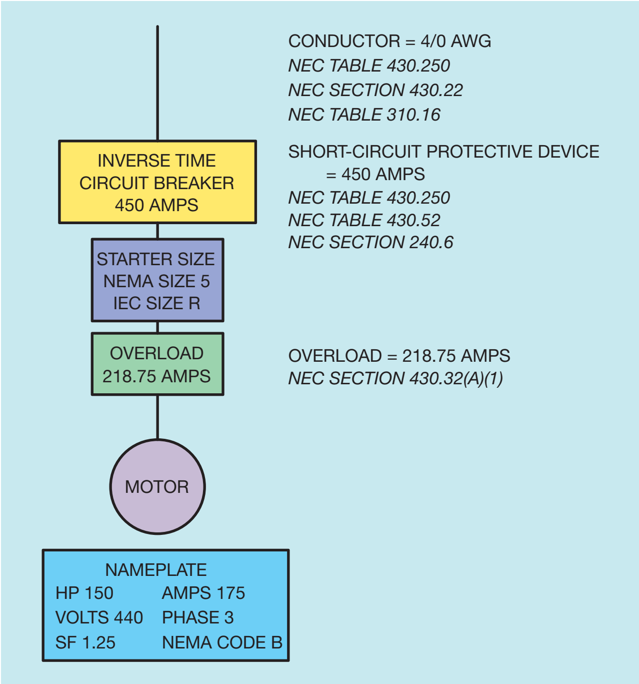


Figure 47–17 Example circuit #2. (Source: Delmar/Cengage Learning.)

The circuit breaker size is determined by *Tables 430.250* and *430.52. Table 430.52* indicates a factor of 250% for squirrel cage motors with NEMA design code B. The value listed in *Table 430.250* will be increased by 250%.

$$180 \times 2.50 = 450 \text{ amperes}$$

One of the standard circuit breaker sizes listed in *NEC Section 240.6* is 450 amperes. A 450 ampere inverse time circuit breaker will be used as the short-circuit protective device.

The proper motor starter sizes are selected from the NEMA and IEC charts shown in Figure 47–14 and Figure 47–15. The minimum size NEMA starter is 5 and the minimum size IEC starter is R.

Multiple Motor Calculations

The main feeder short-circuit protective devices and conductor sizes for multiple motor connections are set forth in *NEC Section 430.62(A)* and *430.24.* In this example, three motors are connected to a common feeder. The feeder is 480 volts three-phase and the conductors are to be copper with type THHN insulation. Each motor is to be protected with dual-element time delay fuses and a separate overload device. The main feeder is also protected by dual-element time delay fuses. The termination temperature rating of the connected devices is not known. The motor nameplates state the following:

Motor #1

Phase	3	HP	20
SF	1.25	NEMA code	C
Volts	480	Amperes	23
Type	Induction		

Motor #2

Phase	3	HP	60
Temp.	40°C	Code	J
Volts	480	Amperes	72
Type	Induction		

Motor #3

Phase	3	HP	100
Code	A	Volts	480
Amperes	96	PF	90%
Type	Synchronous		

Motor #1 Calculation

The first step is to calculate the values for motor amperage, conductor size, overload size, short-circuit protection size, and starter size for each motor. Both NEMA and IEC starter sizes will be determined. The values for motor #1 are shown in Figure 47–18.

The ampere rating from *Table 430.250* is used to determine the conductor and fuse size. The amperage rating must be increased by 25% for the conductor size.

$$27 \times 1.25 = 33.75 \text{ amperes}$$

The conductor size is chosen from *Table 310.16.* Although type THHN insulation is located in the 90°C column, the conductor size will be chosen from the 75°C column. Although the current is less than 100 amperes, *NEC Section 110.14(C)(1)(d)* permits the conductors to be chosen from the 75°C column if the motor has a NEMA Design Code.

$$33.75 \text{ amperes} = \#10 \text{ AWG}$$

The overload size is computed from the nameplate current. The demand factors in *Section 430.32(A)(1)* are used for the overload calculation.

$$23 \times 1.25 = 28.75 \text{ amperes}$$

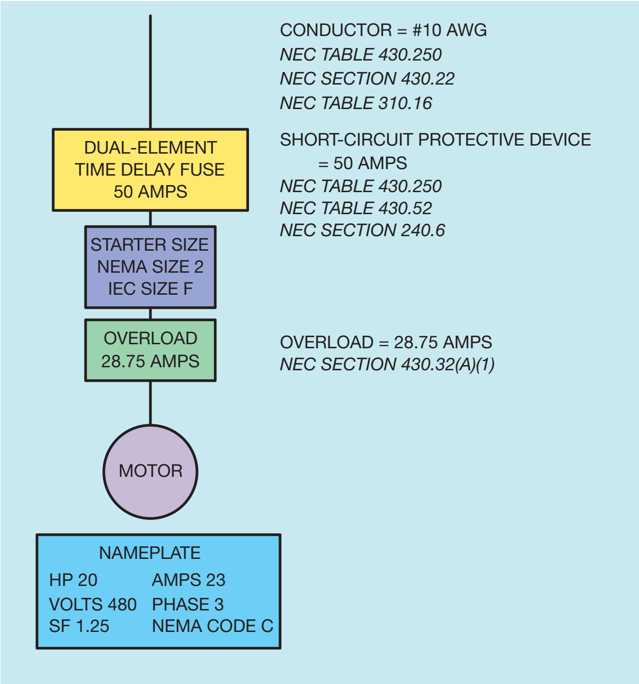


Figure 47–18 Motor #1 calculation. (Source: Delmar/Cengage Learning.)

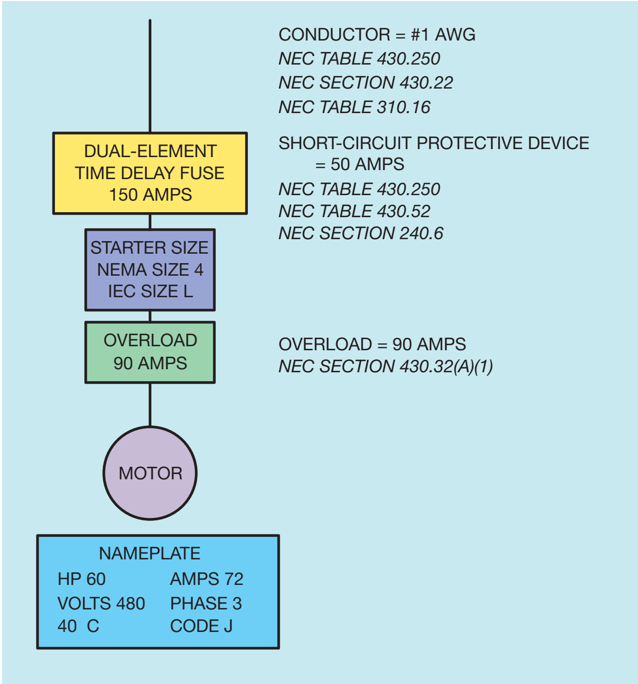


Figure 47–19 Motor #2 calculation. (Source: Delmar/Cengage Learning.)

The fuse size is determined by using the motor current listed in *Table 430.250* and the demand factor from *Table 430.52*. The percent of full load current for a dual-element time delay fuse protecting a squirrel cage motor listed as Design C is 175%. The current listed in *Table 430.250* will be increased by 175%.

$$27 \times 1.75 = 47.25 \text{ amperes}$$

The nearest standard fuse size listed in *Section 240.6* is 50 amperes, so 50 ampere fuses will be used.

The starter sizes are determined from the NEMA and IEC charts shown in Figure 47–14 and Figure 47–15. A 20 horsepower motor connected to 480 volts would require a NEMA size 2 starter and an IEC size F starter.

Motor #2 Calculation

Figure 47–19 shows an example for the calculation for motor #2. *Table 430.250* lists a full load current of 77 amperes for this motor. This value of current is increased by 25% for the calculation of the conductor current.

$$77 \times 1.25 = 96.25 \text{ amperes}$$

Table 310.16 indicates a #1 AWG conductor should be used for this motor connection. The conductor size is chosen from the 60°C column because the circuit current is less than 100 amperes in accord with *Section 110.14(C)*, and the motor nameplate does not indicate a NEMA design code. (The code J indicates the type of bars used in the construction of the rotor.)

The overload size is determined from *Section 430.32(A)(1)*. The motor nameplate lists a temperature rise of 40°C for this motor. The nameplate current will be increased by 25%.

$$72 \times 1.25 = 90 \text{ amperes}$$

The fuse size is determined from *Table 430.52*. The table current is increased by 175% for squirrel cage motors other than design E.

$$77 \times 1.75 = 134.25 \text{ amperes}$$

The nearest standard fuse size listed in *Section 240.6* is 150 amperes, so 150 ampere fuses will be used to protect this circuit.

The starter sizes are chosen from the NEMA and IEC starter charts. This motor would require a NEMA size 4 starter or a size L IEC starter.

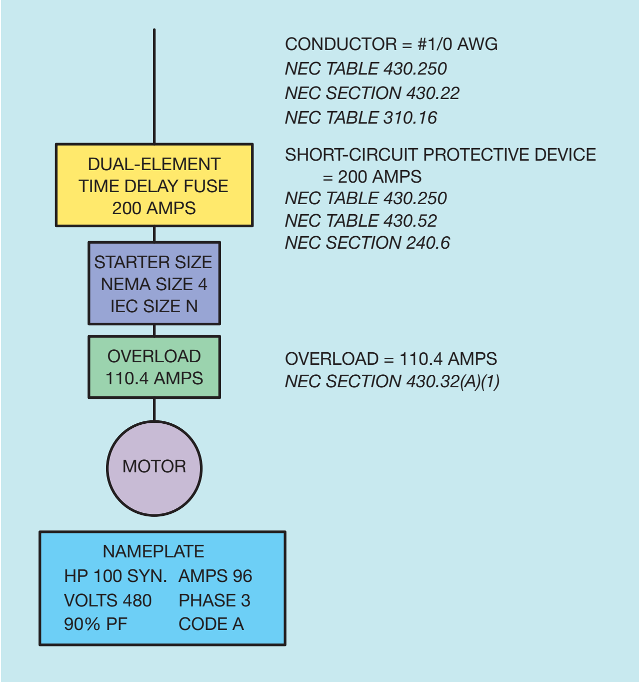


Figure 47–20 Motor #3 calculation. (Source: Delmar/Cengage Learning.)

Motor #3 Calculation

Motor #3 is a synchronous motor intended to operate with a 90% power factor. Figure 47–20 shows an example of this calculation. The notes at the bottom of *Table 430.250* indicate that the listed current is to be increased by 10% for synchronous motors with a listed power factor of 90%.

$$101 \times 1.10 = 111 \text{ amperes}$$

The conductor size is computed by using this current rating and increasing it by 25%.

$$111 \times 1.25 = 138.75 \text{ amperes}$$

Table 310.16 indicates that a #1/0 AWG conductor will be used for this circuit. Since the circuit current is over 100 amperes, the conductor size is chosen from the 75°C column.

This motor does not have a marked service factor or a marked temperature rise. The overload size will be calculated by increasing the nameplate current by 15% as indicated in *Section 430.32(A)(1)* under the heading *all other motors.*

$$96 \times 1.15 = 110.4 \text{ amperes}$$

The fuse size is determined from *Table 430.52*. The percent of full load current for a synchronous motor is 175%.

$$111 \times 1.75 = 194.25 \text{ amperes}$$

The nearest standard size fuse listed in *Section 240.6* is 200 amperes, so 200 ampere fuses will be used to protect this circuit.

The NEMA and IEC starter sizes are chosen from the charts shown in Figure 47–14 and Figure 47–15. The motor will require a NEMA size 4 starter and an IEC size N starter.

Main Feeder Calculation

An example of the main feeder connections is shown in Figure 47–21. The conductor size is computed in accord with *NEC Section 430.24* by increasing the largest amperage rating of the motors connected to the feeder by 25% and then adding the ampere rating of the other motors to this amount. In this example, the 100 horsepower synchronous motor has the largest running current. This current will be increased by 25% and then the running currents of the other motors as determined from *Table 430.250* will be added.

$$111 \times 1.25 = 138.75 \text{ amperes}$$

$$138.75 + 77 + 27 = 242.75 \text{ amperes}$$

Table 310.16 lists that 250 KCmil copper conductors are to be used as the main feeder conductors. The conductors were chosen from the 75°C column.

The size of the short-circuit protective device is determined by *Section 430.62(A)*. The code states that the rating or setting of the short-circuit protective device ***shall not be greater than*** the largest rating or setting of the largest branch circuit short-circuit and ground fault protective device for any motor supplied by the feeder plus the sum of the full load running currents of the other motors connected to the feeder. The largest fuse size in this example is the 100 horsepower synchronous motor. The fuse calculation for this motor is 200 amperes. The running currents of the other two motors will be added to this value to determine the fuse size for the main feeder.

$$200 + 77 + 27 = 304 \text{ amperes}$$

The closest standard fuse size listed in *Section 240.6* without going over 304 amperes is 300 amperes, so 300 ampere, so fuses will be used to protect this circuit.

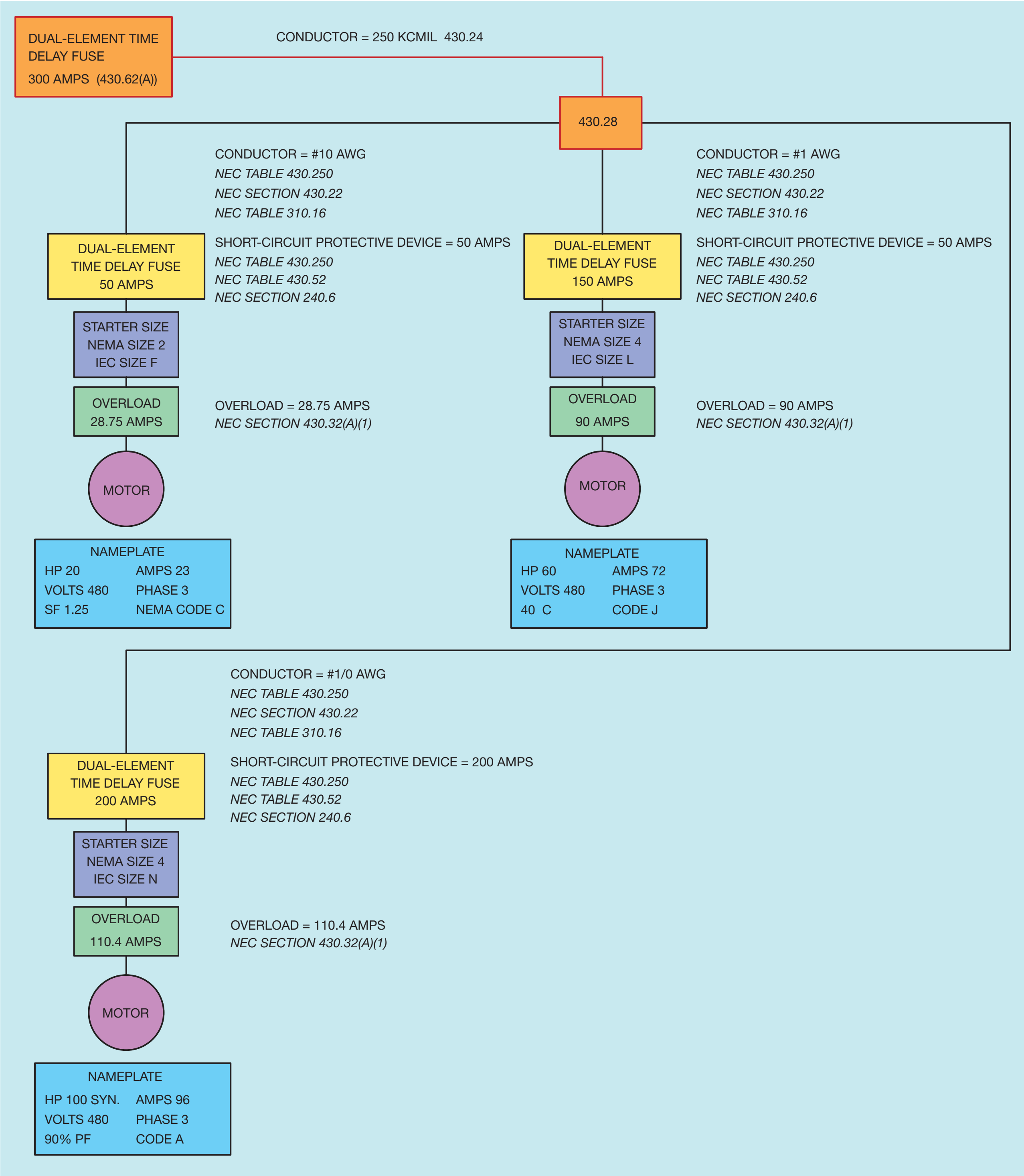


Figure 47–21 Main feeder calculation. (Source: Delmar/Cengage Learning.)

Review Questions

1. A 20 horsepower, DC motor is connected to a 500 volt DC line. What is the full load running current of this motor?
2. What rating is used to find the full load running current of a torque motor?
3. A ¾ horsepower, single-phase squirrel cage motor is connected to a 240 volt AC line. What is the full load current rating of this motor and what is the minimum size NEMA and IEC starters that should be used?
4. A 30 horsepower, two-phase motor is connected to a 230 volt AC line. What is the rated current of the phase conductors and the rated current of the neutral?
5. A 125 horsepower, synchronous motor is connected to a 230 volt three-phase AC line. The motor is intended to operate at 80% power factor. What is the full load running current of this motor? What is the minimum size NEMA and IEC starters that should be used to connect this motor to the line?
6. What is the full load running current of a three-phase, 50 horsepower motor connected to a 560 volt line? What minimum size NEMA and IEC starters should be used to connect this motor to the line?
7. A 125 horsepower, three-phase squirrel cage induction motor is connected to 560 volts. The nameplate current is 115 amperes. It has a marked temperature rise of 40°C and a code letter J. The conductors are to be type THHN copper and they are run in conduit. The short-circuit protective device is dual-element time delay fuses. Find the conductor size, overload size, fuse size, minimum NEMA and IEC starter sizes, and the upper and lower range of starting current for this motor.
8. A 7.5 horsepower, single-phase squirrel cage induction motor is connected to 120 volts AC. The motor has a code letter of H. The nameplate current is 76 amperes. The conductors are copper with type TW insulation. The short-circuit protection device is a non-time delay fuse. Find the conductor size, overload size, fuse size, minimum NEMA and IEC starter sizes, and upper and lower starting currents.
9. A 75 horsepower, three-phase, synchronous motor is connected to a 230 volt line. The motor is to be operated at 80% power factor. The motor nameplate lists a full load current of 185 amperes, a temperature rise of 40°C, and a code letter A. The conductors are to be made of copper and have type THHN insulation. The short-circuit protective device is to be an inverse time circuit breaker. Determine the conductor size, overload size, circuit breaker size, minimum size NEMA and IEC starters, and the upper and lower starting current.
10. Three motors are connected to a single branch circuit. The motors are connected to a 480 volt three-phase line. Motor #1 is a 50 horsepower induction motor with a NEMA code B. Motor #2 is 40 horsepower with a code letter of H, and motor #3 is 50 horsepower with a NEMA code C. Determine the conductor size needed for the branch circuit supplying these three motors. The conductors are copper with type THWN-2 insulation.
11. The short-circuit protective device supplying the motors in question #10 is an inverse time circuit breaker. What size circuit breaker should be used?
12. Five 5 horsepower, three-phase motors with NEMA code B are connected to a 240 volt line. The conductors are copper with type THWN insulation. What size conductor should be used to supply all of these motors?
13. If dual-element time delay fuses are to be used as the short-circuit protective device, what size fuses should be used to protect the circuit in question #12?
14. A 75 horsepower, three-phase squirrel cage induction motor is connected to 480 volts. The motor has a NEMA code D. What is the starting current for this motor?
15. A 20 horsepower, three-phase squirrel cage induction motor has a NEMA code B. The motor is connected to 208 volts. What is the starting current for this motor?

CHAPTER 48

DEVELOPING CONTROL CIRCUITS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss steps for developing a motor control circuit from a list of requirements.
- Draw a control circuit using a list of requirements.

There are times when it becomes necessary to develop a motor control circuit to fulfill a particular need. The idea of designing a motor control circuit may seem almost impossible, but with practice and by following a logical procedure it is generally not as difficult as it would first appear. The best method of designing a motor control circuit is to solve one requirement at a time. When one part is operating, move to the next requirement. A man was once asked, "How do you eat an elephant?" His reply was, "One bite at a time." The same is true for designing a circuit. Don't try to fulfill all the requirements at once.

The following circuits will illustrate a step-by-step procedure for designing a control circuit. Each illustration begins with a statement of the problem and the requirements for the circuit.

Developing Control Circuits

Circuit #1: Two-Pump Motors

The water for a housing development is supplied by a central tank. The tank is pressurized by the water as it is filled. Two separate wells supply water to the tank, and each well has a separate pump. It is desirable that water be taken from each well equally, but it is undesirable that both pumps operate at the same time. A circuit is to be constructed that will let the pumps work alternately. Also, a separate switch must be installed that will override the automatic control and let either pump operate independently of the other in the event one pump fails. The requirements of the circuit are as follows:

1. The pump motors are operated by a 480 volt three-phase system, but the control circuit must operate on a 120 volt supply.
2. Each pump motor contains a separate overload protector. If one pump overloads, it must not prevent operation of the second pump.
3. A manual ON-OFF switch can be used to control power to the circuit.
4. A pressure switch mounted on the tank controls the operation of the pump motors. When the pressure of the tank drops to a certain level, one of the pumps will be started. When the tank has been filled with water, the pressure switch will turn the pump off. When the pressure of the tank drops low enough again, the other pump will be started and run until the pressure switch is satisfied. Each time the pressure drops to a low enough level, the alternate pump motor will be used.
5. An override switch can be used to select the operation of a particular pump, or to permit the circuit to operate automatically.

When developing a control circuit, the logic of the circuit is developed one stage at a time until the circuit operates as desired. The first stage of the circuit is shown in Figure 48–1. In this stage, a control transformer has been used to step the 480 volt supply line voltage down to 120 volts for use by the control circuit. A fuse is used as short-circuit protection for the control wiring. A manually operated ON-OFF switch permits the control circuit to be disconnected from the power source. The pressure switch must close when the pressure drops. For this reason, it will be connected as normally closed. This is a normally closed held open switch. A set of normally closed overload contacts are connected in series with coil 1M, which will operate the motor starter of pump motor #1.

To understand the operation of this part of the circuit, assume that the manual power switch has been set to the ON position. When the tank pressure drops sufficiently, pressure switch PS will close and energize coil 1M, starting pump #1. As water fills the tank, the pressure increases. When the pressure has increased sufficiently, the pressure switch opens and disconnects coil 1M, stopping the operation of pump #1.

If pump #1 is to operate alternately with pump #2, some method must be devised to remember which pump operated last. This function will be performed by control relay CR. Since relay CR is to be used as a memory device, it must be permitted to remain energized when either or both of the motor starters are not energized. For this reason, this section of the circuit is connected to the input side of pressure switch PS. This addition to the circuit is shown in Figure 48–2.

The next stage of circuit development can be seen in Figure 48–3. In this stage of the circuit, motor starter 2M has been added. When pressure switch PS closes and energizes motor starter coil 1M, all 1M contacts change position. Contacts $1M_1$ and $1M_2$ close at the same time. When $1M_1$ contact closes, coil CR is energized, changing the position of all CR contacts. Contact CR_1 opens, but the current path to coil 1M is maintained by contact $1M_1$. Contact CR_2 is used as a holding contact around contact $1M_2$. Notice that each motor starter coil is protected by a separate overload contact. This fulfills the requirement that an overload on either motor will not prevent the operations of the other motor. Also notice that this section of the circuit has been connected to the output side of pressure switch PS.

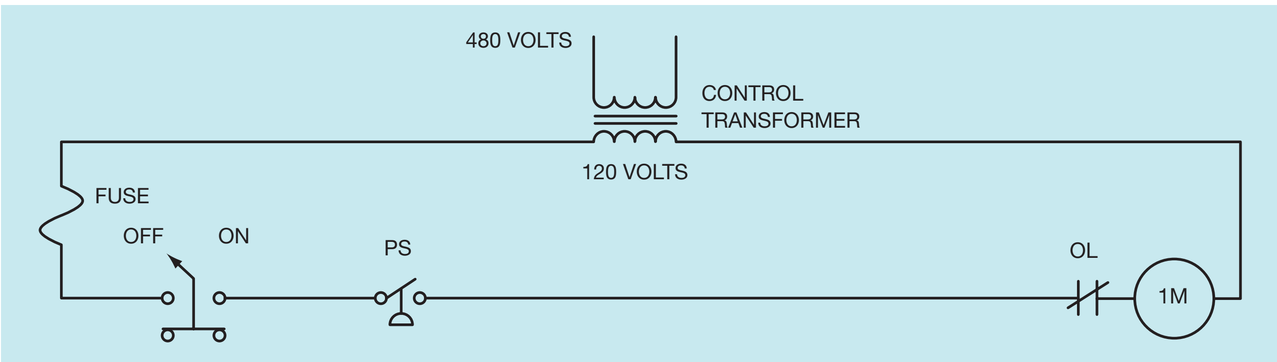


Figure 48–1 The pressure switch starts pump #1. (Source: Delmar/Cengage Learning.)

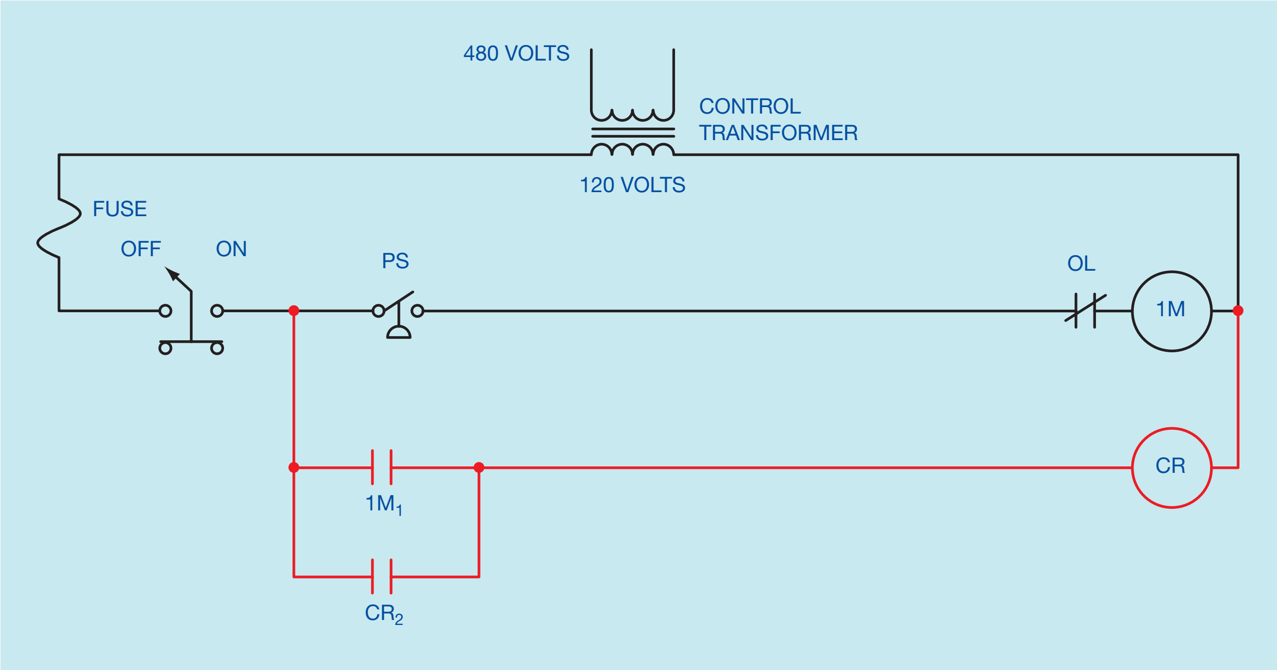


Figure 48–2 The control relay is used as a memory device. (Source: Delmar/Cengage Learning.)

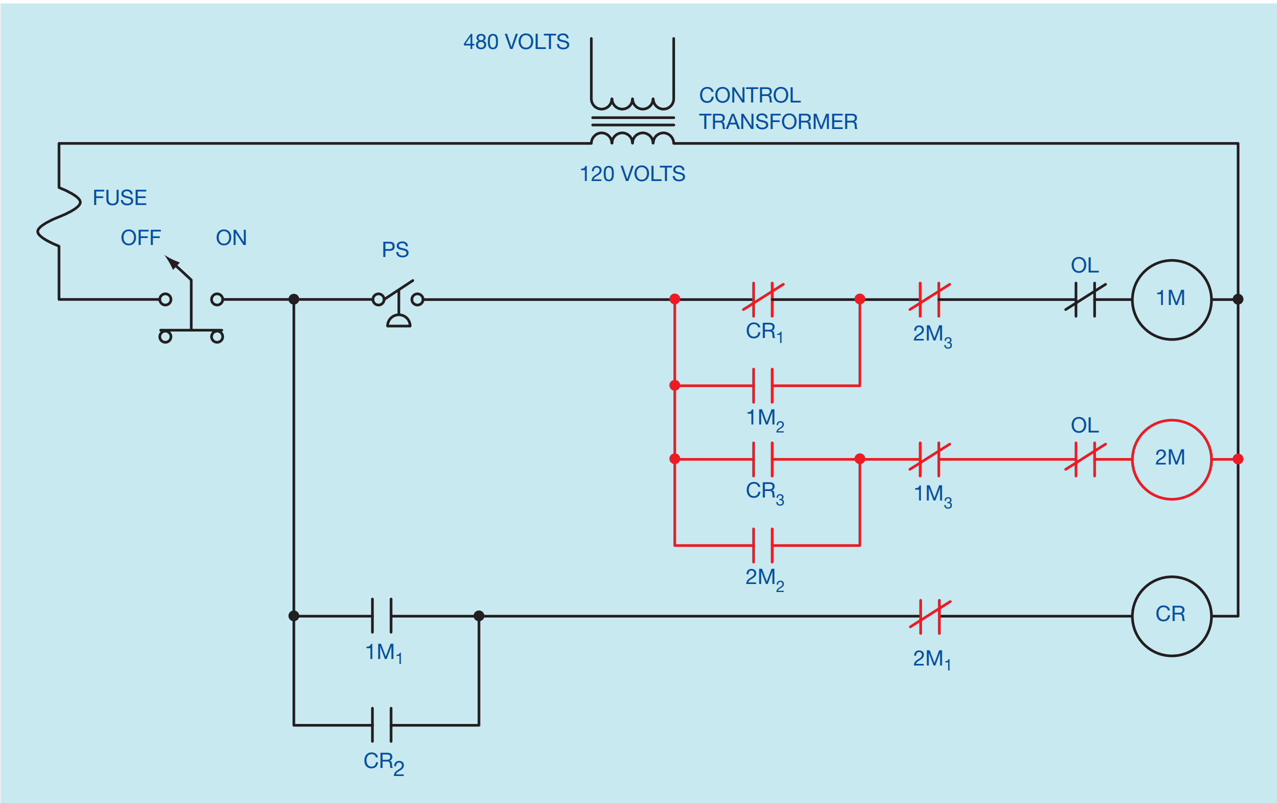


Figure 48–3 The addition of the second motor starter. (Source: Delmar/Cengage Learning.)

This permits the pressure switch to control the operation of both pumps.

To understand the operation of the circuit, assume pressure switch PS closes. This provides a current path to motor starter coil 1M. When coil 1M energizes, all 1M contacts change position and pump #1 starts. Contact $1M_1$ closes and energizes coil CR. Contact $1M_2$ closes to maintain a current path to coil 1M. Contact $1M_3$ opens to provide interlock with coil 2M, which prevents it from energizing whenever coil 1M is energized.

When coil CR energizes, all CR contacts change position. Contact CR_1 opens to break the circuit to coil 1M. Contact CR_2 closes to maintain a current path around contact $1M_1$, and contact CR_3 closes to provide a current path to motor starter coil 2M. Coil 2M cannot be energized, however, because of the now open $1M_3$ contact.

When the pressure switch opens, coil 1M will de-energize, permitting all 1M contacts to return to their normal positions, and the circuit will be left as shown in Figure 48–4. Note that this diagram is intended to show the condition of the circuit when the pressure switch is opened; it is not intended to show the contacts in their normal de-energized position. At this point in time, a current path is maintained to control relay CR.

When pressure switch PS closes again, contact CR_1 prevents a current path from being established to coil 1M, but contact CR_3 permits a current path to be established to coil 2M. When coil 2M energizes, pump #2 starts and all 2M contacts change position.

Contact $2M_1$ opens and causes coil CR to de-energize. Contact $2M_2$ closes to maintain a circuit to coil 2M when contact CR_3 returns to its normally open position, and contact $2M_3$ opens to prevent coil 1M from being energized when contact CR_1 returns to its normally closed position. The circuit will continue to operate in this manner until pressure switch PS opens and disconnects coil 2M from the line. When this happens, all 2M contacts will return to their normal positions as shown in Figure 48–3.

The only requirement not fulfilled is a switch that permits either pump to operate independently if one pump fails. This addition to the circuit is shown in

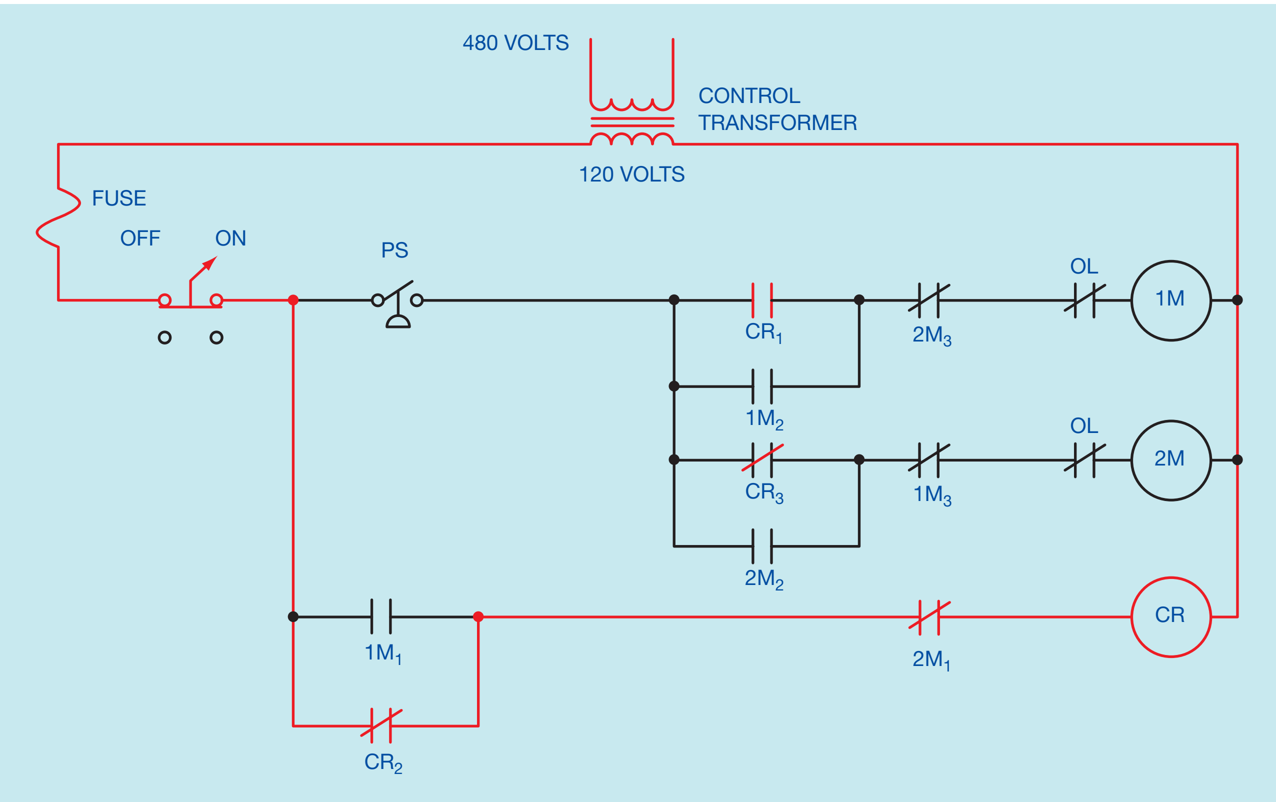


Figure 48–4 Coil CR remembers which pump operated last. (Source: Delmar/Cengage Learning.)

Figure 48–5. A three-position selector switch is connected to the output of the pressure switch. The selector switch will permit the circuit to alternate operation of the two pumps, or permit the operation of one pump only.

Although the logic of the circuit is now correct, there is a potential problem. After pump #1 has completed a cycle and the circuit is set as shown in Figure 48–4, there is a possibility that contact CR_3 will reopen before contact $2M_2$ closes to seal the circuit. If this happens, coil 2M will de-energize and coil 1M will be energized. This is often referred to as a contact race. To prevent this problem, an off-delay timer will be added as shown in Figure 48–6. In this circuit, coil CR has been replaced by coil TR of the timer. When coil TR energizes, contact TR will close immediately, energizing coil CR. When coil TR de-energizes, contact TR will remain closed for one second before reopening and permitting coil CR to de-energize. This short delay time will ensure proper operation of the circuit.

Circuit #2: Speed Control of a Wound Rotor Induction Motor

The second circuit to be developed will control the speed of a wound rotor induction motor. The motor will have three steps of speed. Separate push buttons are used to select the speed of operation. The motor will accelerate automatically to the speed selected. For example, if second speed is selected, the motor must start in the first or lowest speed and then accelerate to second speed. If third speed is selected, the motor must start in first speed, accelerate to second speed, and then accelerate to third speed. The requirements of the circuit are as follows:

1. The motor is to operate on a 480 volt three-phase power system, but the control system is to operate on 120 volts.
2. One stop button can stop the motor regardless of which speed has been selected.

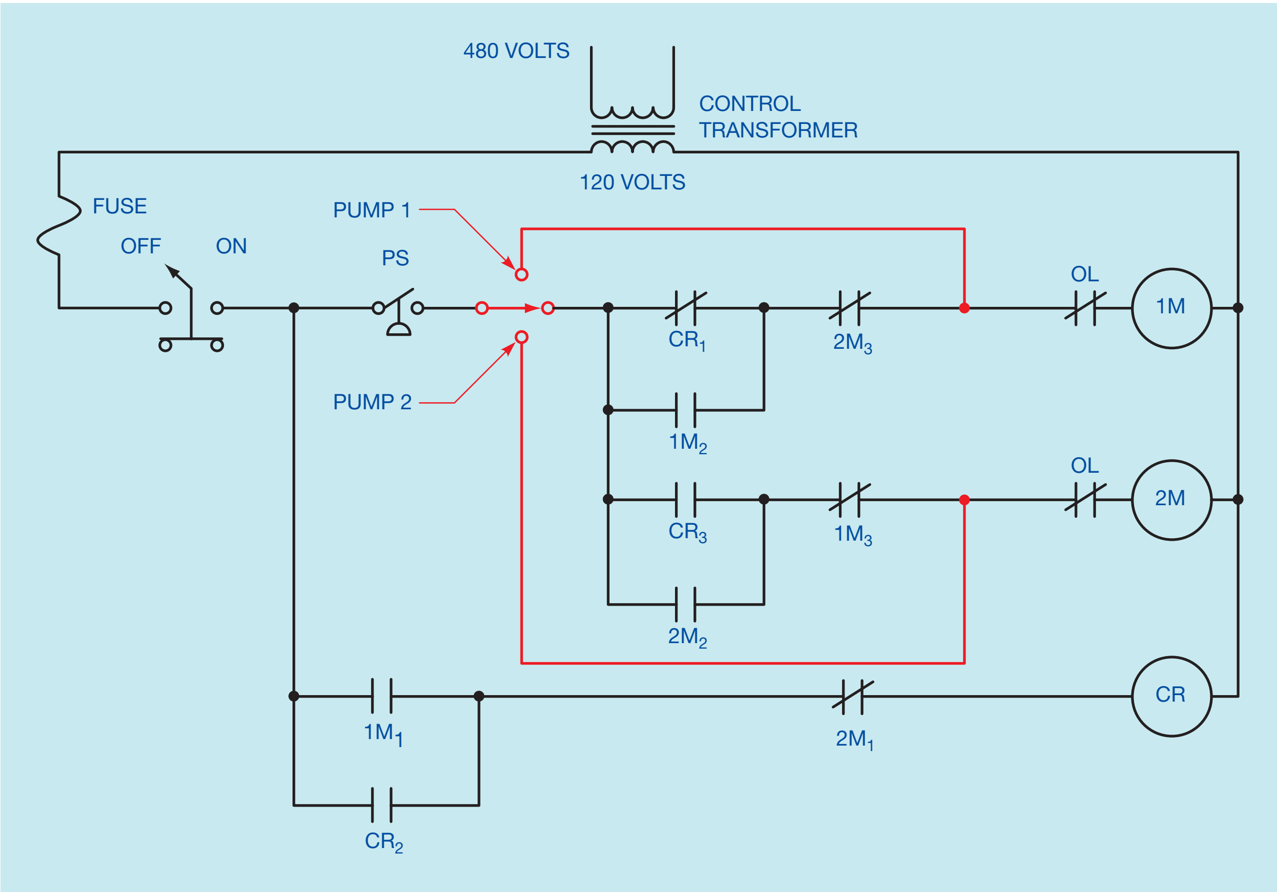


Figure 48–5 The basic logic of the circuit is complete. (Source: Delmar/Cengage Learning.)

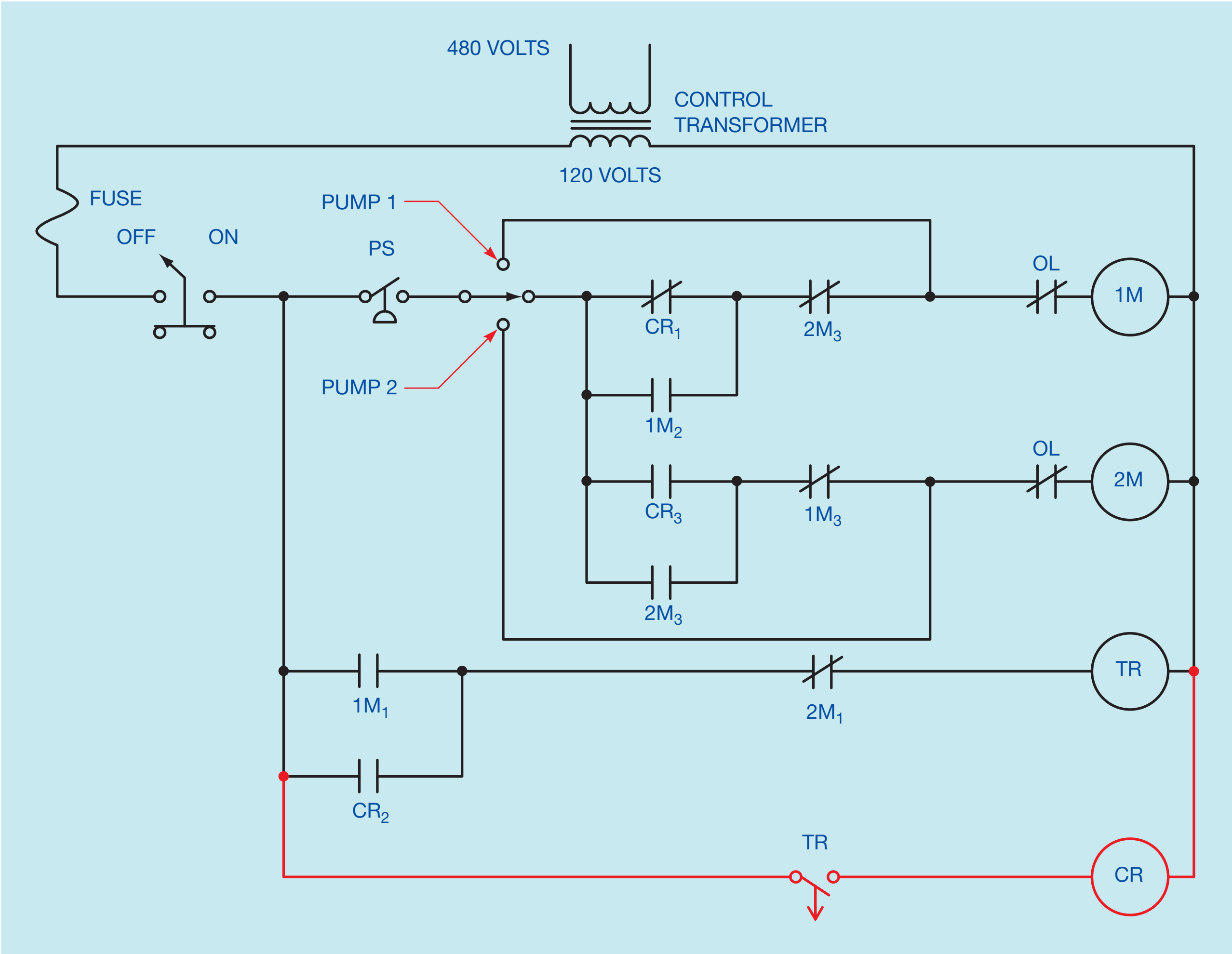


Figure 48–6 A timer is added to ensure proper operation. (Source: Delmar/Cengage Learning.)

3. The motor will have overload protection.
4. Three separate push buttons will select first, second, or third speed.
5. There will be a three-second time delay between accelerating from one speed to another.
6. If the motor is in operation and a higher speed is desired, it can be obtained by pushing the proper button. If the motor is operating and a lower speed is desired, the stop button must be pressed first.

Recall that speed control for a wound rotor motor is obtained by placing resistance in the secondary or rotor circuit as shown in Figure 48–7. In this circuit, load contacts 1M are used to connect the stator or primary of the motor to the power line. Two banks of three-phase resistors have been connected to the rotor. When power is applied to the stator, all resistance is connected in the rotor circuit and the motor will operate in its lowest or first speed. Second speed is obtained by closing contacts 1S and shorting out the first three-phase resistor bank. Third speed is obtained by closing contacts 2S. This shorts the rotor winding and the motor operates as a squirrel cage motor. A control transformer is connected to two of the three-phase lines to provide power for the control system.

The first speed can be obtained by connecting the circuit shown in Figure 48–8. When the FIRST SPEED button is pressed, motor starter coil 1M will close and connect the stator of the motor to the power line. Because all the resistance is in the rotor circuit, the motor

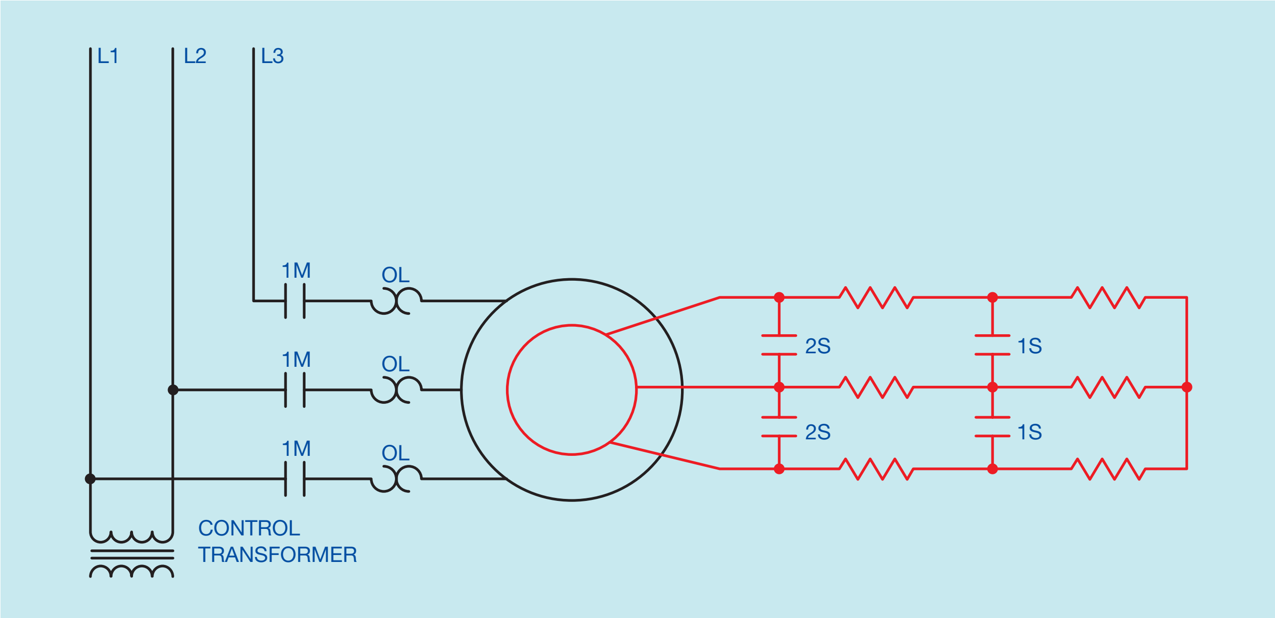


Figure 48–7 Speed is controlled by connecting resistance in the rotor circuit. (Source: Delmar/Cengage Learning.)

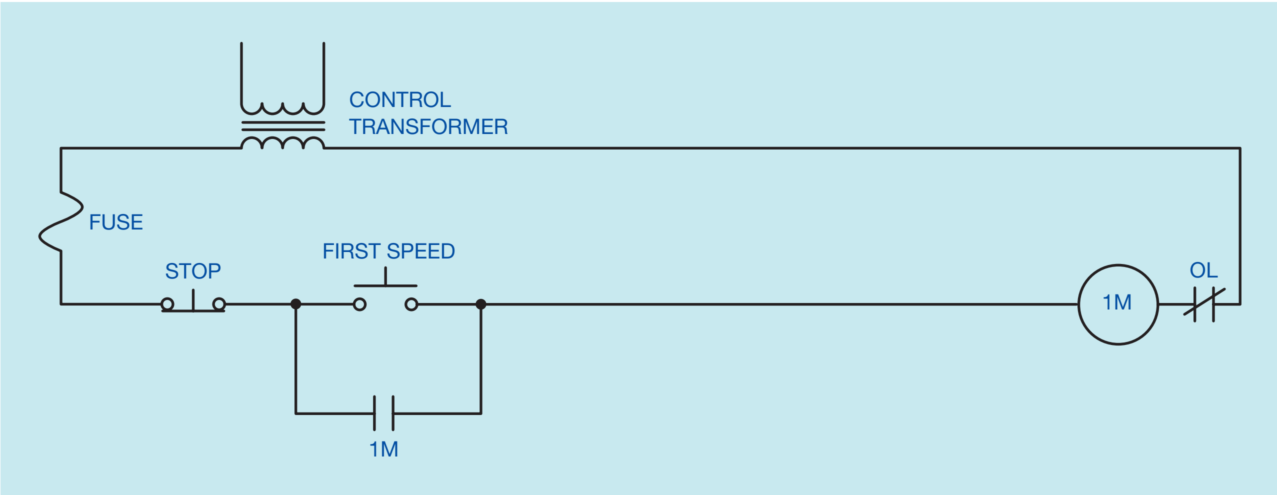


Figure 48–8 First speed. (Source: Delmar/Cengage Learning.)

will operate in its lowest speed. Auxiliary contact $1M_1$ is used as a holding contact. A normally closed overload contact is connected in series with coil 1M to provide overload protection. Notice that only one overload contact is shown, indicating the use of a three-phase overload relay.

The second stage of the circuit can be seen in Figure 48–9. When the SECOND SPEED button is pressed, the coil of on-delay timer 1TR is energized. Since the motor must be started in the first speed position, instantaneous timer contact $1TR_1$ closes to energize coil 1M and connect the stator of the motor to the line. Contact $1TR_2$ is used as a holding contact to keep coil 1TR energized when the SECOND SPEED button is released. Contact $1TR_3$ is a timed contact. At the end of 3 seconds, it will close and energize contactor coil 1S, causing all 1S contacts to close and shunt the first set of resistors. The motor now operates in second speed.

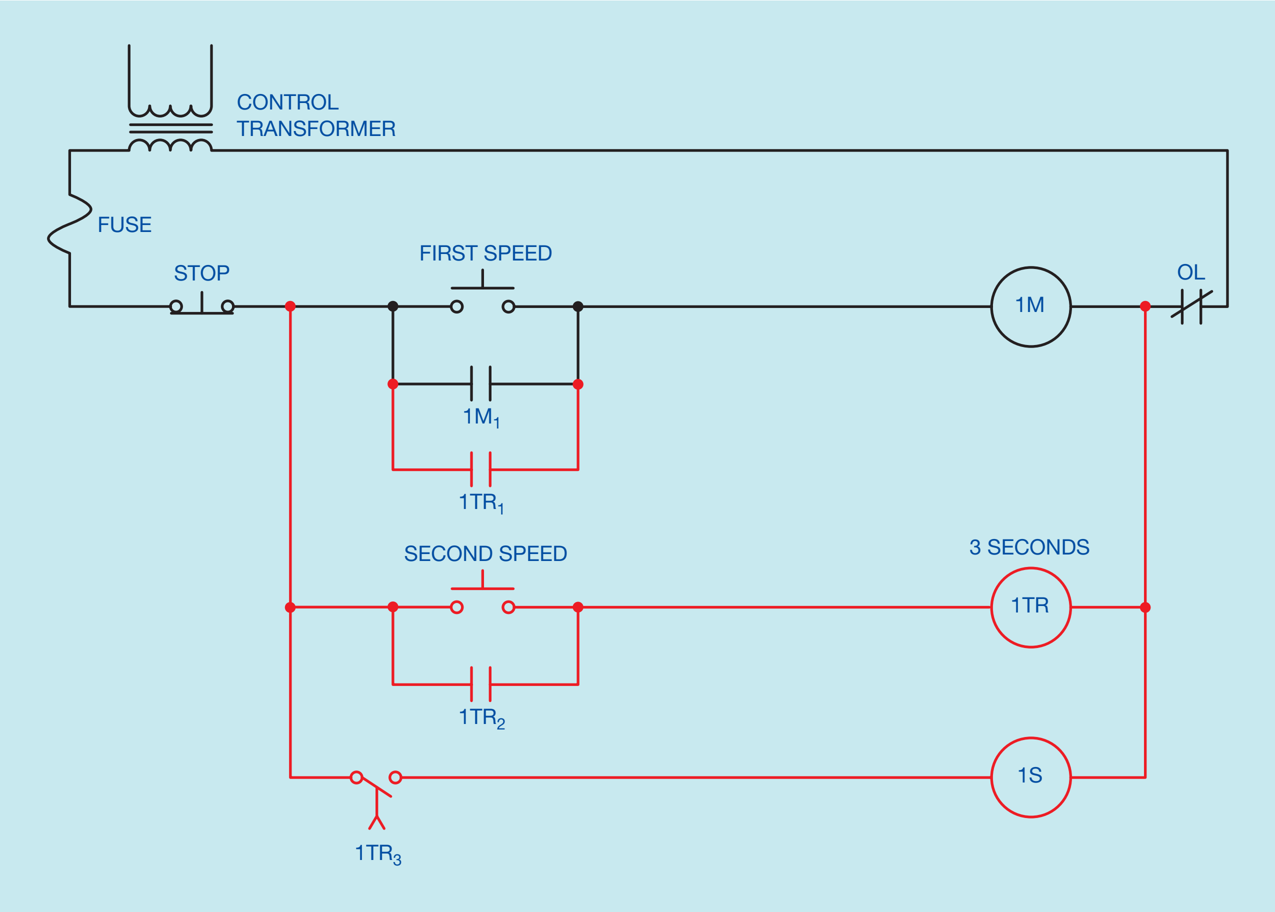


Figure 48–9 Second speed. (Source: Delmar/Cengage Learning.)

The final stage of the circuit is shown in Figure 48–10. The THIRD SPEED button is used to energize the coil of control relay 1CR. When coil 1CR is energized, all 1CR contacts change position. Contact $1CR_1$ closes to provide a current path to motor starter coil 1M, causing the motor to start in its lowest speed. Contact $1CR_2$ closes to provide a current path to timer 1TR. This permits timer 1TR to begin its timer operation. Contact $1CR_3$ maintains a current path to coil 1CR after the THIRD SPEED button is opened, and contact $1CR_4$ permits a current path to be established to timer 2TR. This contact is also used to prevent a current path to coil 2TR when the motor is to be operated in the second speed.

After timer 1TR has been energized for a period of 3 seconds, contact $1TR_3$ closes and energizes coil 1S. This permits the motor to accelerate to the second speed. Coil 1S also closes auxiliary contact $1S_1$ and completes a circuit to timer 2TR.

After a delay of 3 seconds, contact 2TR closes and energizes coil 2S. This causes contacts 2S to close and the motor operates in its highest speed.

Circuit #3: An Oil Heating Unit

In the circuit shown in Figure 48–11, motor starter 1M controls a motor that operates a high pressure

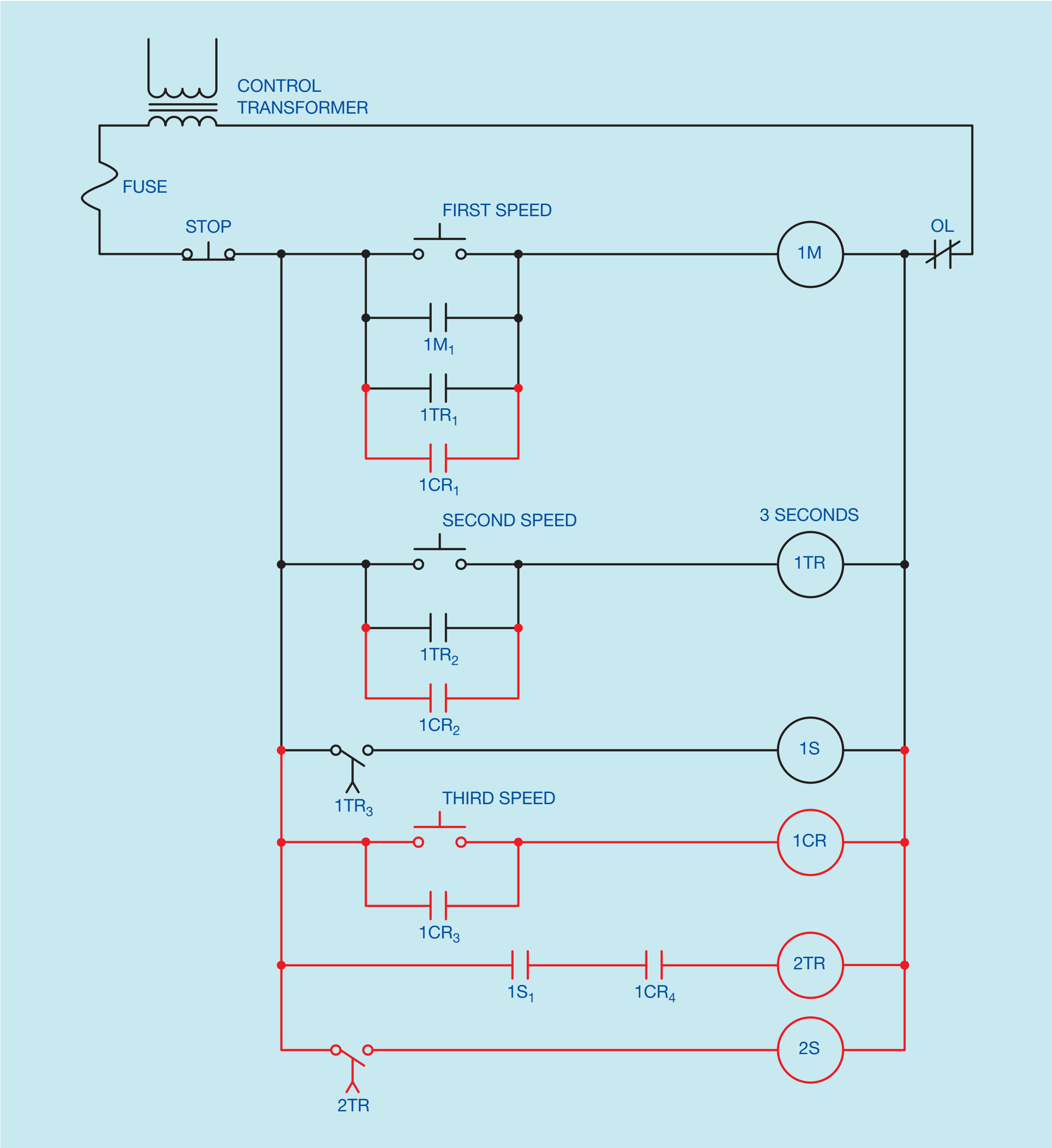


Figure 48–10 Third speed. (Source: Delmar/Cengage Learning.)

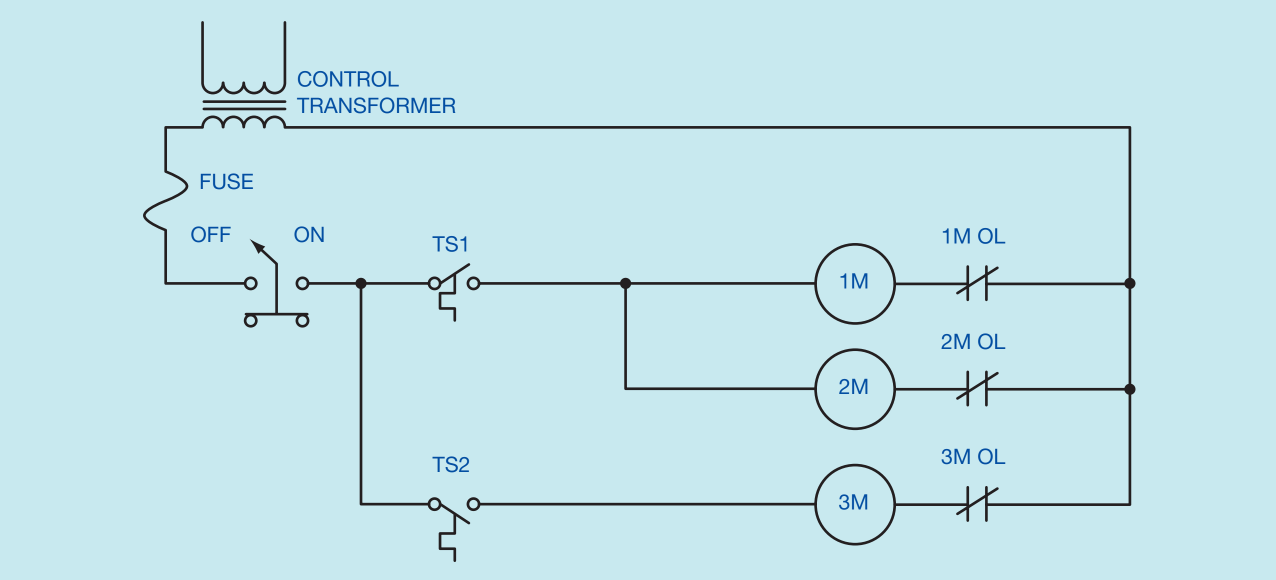


Figure 48–11 Heating system control. (Source: Delmar/Cengage Learning.)

pump. The pump is used to inject fuel oil into a combustion chamber where it is burned. Motor starter 2M operates an air induction blower that forces air into the combustion chamber when the oil is being burned. Motor starter 3M controls a squirrel cage blower, which circulates air across a heat exchanger to heat a building. A control transformer is used to change the incoming voltage from 240 volts to 120 volts, and a separate OFF-ON switch can be used to disconnect power from the circuit. Thermostat TS1 senses temperature inside the building and thermostat TS2 is used to sense the temperature of the heat exchanger.

To understand the operation of the circuit, assume the manual OFF-ON switch is set in the ON position. When the temperature inside the building drops to a low enough level, thermostat TS1 closes and provides power to starters 1M and 2M. This permits the pump motor and air induction blower to start. When the temperature of the heat exchanger rises to a high enough level, thermostat TS2 closes and energizes starter 3M. The blower circulates the air inside the building across the heat exchanger and raises the temperature inside the building. When the building temperature rises to a high enough level, thermostat TS1 opens and disconnects the pump motor and air induction motor. The blower will continue to operate until the heat exchanger has been cooled to a low enough temperature to permit thermostat TS2 to open its contact.

After some period of operation, it is discovered that the design of this circuit can lead to some serious safety hazards. If the overload contact connected to starter 2M should open, the high pressure pump motor will continue to operate without sufficient air being injected into the combustion chamber. Also, there is no safety switch to turn the pump motor off if the blower motor fails to provide cooling air across the heat exchanger. It is recommended that the following changes be made to the circuit:

1. If an overload occurs to the air induction motor, it will stop operation of both the high pressure pump motor and the air induction motor.
2. An overload of the high pressure pump motor will stop only that motor and permit the air induction motor to continue operation.
3. The air induction motor will continue operating for 1 minute after the high pressure pump motor has been turned off. This will clear the combustion chamber of excessive smoke and fumes.
4. A high limit thermostat is added to the heat exchanger to turn the pump motor off if the temperature of the heat exchanger should become excessive.

These circuit changes can be seen in Figure 48–12. Thermostat TS3 is the high limit thermostat. Since it is to be used to perform the function of stop, it is normally closed and connected in series with motor starter 1M.

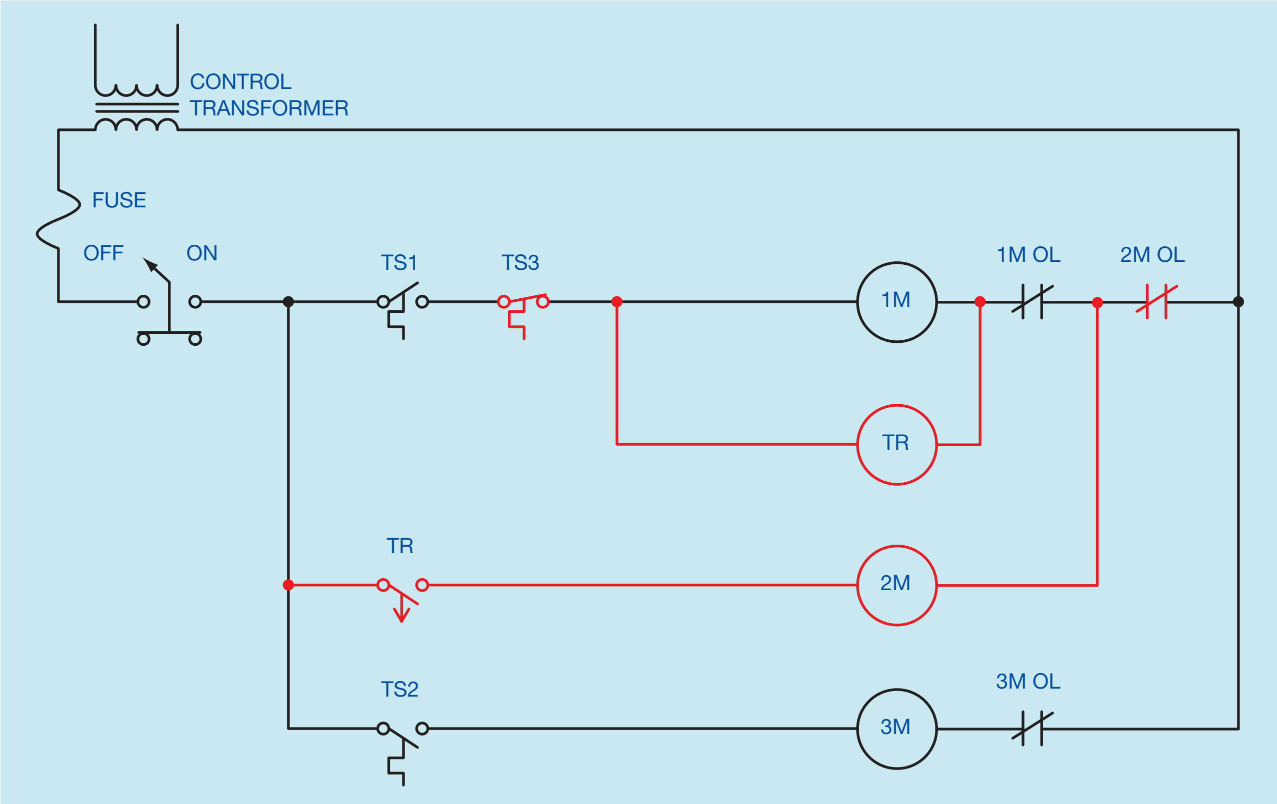


Figure 48–12 A timer is added to operate the air induction blower. (Source: Delmar/Cengage Learning.)

An off-delay timer is used to control starter 2M, and the overload contact of starter 2M has been connected in such a manner that it can stop the operation of both the air induction blower and the high pressure pump. Notice, however, that if 1M overload contact opens, it will not stop the operation of the air induction blower motor. The air induction blower motor would continue to operate for a period of one minute before stopping.

The logic of the circuit is as follows: When thermostat TS1 closes its contact, coils 1M and TR are energized. Because timer TR is an off-delay timer, contact TR closes immediately, permitting motor starter 2M to energize. When thermostat TS1 is satisfied and reopens its contact, or if thermostat TS3 opens its contact, coils 1M and TR will de-energize. Contact TR will remain closed for a period of one minute before opening and disconnecting starter 2M from the power line.

Although the circuit in Figure 48–12 satisfies the basic circuit requirement, there is still a potential problem. If the air induction blower fails for some reason other than the overload contact opening, the high pressure pump motor will continue to inject oil into the combustion chamber. To prevent this situation, an air flow switch, FL1, is added to the circuit as shown in Figure 48–13. This flow switch is mounted in such a position that it can sense the movement of air produced by the air induction blower.

When thermostat contact TS1 closes, coil TR energizes and closes contact TR. This provides a circuit to motor starter 2M. When the air injection blower starts, flow switch FL1 closes its contact and permits the high pressure pump motor to start. If the air injection blower motor stops for any reason, flow switch FL1 will disconnect motor starter 1M from the power line and stop operation of the high pressure pump.

Although the circuit now operates as desired, the owner of the building later decides the blower should circulate air inside the building when the heating system is not in use. To satisfy this request, an AUTO-MANUAL switch is added as shown in Figure 48–14. When the switch is set in the AUTO position, it permits the blower motor to be controlled by the thermostat TS2. When the switch is set in the MAN position, it connects the coil of starter 3M directly to the power line and permits the blower motor to operate independently of the heating system.

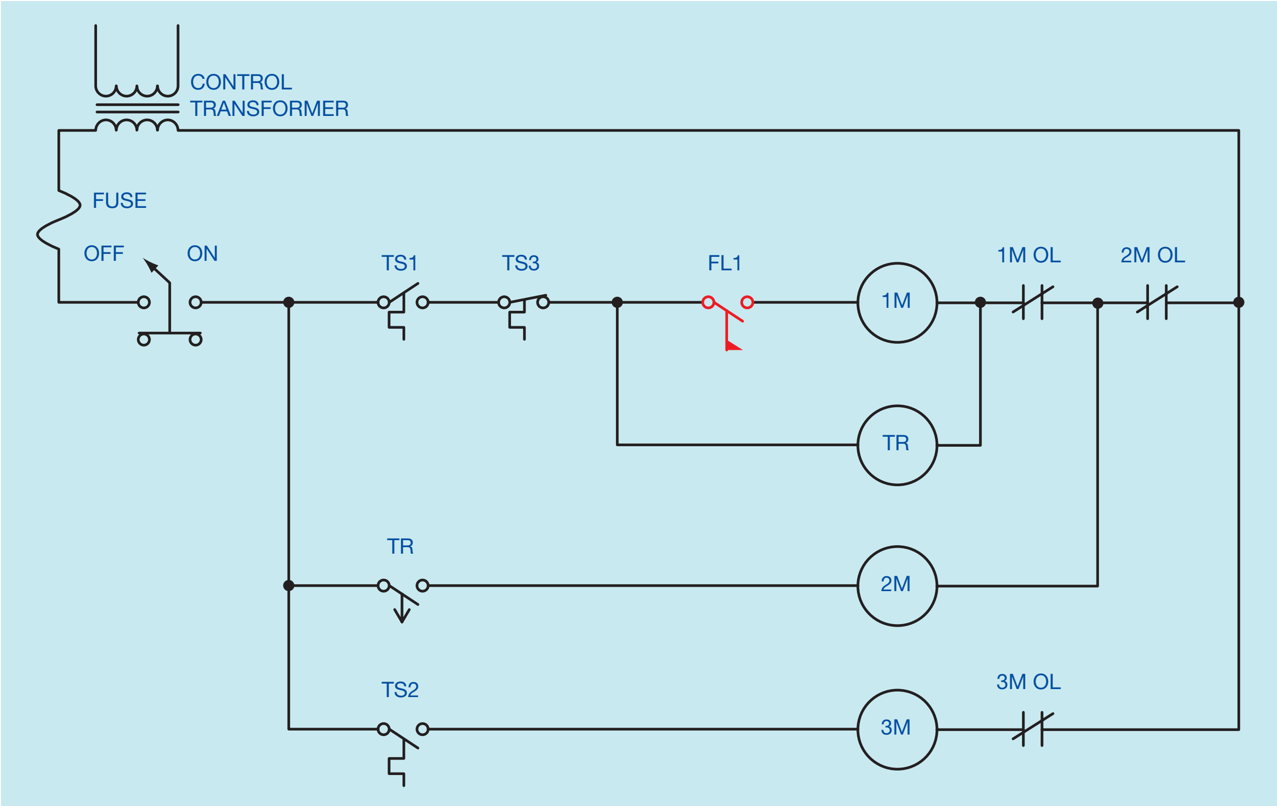


Figure 48–13 An air flow switch controls operation of the high-pressure burner motor. (Source: Delmar/Cengage Learning.)

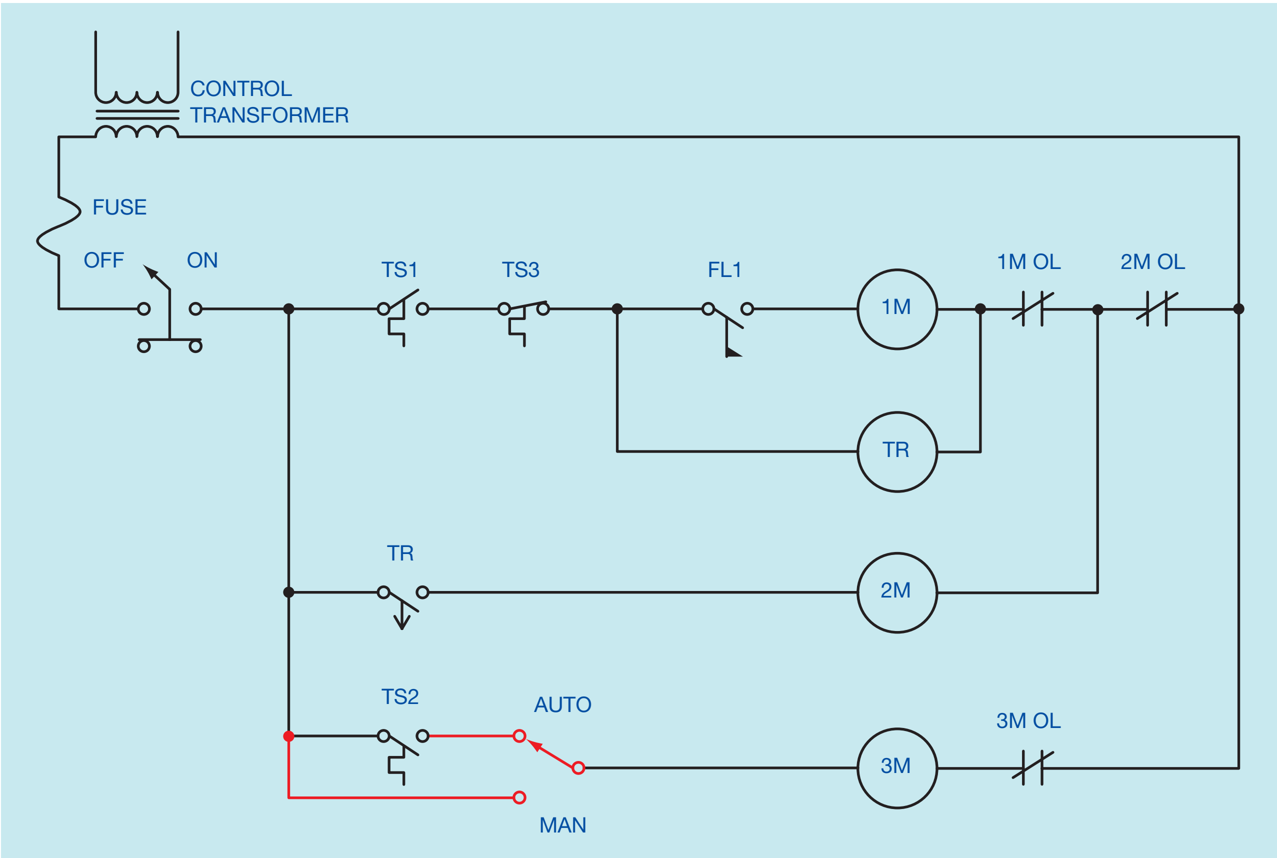


Figure 48–14 An AUTO-MANUAL switch is added to the blower motor. (Source: Delmar/Cengage Learning.)

Review Questions

To answer the following questions, refer to the circuit in Figure 48–6

1. The pressure switch is shown as:
   a. Normally open.
   b. Normally closed.
   c. Normally open held closed.
   d. Normally closed held open.
2. When the pressure switch closes, which starter will energize first, 1M or 2M? Explain your answer.
3. Is timer TR an on-delay timer or an off-delay timer? Explain how you can determine which it is by looking at the schematic diagram.
4. What is the purpose of timer TR in this circuit?
5. What is the purpose of the rotary switch connected after the pressure switch?

To answer the following questions, refer to the circuit shown in Figure 48–10

6. Is timer 1TR an on-delay or off-delay timer?
7. Assume that the THIRD SPEED push button is pressed. Explain the sequence of operation for the circuit.
8. Assume that the THIRD SPEED push button is pressed and the motor starts in its first or lowest speed. After a delay of 3 seconds the motor accelerates to its second speed, but never accelerates to its highest or third speed. Which of the following could cause this problem?
   a. CR coil is open.
   b. Coil 2TR is open.
   c. Coil 1TR is open.
   d. Coil 1S is open.
9. Assume that both timers are set for a delay of 3 seconds. Now assume that coil 1S is open. If the THIRD SPEED push button is pressed, will the motor accelerate to third speed after a delay of 6 seconds? Explain your answer.
10. Assume that timer 2TR is replaced with an off-delay timer, and that both timers are set for a delay of 3 seconds. Explain the operation of the circuit when the THIRD SPEED push button is pressed. Also explain the operation of the circuit when the STOP button is pressed.

To answer the following questions, refer to the circuit shown in Figure 48–14

11. Temperature switch TS1 is shown as:
    a. Normally open.
    b. Normally closed.
    c. Normally open held closed.
    d. Normally closed held open.
12. Temperature switch TS2 is shown as:
    a. Normally open.
    b. Normally closed.
    c. Normally open held closed.
    d. Normally closed held open.
13. Is timer TR an on-delay or off-delay timer?
14. Temperature switch TS3 is shown as:
    a. Normally open.
    b. Normally closed.
    c. Normally open held closed.
    d. Normally closed held open.
15. Assume that contact TS1 closes and the air injection blower motor starts operating, but the high pressure pump motor does not start. What could cause this problem?
    a. Temperature switch TS3 is open.
    b. Coil 2M is open.
    c. Flow switch FL1 is defective and did not close.
    d. Coil TR is open.

CHAPTER 49
TROUBLESHOOTING

OBJECTIVES

After studying this chapter, the student will be able to:

- Safely check a circuit to determine if power is disconnected.
- Use a voltmeter to troubleshoot a control circuit.
- Use an ohmmeter to test for continuity.
- Use an ammeter to determine if a motor is overloaded.

It is not a question of if a control circuit will eventually fail, but when will it fail. One of the main jobs of an industrial electrician is to troubleshoot and repair a control circuit when it fails. In order to repair or replace a faulty component, it is first necessary to determine which component is at fault. The three main instruments used by an electrician to troubleshoot a circuit are the voltmeter, ohmmeter, and ammeter. The voltmeter and ohmmeter are generally contained in the same meter (Figure 49–1). These meters are called *multimeters* because they can measure several different electrical quantities. Some electricians prefer to use plunger type voltage testers because they are not susceptible to ghost voltages. High impedance voltmeters often give an indication of some amount of voltage, caused by feedback and induction. Plunger type voltage testers are low impedance devices and require several milliamperes to operate. The disadvantage of plunger type voltage testers is that they cannot be used to test control systems that operate on low voltage, such as 24 volt systems.

Ammeters are generally clamp-on type (Figure 49–2). Both analog and digital meters are in common use. Clamp-on type ammeters have an advantage in that the circuit does not have to be broken to insert the meter in the line.

Safety Precautions

It is often necessary to troubleshoot a circuit with power applied to the circuit. **When this is the case, safety should be the first consideration. When de-energizing or energizing a control cabinet or motor control center module, the electrician should be dressed in flame retardant clothing and wearing safety glasses, a face shield, and hard hat. Motor control centers employed throughout industry generally have the ability to release enough energy in an arc-fault situation to kill a person thirty feet away.** Another rule that should always be observed

Figure 49–1 Digital multimeter. (Courtesy of Advanced Test Products.)

when energizing or de-energizing a circuit is to stand to the side of the control cabinet or module. Do not stand in front of the cabinet door when opening or closing the circuit. A direct short condition can cause the cabinet door to be blown off.

After the cabinet or module door has been opened, the power should be checked with a voltmeter to make certain the power is off. A procedure called *check, test, check,* should be used to make certain that the power is off:

1. Check the voltmeter on a known source of voltage to make certain the meter is operating properly.
2. Test the circuit voltage to make certain that it is off.
3. Check the voltmeter on a known source of voltage again to make certain that the meter is still working properly.

Voltmeter Basics

Recall that one definition of voltage is *electrical pressure.* The voltmeter indicates the amount of potential between two points in much the same way a pressure gauge indicates the pressure difference between two points. The circuit in Figure 49–3 assumes that a voltage of 120 volts exists between L1 and N. If the leads of a voltmeter were to be connected between L1 and N, the meter would indicate 120 volts.

Now assume that the leads of the voltmeter are connected across the lamp (Figure 49–4).

Question 1: Assuming that the lamp filament is good, would the voltmeter indicate 0 volts, 120 volts, or some value between 0 and 120 volts?

Answer: The voltmeter would indicate 0 volts. In the circuit shown in Figure 49–4, the switch and lamp are connected in series. One of the basic rules for series circuits is that the voltage drop across all circuit components must equal the applied voltage. The amount of voltage drop across each component is proportional to the resistance of the components and the amount of current flow. Since the switch is open in this example, there is no current flow through the lamp filament and no voltage drop.

Question 2: If the voltmeter is connected across the switch as shown in Figure 49–5, would it indicate 0 volts, 120 volts, or some value between 0 and 120 volts?

Answer: The voltmeter would indicate 120 volts. Since the switch is an open circuit, the resistance is infinite at this point, which is millions of times greater than the resistance of the lamp filament. Recall that voltage is electrical pressure. The only current flow through this circuit is the current flowing through the voltmeter and the lamp filament (Figure 49–6).

Question 3: If the total or applied voltage in a series circuit must equal the sum of the voltage drops across each component, why is all the voltage drop across the voltmeter resistor and none across the lamp filament?

Answer: There is some voltage drop across the lamp filament because the current of the voltmeter is flowing through it. The amount of voltage drop across the filament, however, is so small as compared to the voltage drop across the voltmeter that it is generally considered to be zero. Assume the lamp filament to have a resistance of 50 ohms. Now assume that the voltmeter is a digital meter and has a resistance of 10,000,000 ohms. The total circuit resistance is 10,000,050 ohms. The total circuit current is 0.000,011,999 ampere (120/10,000,050) or about 12 microamperes. The voltage drop across the lamp filament would be approximately 0.0006 volts or 0.6 millivolts (50 $\Omega \times 12\ \mu$A).

Question 4: Now assume that the lamp filament is open or burned out. Would the voltmeter in Figure 49–7 indicate 0 volts, 120 volts, or some value between 0 and 120 volts?

Answer: The voltmeter would indicate 0 volts. If the lamp filament is open or burned out, a current

(A) (B) (C)

Figure 49–2 (A) Analog type clamp-on ammeter with vertical scale. (B) Analog type clamp-on ammeter with flat scale. (C) Clamp-on ammeter with digital scale. (Courtesy of Advanced Test Products.)

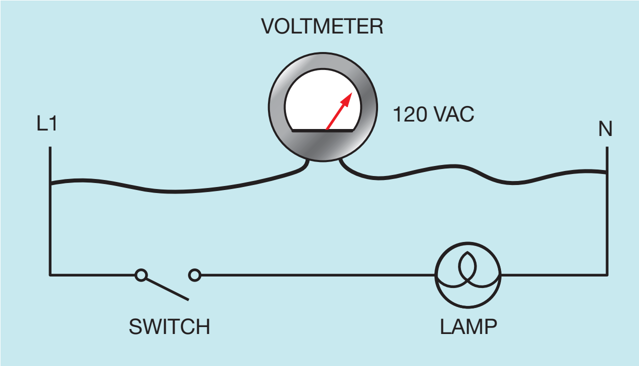


Figure 49–3 The voltmeter measures electrical pressure between two points. (Source: Delmar/Cengage Learning.)

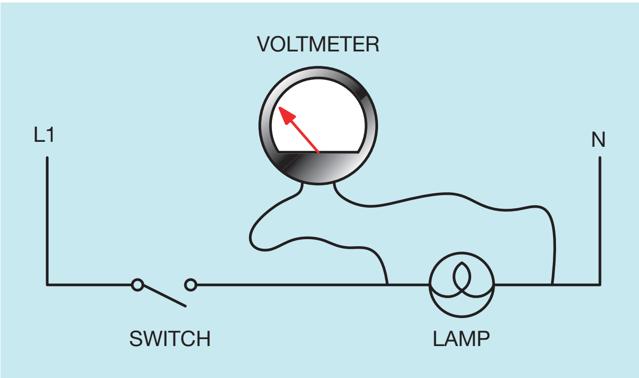


Figure 49–4 The voltmeter is connected across the lamp. (Source: Delmar/Cengage Learning.)

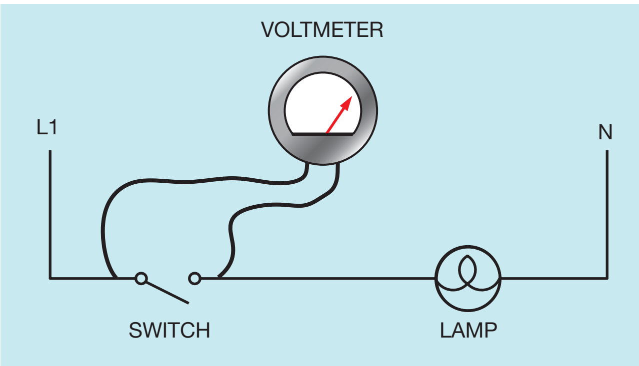


Figure 49–5 The voltmeter is connected across the switch. (Source: Delmar/Cengage Learning.)

path for the voltmeter does not exist and the voltmeter would indicate 0 volts. In order for the voltmeter to indicate voltage, it would have to be connected across both components so that a complete circuit would exist from L1 to N (Figure 49–8).

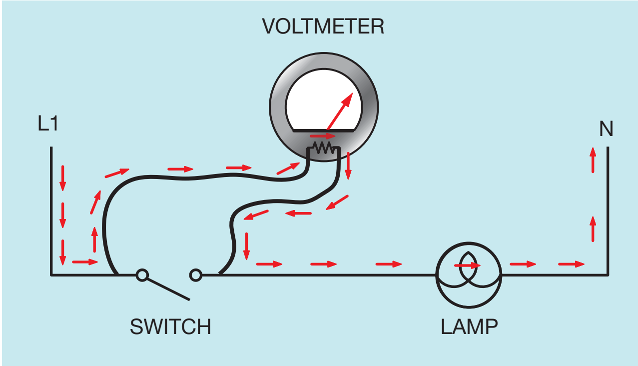


Figure 49–6 A current path exists through the voltmeter and lamp filament. (Source: Delmar/Cengage Learning.)

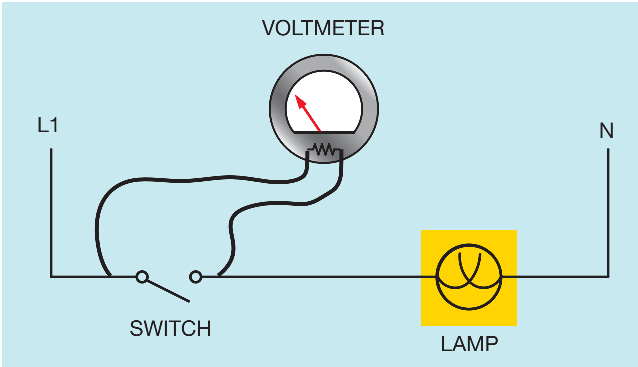


Figure 49–7 The lamp filament is burned open. (Source: Delmar/Cengage Learning.)

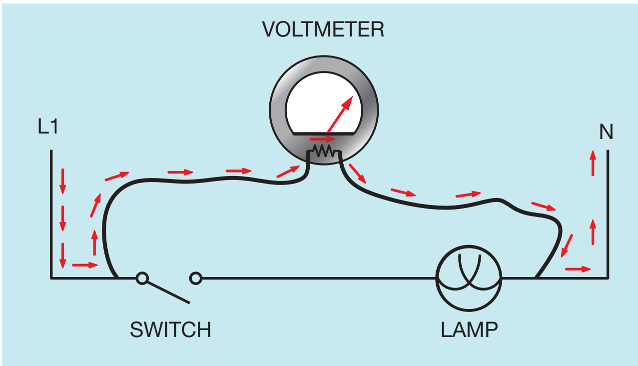


Figure 49–8 The voltmeter is connected across both components. (Source: Delmar/Cengage Learning.)

Question 5: Assume that the lamp filament is not open or burned out and that the switch has been closed or turned on. If the voltmeter is connected across the switch, would it indicate 0 volts, 120 volts or some value between 0 and 120 volts (Figure 49–9)?

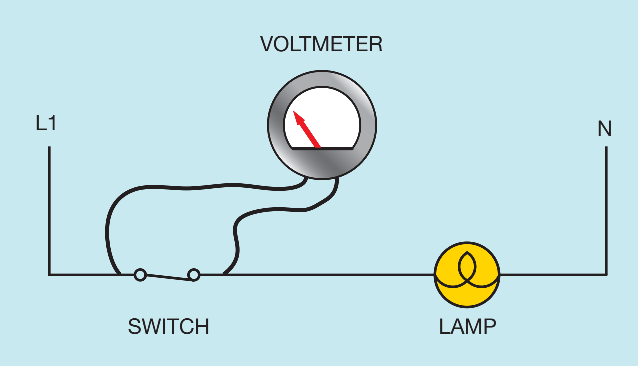


Figure 49–9 The switch is turned on or closed. (Source: Delmar/Cengage Learning.)

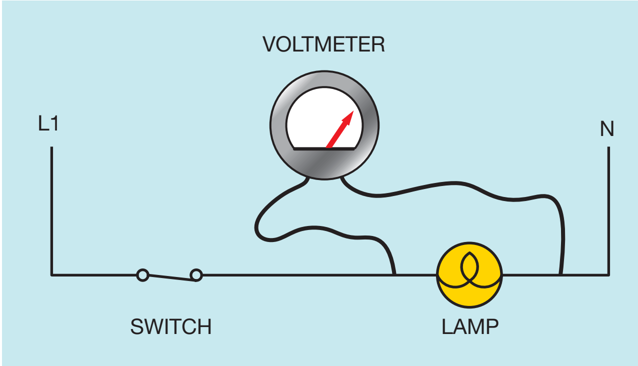


Figure 49–10 Practically all the voltage drop is across the lamp. (Source: Delmar/Cengage Learning.)

Answer: The voltmeter would indicate 0 volts. Now that the switch is closed, the contact resistance is extremely small and the lamp filament now exhibits a much higher resistance than the switch. Practically all the voltage drop will now appear across the lamp (Figure 49–10).

Test Procedure Example 1

The type of problem determines the procedure to be employed when troubleshooting a circuit. For example, assume that an overload relay has tripped several times. The first step is to determine what conditions could cause this problem. If the overload relay is a thermal type, a source of heat is the likely cause of the problem. Make mental notes of what could cause the overload relay to become overheated:

1. Excessive motor current.
2. High ambient temperature.
3. Loose connections.
4. Incorrect wire size.

If the motor has been operating without a problem for some period of time, incorrect wire size can probably be eliminated. If it is a new installation, that would be a factor to consider.

Since overload relays are intended to disconnect the motor from the power line in the event that the current draw becomes excessive, the motor should be checked for excessive current. The first step is to determine the normal full load current from the nameplate on the motor. The next step is to determine the percentage of full load current setting for the overload relay.

EXAMPLE:

A motor nameplate indicates the full load current of the motor is 46 amperes. The nameplate also indicates the motor has a service factor of 1.00. The National Electrical Code indicates the overload should be set to trip at 115% of the full load current. The overload heaters should be sized for 52.9 amperes (46×1.15).

The next step is to check the running current of the motor with an ammeter. This is generally accomplished by measuring the motor current at the overload relay (Figure 49–11). The current in each phase should be

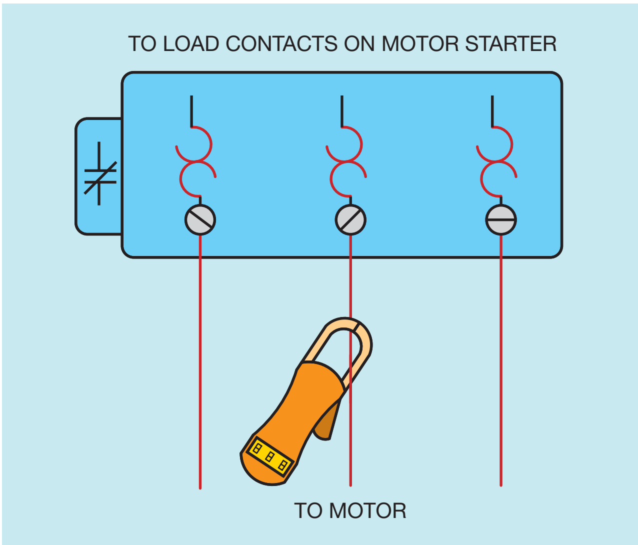


Figure 49–11 A clamp-on ammeter is used to check motor current. (Source: Delmar/Cengage Learning.)

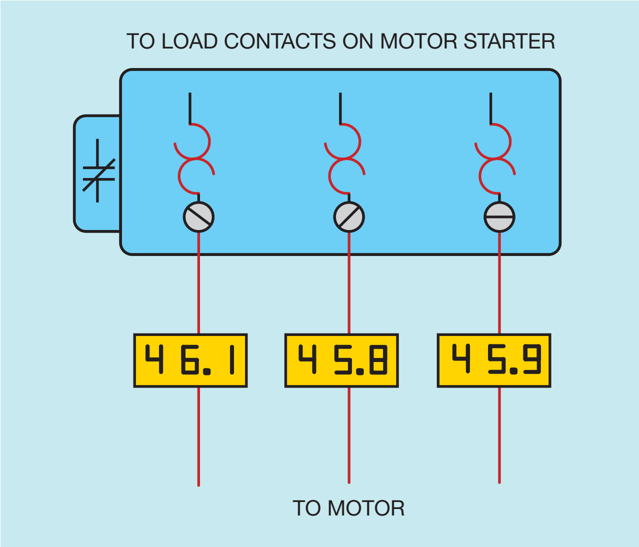


Figure 49–12 Ammeter readings indicate that the motor is operating normally. (Source: Delmar/Cengage Learning.)

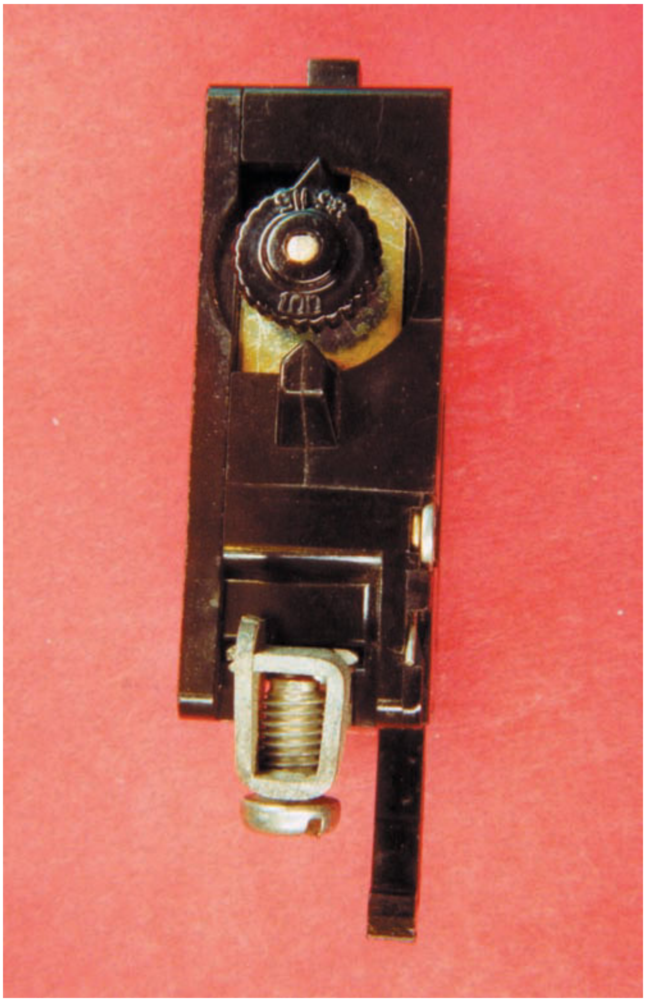


Figure 49–13 Bimetal strip type overload relays can be set for a higher value of current. (Source: Delmar/Cengage Learning.)

measured. If the motor is operating properly, the readings may not be exactly the same, but they should be close to the full load current value if the motor is operating under load, and relatively close to each other. In the example shown in Figure 49–12, phase 1 has a current flow of 46.1 amperes, phase 2 has a current flow of 45.8 amperes, and phase 3 has a current flow of 45.9 amperes. These values indicate that the motor is operating normally. Since the ammeter indicates that the motor is operating normally, other sources of heat should be considered. After turning off the power, check all connections to ensure that they are tight. Loose connections can generate a large amount of heat, and loose connections close to the overload relay can cause the relay to trip.

Another consideration should be ambient temperature. If the overload relay is located in an area of high temperature, the excess heat could cause the overload relay to trip prematurely. If this is the case, bimetal strip type overload relays (Figure 49–13) can often be adjusted for a higher setting to offset the problem of ambient temperature. If the overload relay is the solder melting type, it will be necessary to change the heater size to offset the problem, or to install some type of cooling device such as a small fan. If a source of heat cannot be identified as the problem, the overload relay probably has a mechanical defect and should be replaced.

Now assume that the ammeter indicates excessively high current reading on all three phases. In the example shown in Figure 49–14, phase 1 has a current flow of 58.1 amperes, phase 2 has a current flow of 59.2 amperes, and phase 3 has a current flow of 59.3 amperes. Recall that the full load nameplate current for this motor is 46 amperes. These values indicate that the motor is overloaded. The motor and load should be checked for some type of mechanical problem such as a bad bearing or possibly a brake that has become engaged.

Now assume that the ammeter indicates one phase with normal current and two phases that have excessively high current. In the example shown in Figure 49–15, phase 1 has a current flow of 45.8 amperes, phase 2 has a current flow of 73.2 amperes, and phase 3 has a current flow of 74.3 amperes. Two phases with excessively high current indicate that the motor

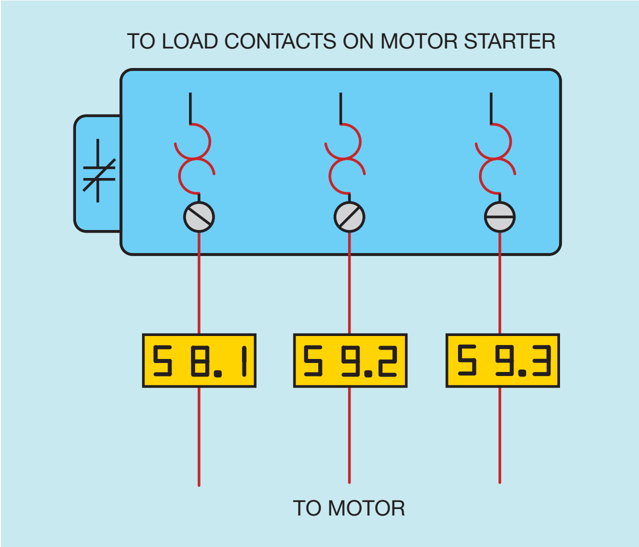


Figure 49–14 Ammeter readings indicate that the motor is overloaded. (Source: Delmar/Cengage Learning.)

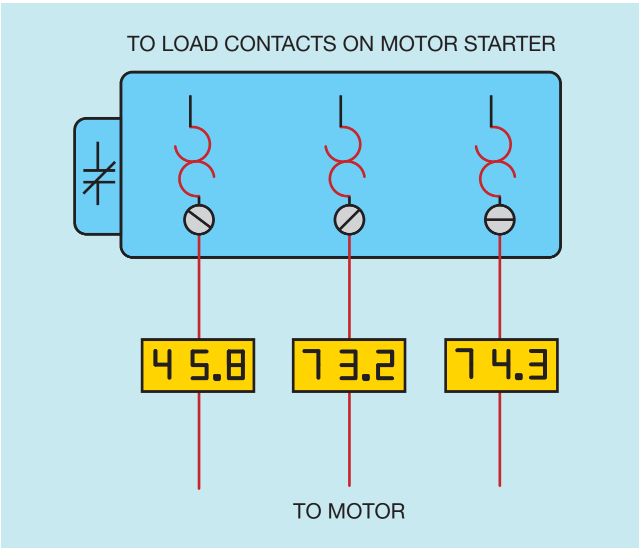


Figure 49–15 Ammeter readings indicate that the motor has a shorted winding. (Source: Delmar/Cengage Learning.)

probably has a shorted winding. If two phases have a normal amount of current and one phase is excessively high, it is a good indication that one of the phases has become grounded to the case of the motor.

Test Procedure Example 2

The circuit shown in Figure 49–16 is a reversing starter with electrical and mechanical interlocks. Note that double acting push buttons are used to disconnect one contactor if the start button for the other contactor is pressed. Now assume that if the motor is operating in the forward direction, and the REVERSE pushbutton is pressed, the forward contactor de-energizes but the reverse contactor does not. If the FORWARD push button is pressed, the motor will restart in the forward direction.

To begin troubleshooting this problem, make mental notes of problems that could cause this condition:

1. The reverse contactor coil is defective.
2. The normally closed F auxiliary contact is open.
3. The normally closed side of the FORWARD push button is open.
4. The normally open side of the REVERSE push button does not complete a circuit when pressed.
5. The mechanical linkage between the forward and reversing contactors is defective.

Also make mental notes of conditions that could **not** cause the problem:

1. The STOP button is open. (If the STOP button were open, the motor would not run in the forward direction.)
2. The overload contact is open. (Again, if this were true, the motor would not run in the forward direction.)

To begin checking this circuit, an ohmmeter can be used to determine if a complete circuit path exists through certain components. **When using an ohmmeter, make certain that the power is disconnected from the circuit.** A good way to do this in most control circuits is to remove the control transformer fuse. The ohmmeter can be used to check the continuity of the reverse contactor coil, the normally closed F contact, the normally closed section of the FORWARD push-button, and across the normally open REVERSE push-button when it is pressed (Figure 49–17).

The ohmmeter can be used to test the starter coil for a complete circuit to determine if the winding has been burned open, but it is generally not possible to determine in this way if the coil is shorted. To make a final determination, it is generally necessary to apply power to the circuit and check for voltage across the coil. Since the REVERSE push button must be closed to make this measurement, it is common practice to connect a fused jumper across the push button if there is no one to hold the button closed (Figure 49–18). A fused jumper is shown in Figure 49–19. When using a

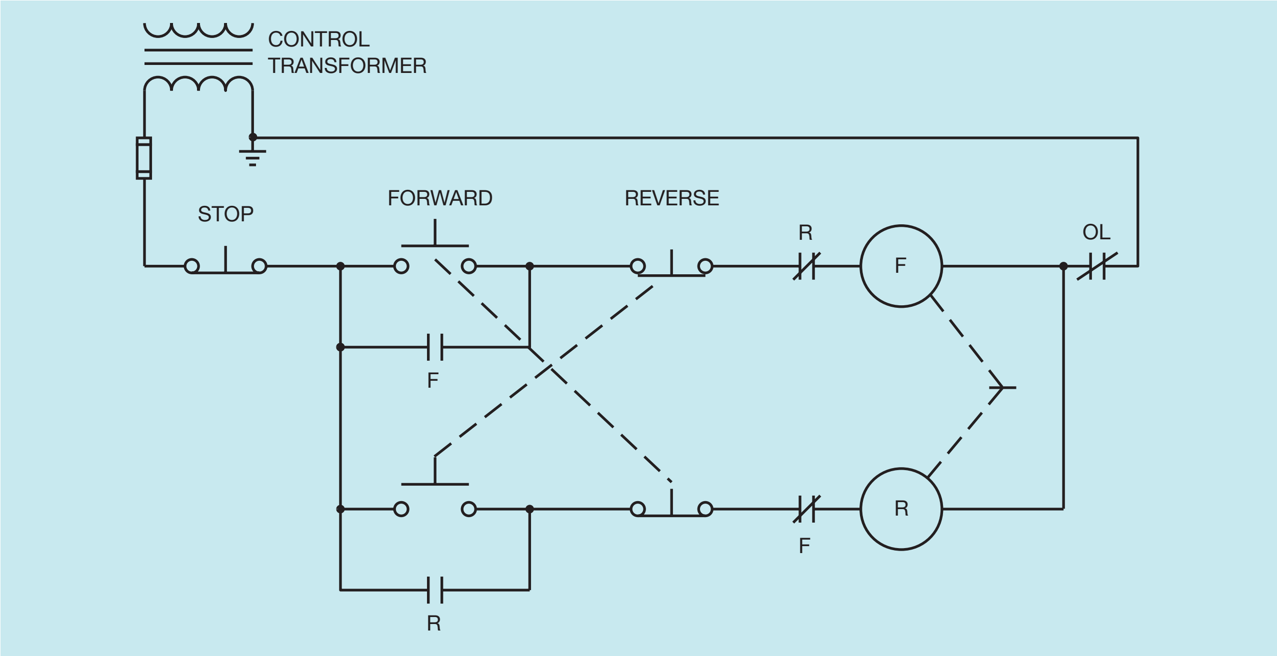


Figure 49–16 Reversing starter with interlocks. (Source: Delmar/Cengage Learning.)

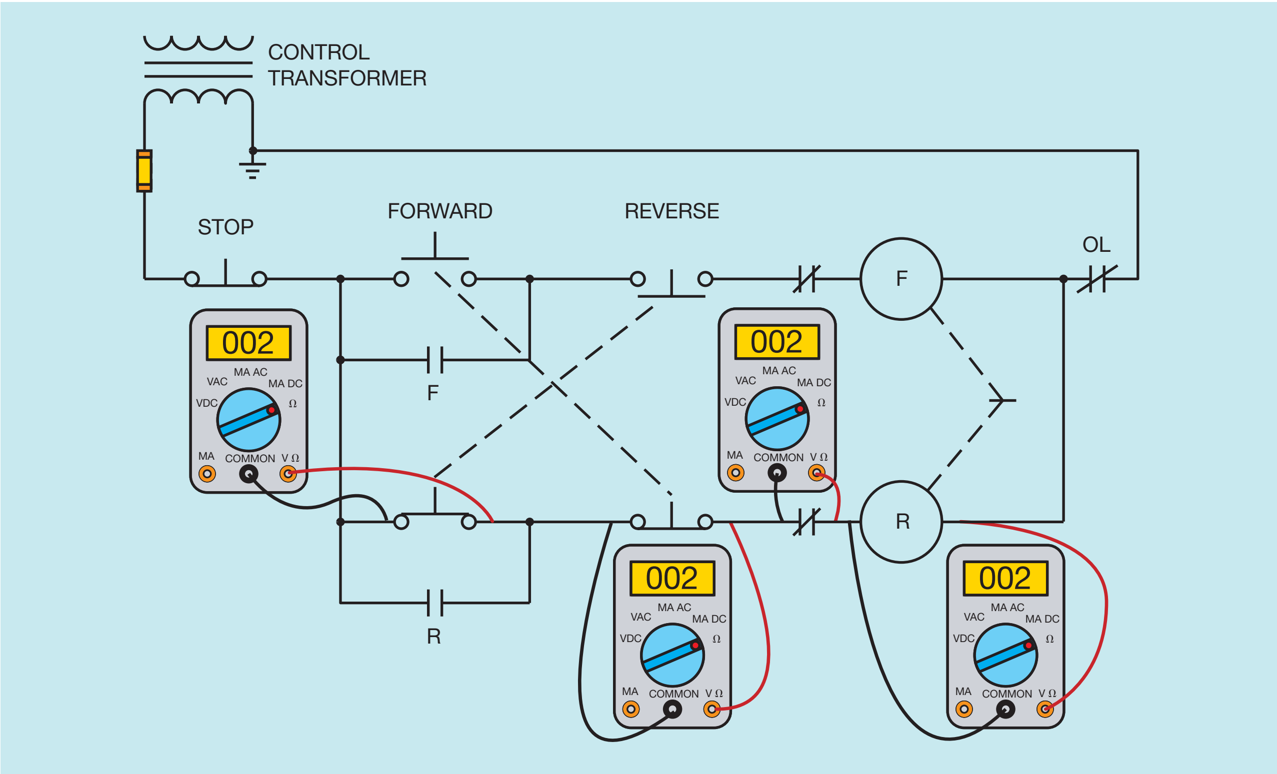


Figure 49–17 Checking components for continuity with an ohmmeter. (Source: Delmar/Cengage Learning.)

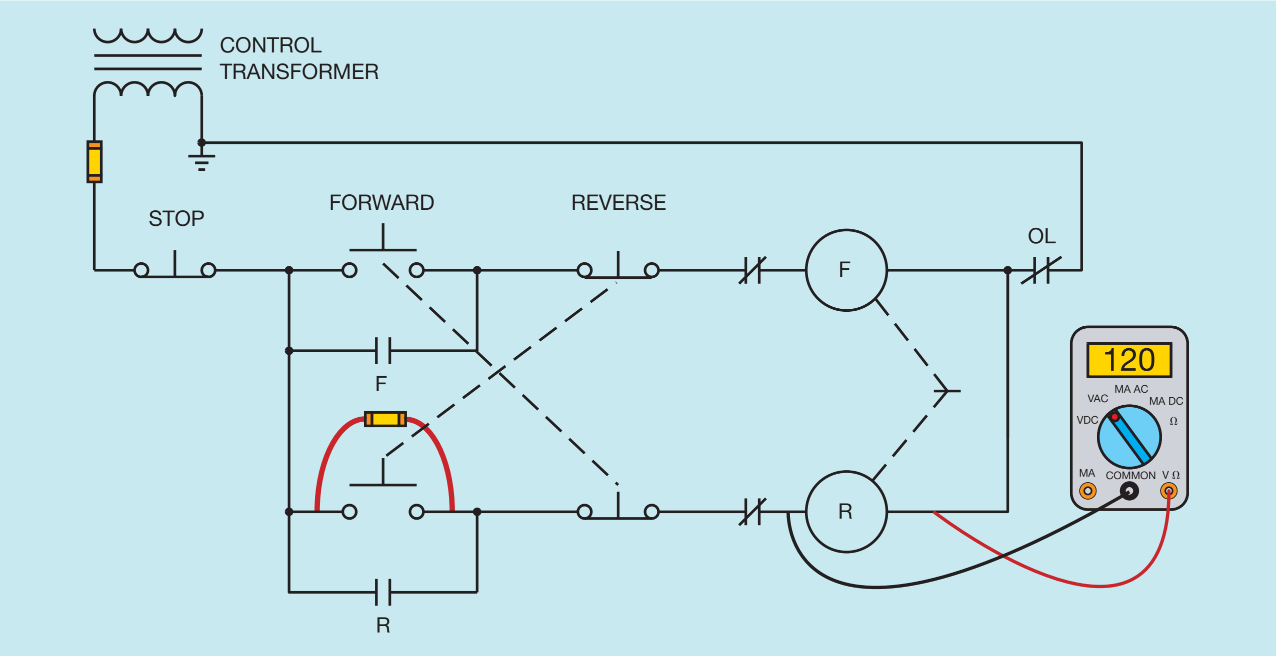


Figure 49–18 Testing to determine if voltage is being applied to the coil. (Source: Delmar/Cengage Learning.)

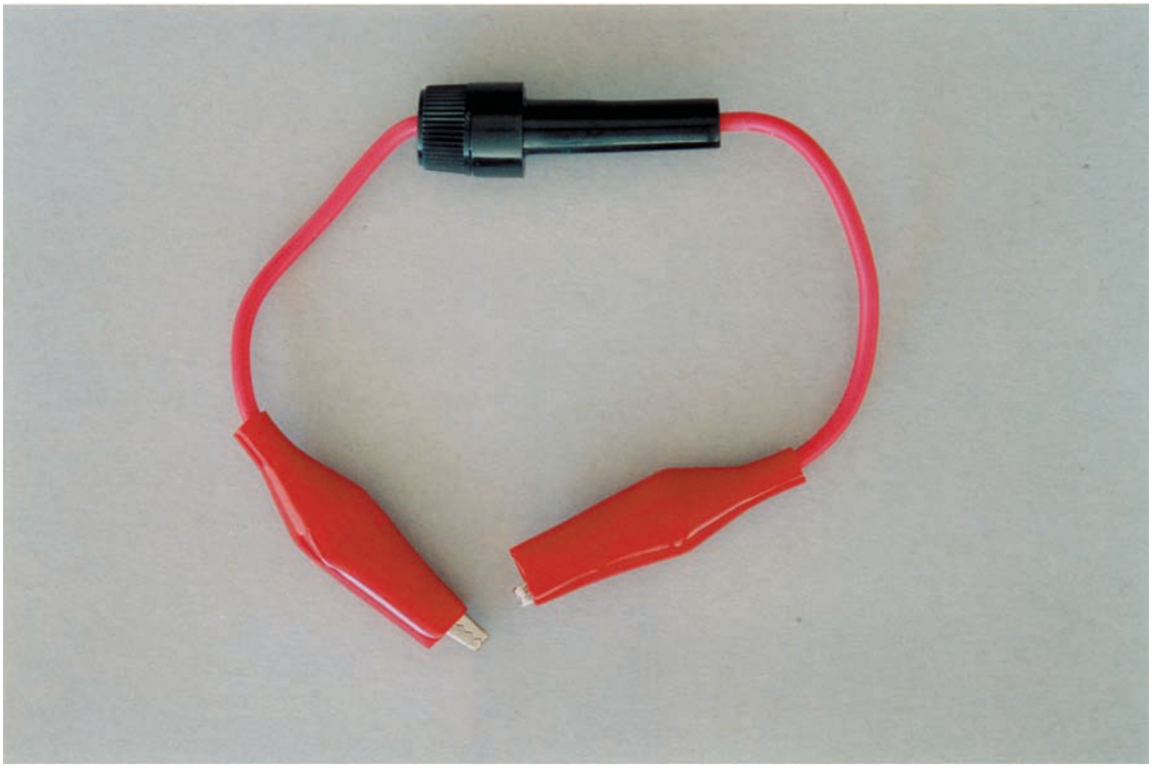


Figure 49–19 A fused jumper is often used to complete a circuit when troubleshooting. (Source: Delmar/Cengage Learning.)

fused jumper, power should be disconnected when the jumper is connected across the component. After the jumper is in position, power can be restored to the circuit. If voltage appears across the coil, it is an indication that the coil is defective and should be replaced or that the mechanical interlock between the forward and reverse contactors is defective.

Test Procedure Example 3

The next circuit to be discussed is shown in Figure 49–20. This circuit permits the motor to be started in any of three speeds with a 5 second time delay between accelerating from one speed to another. Regardless of which speed push button is pressed, the motor must start in its lowest speed and progress to the selected speed. It is assumed that eight-pin on-delay timers are used to provide the time delay for acceleration to the next speed.

Assume that when the THIRD SPEED push button is pressed, the motor starts in it lowest speed. After 5 seconds the motor accelerates to second speed but never increases to third speed. As in the previous examples, start by making a mental list of the conditions that could cause this problem:

1. Contactor S2 is defective.
2. Timed contact TR2 did not close.
3. Timer TR2 is defective.
4. CR2 or S1 contacts connected in series with timer TR2 did not close.

Begin troubleshooting this circuit by pressing the THIRD SPEED push button and permitting the motor to accelerate to second speed. Wait at least 5 seconds after the motor has reached third speed and connect a voltmeter across the coil of S2 contactor (Figure 49–21). Now, assume that the voltmeter indicated a reading of 0 volts. This indicates that there is no power being applied to the coil of S2 contactor. The next step is to check for voltage across pins 1 and 3 of timer TR2 (Figure 49–22). If the voltmeter indicates a value of 120 volts, it is an indication that the normally open timed contact has not closed.

If timed contact TR2 has not closed, check for voltage across timer TR2 (Figure 49–23). This can be done by checking for voltage across pins 2 and 7 of the timer. If a value of 120 volts is present, the timer is receiving power, but contact TR2 did not close. This is an indication that the timer is defective and should be replaced. If the voltage across timer coil TR2 is 0, then the voltmeter should be used to determine if contact CR2 or S1 is open.

Troubleshooting is a matter of progressing logically through a circuit. It is virtually impossible to troubleshoot a circuit without a working knowledge of schematics. You canít determine what a circuit is or is not doing if you donít understand what it is intended to do in normal operation. Good troubleshooting techniques take time and practice. As a generally rule, it is easier to progress backward though the circuit until the problem is identified. For example, in this circuit, contactor S2 provided the last step of acceleration for the motor. Starting at contactor S2 and progressing backward until determining what component was responsible for no power being applied to the coil of S2 was much simpler and faster than starting at the beginning of the circuit and each component.

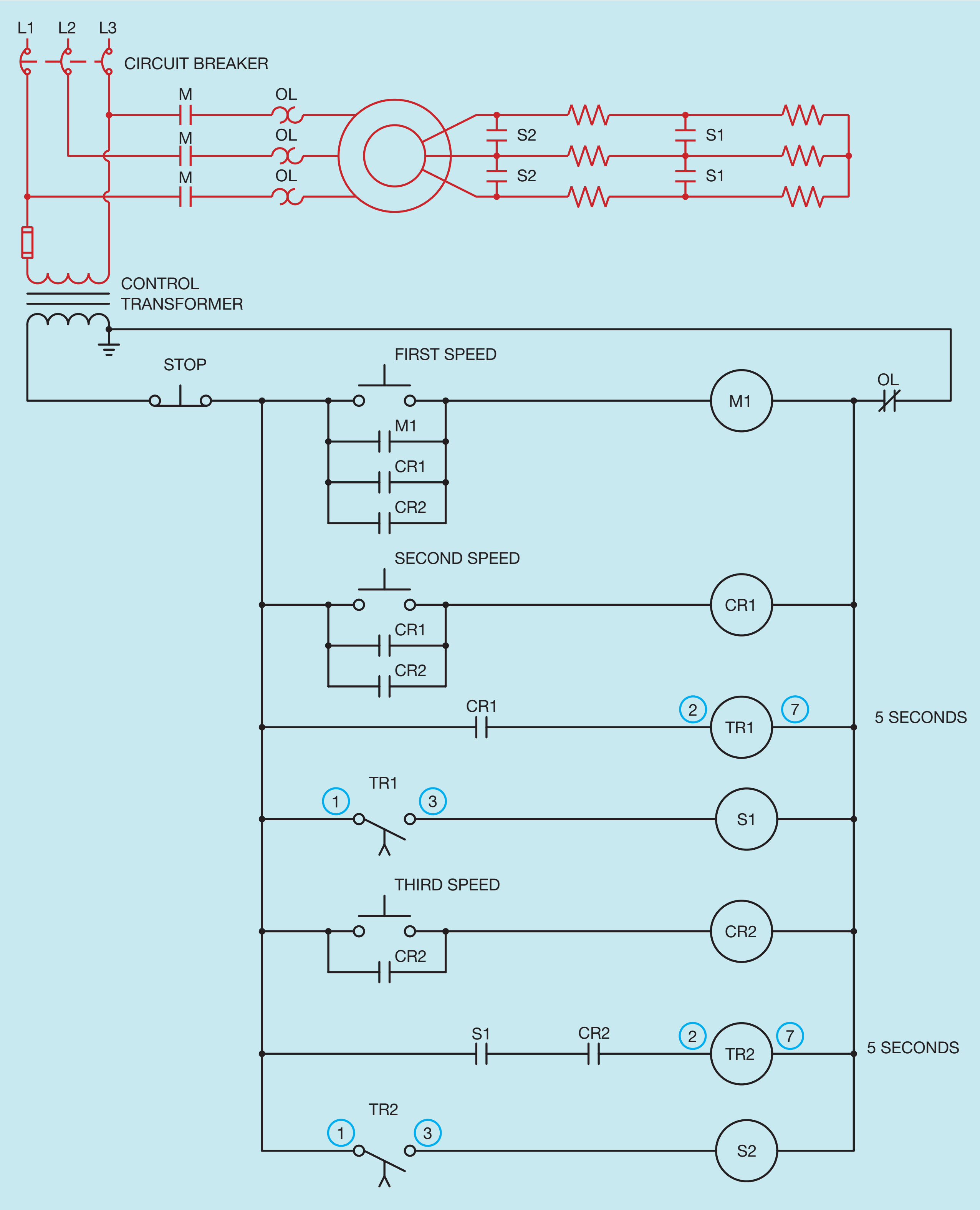


Figure 49–20 Three speed control for a wound rotor induction motor. (Source: Delmar/Cengage Learning.)

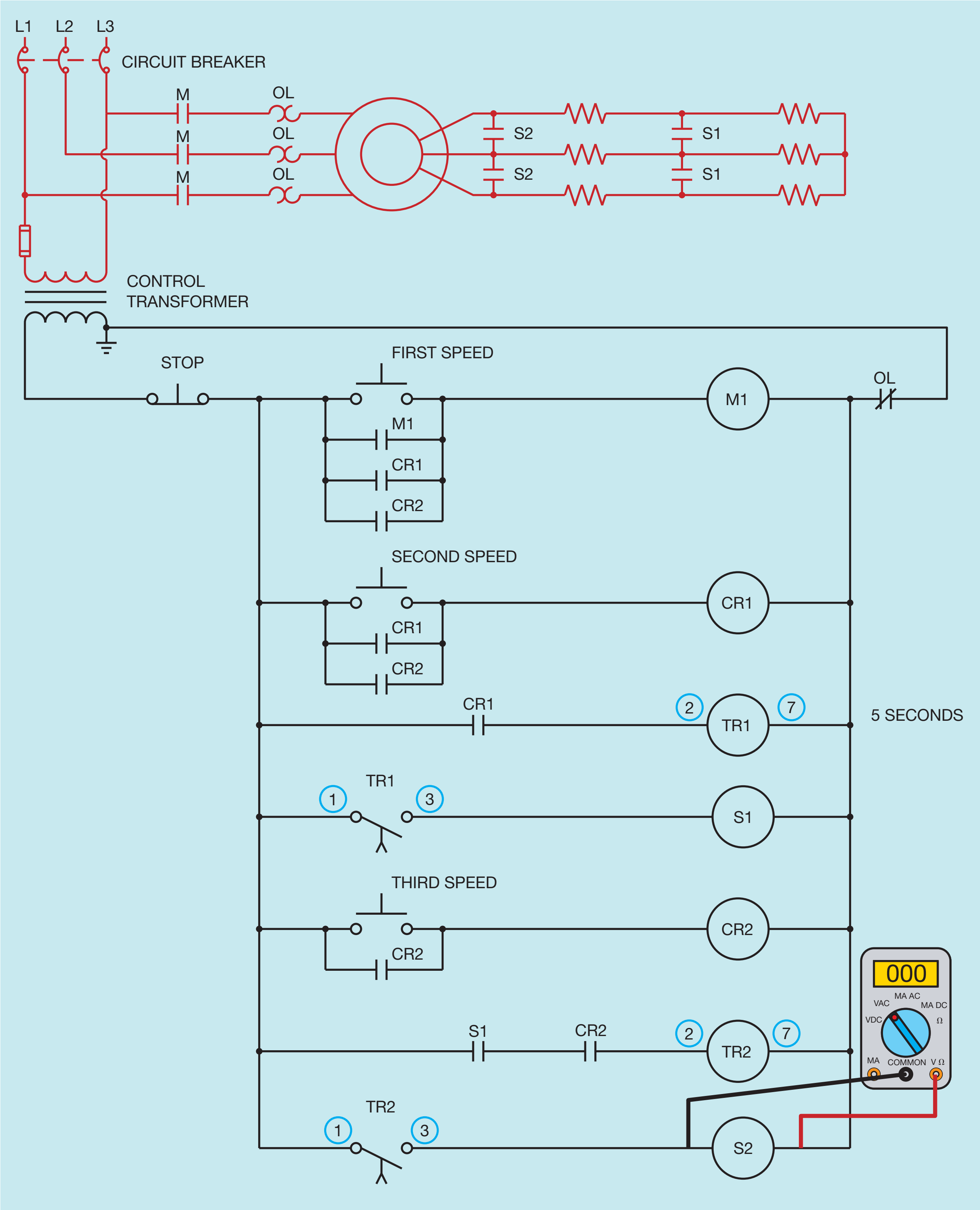


Figure 49–21 Checking for voltage across S2 coil. (Source: Delmar/Cengage Learning.)

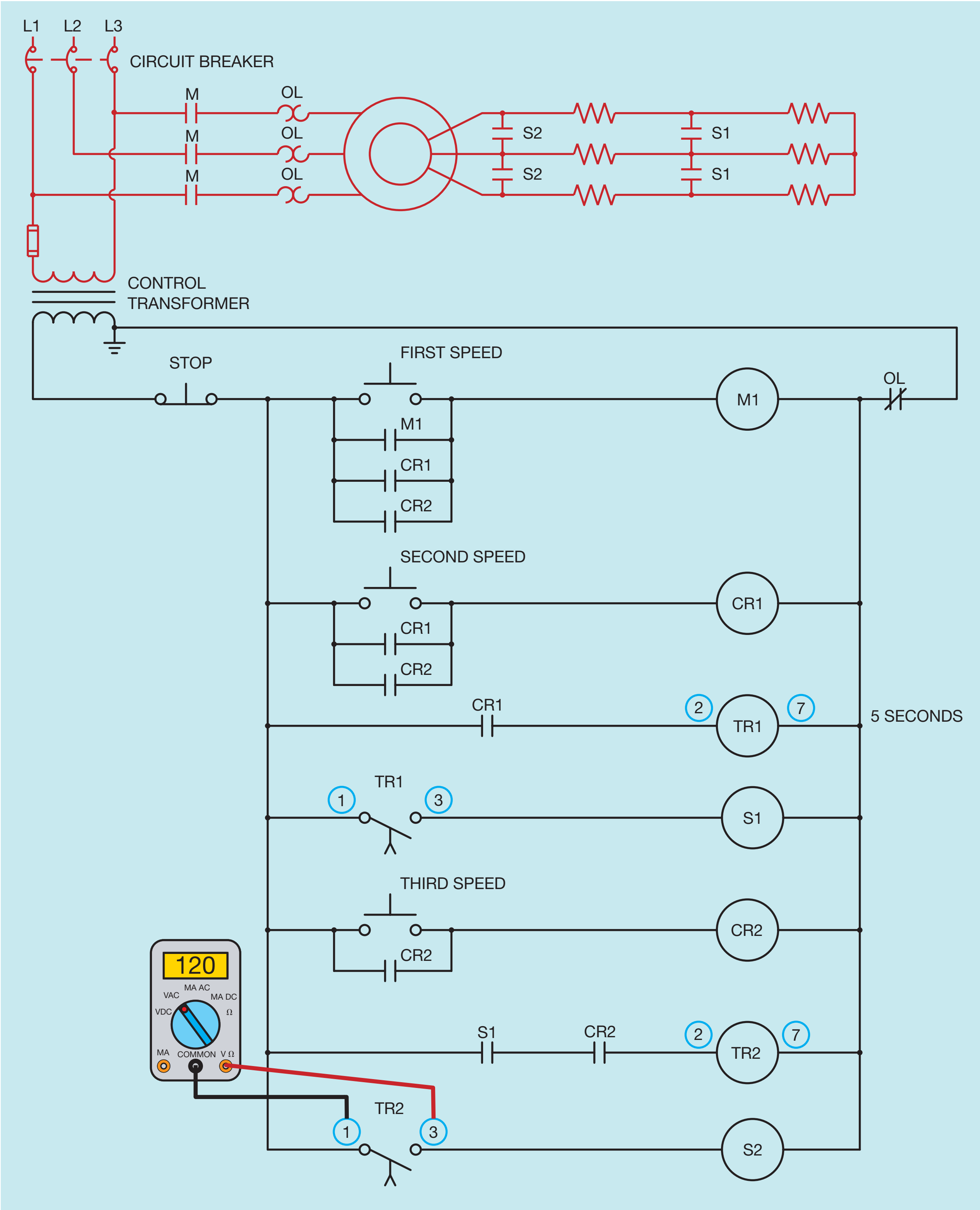


Figure 49–22 Checking for voltage across pins 1 and 3 of TR2 timer. (Source: Delmar/Cengage Learning.)

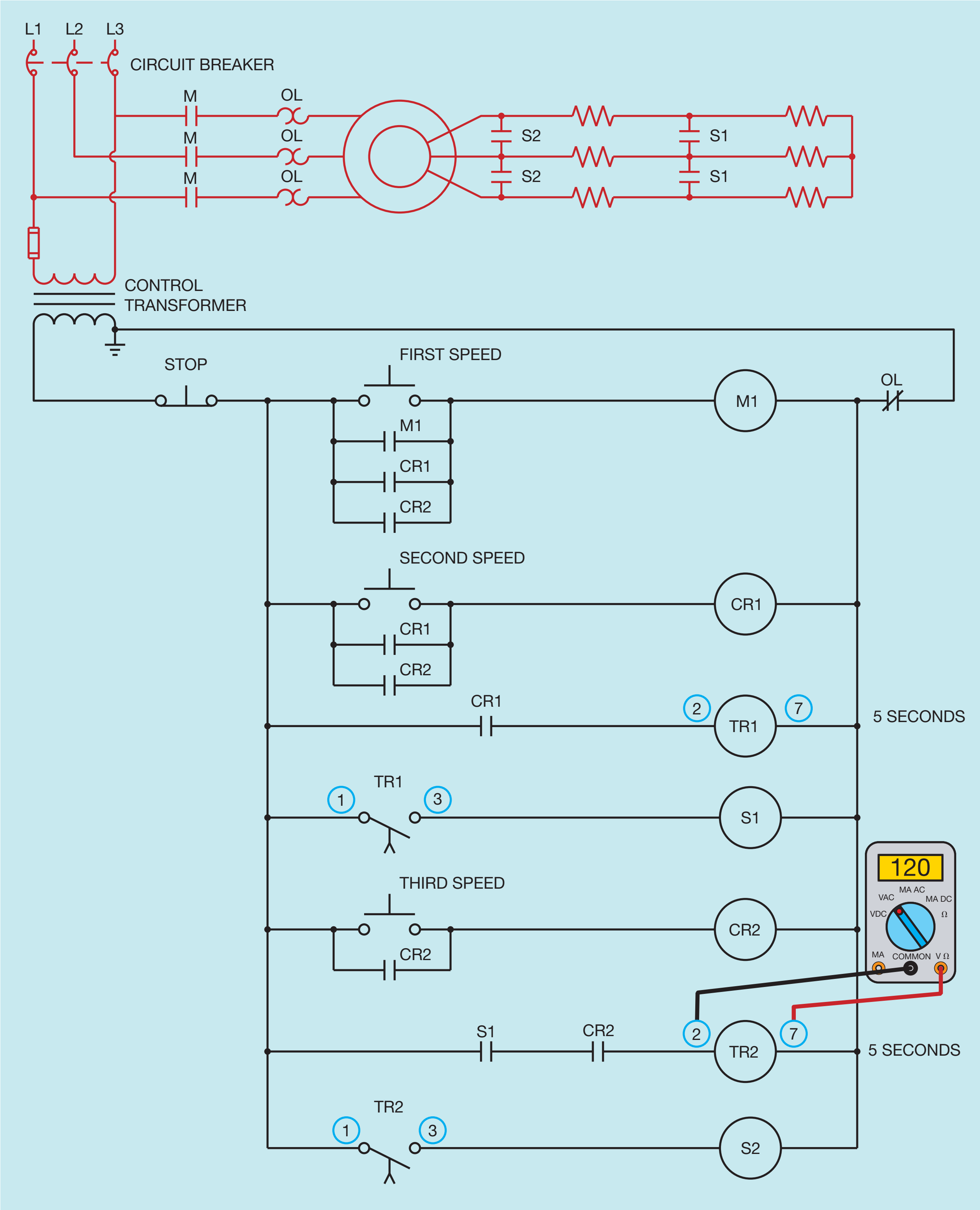


Figure 49–23 Checking for voltage across TR2 coil. (Source: Delmar/Cengage Learning.)

Review Questions

1. What are the three main electrical test instruments used in troubleshooting?
2. What is the advantage of a plunger type voltage tester?
3. A motor is tripping out on overload. The motor nameplate reveals a full load current of 68 amperes. When the motor is operating under load, an ammeter indicates the following: Phase #1 = 106 amperes, Phase #2 = 104 amperes, and Phase #3 = 105 amperes. What is the most likely problem with this motor?
4. A motor is tripping out on overload. The motor nameplate reveals a full load current of 168 amperes. When the motor is operating under load, an ammeter indicates the following: Phase #1 = 166 amperes, Phase #2 = 164 amperes, and Phase #3 = 225 amperes. What is the most likely problem with this motor?
5. Refer to the circuit shown in Figure 49–16. The motor will not start in either the forward or reverse direction when the start push buttons are pressed. Which of the following could **not** cause this problem?
   a. F coil is open.
   b. The overload contact is open.
   c. The control transformer fuse is blown.
   d. The STOP push button is not making a complete circuit.
6. Refer to the circuit shown in Figure 49–16. Assume that the motor is running in the forward direction. When the REVERSE push button is pressed, the motor continues to run in the forward direction. Which of the following could cause this problem?
   a. The normally open side of the REVERSE push button is not making a complete circuit when pressed.
   b. R contactor coil is open.
   c. The normally closed side of the REVERSE push button is not breaking the circuit when the REVERSE push button is pressed.
   d. There is nothing wrong with the circuit. The STOP push button must be pressed before the motor will stop running in the forward direction and permit the motor to be reverse.
7. Refer to the circuit shown in Figure 49–20. When the THIRD SPEED push button is pressed, the motor starts in first speed but never accelerates to second or third speed. Which of the following could **not** cause this problem?
   a. Control relay CR1 is defective.
   b. Control relay CR2 is defective.
   c. Timer TR1 is defective.
   d. Contactor coil S1 is open.
8. Refer to the circuit shown in Figure 49–20. Assume that the THIRD SPEED push button is pressed. The motor starts in it second speed, skipping first speed. After 5 seconds the motor accelerates to third speed. Which of the following could cause this problem?
   a. S1 contactor coil is open.
   b. CR1 contactor coil is open.
   c. TR1 timer coil is open.
   d. S1 load contacts are shorted.
9. Refer to the circuit shown in Figure 49–16. If a voltmeter is connected across the normally open FORWARD push button, the meter should indicate a voltage value of:
   a. 0 volt
   b. 30 volts
   c. 60 volts
   d. 120 volts
10. Refer to the circuit shown in Figure 49–20. Assume that a fused jumper is connected across terminals 1 and 3 of TR2 timer. What would happen if the jumper were left in place and the FIRST SPEED push button pressed?
    a. The motor would start in its lowest speed and progress to second speed, but never increase to third speed.
    b. The motor would start operating immediately in third speed.
    c. The motor would not start.
    d. The motor would start in second speed and then increase to third speed.

CHAPTER 50
DIGITAL LOGIC

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss similarities between digital logic circuits and relay logic circuits.
- Discuss different types of digital logic circuits.
- Recognize gate symbols used for computer logic circuits.
- Recognize gate symbols used for NEMA logic circuits.
- Complete a truth table for the basic gates.

The electrician in today's industry must be familiar with solid-state digital logic circuits. Digital, of course, means a device that has only two states, ON or OFF. Most electricians have been using digital logic for many years without realizing it. Magnetic relays, for instance, are digital devices. Relays are generally considered to be single-input, multi-output devices. The coil is the input and the contacts are the output. A relay has only one coil, but it may have a large number of contacts (Figure 50–1).

Although relays are digital devices, the term "digital logic" has come to mean circuits that use solid-state control devices known as gates. There are five basic types of gates: the AND, OR, NOR, NAND, and INVERTER. Each of these gates will be covered later in this text.

There are also different types of logic. For instance, one of the earliest types of logic to appear was *RTL,* which stands for resistor-transistor logic. This was followed by *DTL,* which stands for diode-transistor logic,

Figure 50–1 Magnetic relay. (Source: Delmar/Cengage Learning.)

and *TTL,* which stands for transistor-transistor logic. RTL and DTL are not used much anymore, but TTL is still used to a fairly large extent. TTL can be identified because it operates on 5 volts.

Another type of logic frequently used in industry is *HTL,* which stands for high-transit logic. HTL is used because it does a better job of ignoring the voltage spikes and drops caused by the starting and stopping of inductive devices such as motors. HTL generally operates on 15 volts.

Another type of logic that has become very popular is CMOS, which has very high input impedance. *CMOS comes from COSMOS which means complementary-symmetry metal-oxide-semiconductor.* The advantage of CMOS logic is that it requires very little power to operate, but there are also some disadvantages. One disadvantage is that CMOS logic is so sensitive to voltage that the static charge of a person's body can sometimes destroy an IC just by touching it. People that work with CMOS logic often use a ground strap that straps around the wrist like a bracelet. This strap is used to prevent a static charge from building up on the body.

Another characteristic of CMOS logic is that unused inputs cannot be left in an indeterminate state. Unused inputs must be connected to either a high state or a low state.

The AND Gate

While magnetic relays are single-input, multi-output devices, gate circuits are multi-input, single-output devices. For instance, an AND gate may have several inputs, but only one output. Figure 50–2 shows the USASI symbol for an AND gate with three inputs, labeled A, B, and C, and one output, labeled Y.

USASI symbols are more commonly referred to as computer logic symbols. Unfortunately for industrial electricians, there is another system known as NEMA logic, which uses a completely different set of symbols. The NEMA symbol for a three-input AND gate is shown in Figure 50–3.

Although both symbols mean the same thing, they are drawn differently. Electricians working in industry must learn both sets of symbols because both types of symbols are used. Regardless of which type of symbol is used, the AND gate operates the same way. An AND gate must have all of its inputs high in order to get an output. If it is assumed that TTL logic is being used, a high level is considered to be +5 volts and a low level is considered to be 0 volts. Figure 50–4 shows the truth table for a two-input AND gate.

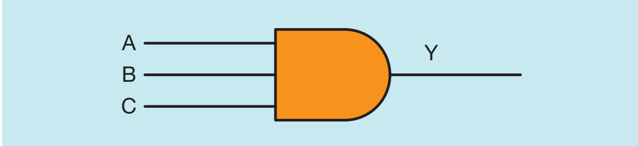


Figure 50–2 USASI symbol for a three-input AND gate. (Source: Delmar/Cengage Learning.)

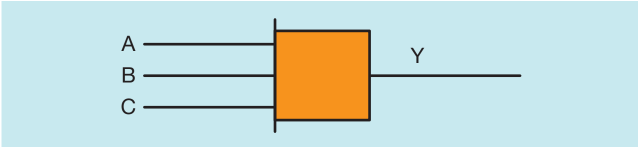


Figure 50–3 NEMA logic symbol for a three-input AND gate. (Source: Delmar/Cengage Learning.)

The truth table is used to illustrate the state of a gate's output with different conditions of input. The number one represents a high state and zero represents a low state. Notice in Figure 50–4 that the output of the AND gate is high only when both of its inputs are high. The operation of the AND gate is very similar to that of the simple relay circuit shown in Figure 50–5.

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

Figure 50–4 Truth table for a two-input AND gate. (Source: Delmar/Cengage Learning.)

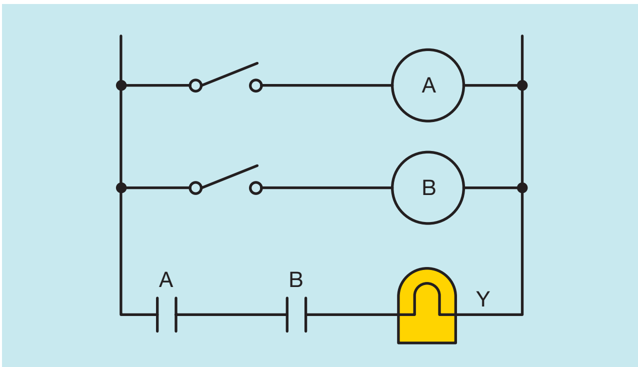


Figure 50–5 Relay equivalent circuit for a three-input AND gate. (Source: Delmar/Cengage Learning.)

A	B	C	Y
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	0
1	1	0	0
1	1	1	1

Figure 50–6 Truth table for a three-input AND gate. (Source: Delmar/Cengage Learning.)

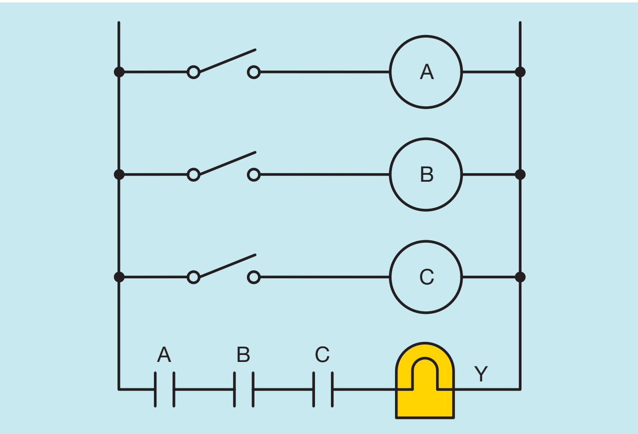


Figure 50–7 Relay equivalent circuit for a three-input AND gate. (Source: Delmar/Cengage Learning.)

If a lamp is used to indicate the output of the AND gate, both relay coils A and B must be energized before there can be an output. Figure 50–6 shows the truth table for a three-input AND gate. Notice that there is still only one condition that permits a high output for the gate, and that condition is when all inputs are high or at logic level one. *When using an AND gate, any zero input = a zero output.* An equivalent relay circuit for a three-input AND gate is shown in Figure 50–7.

The OR Gate

The computer logic symbol and the NEMA logic symbol for the OR gate are shown in Figure 50–8. The OR gate has a high output when either or both of its inputs are high. Refer to the truth table shown in Figure 50–9. *An easy way to remember how an OR gate functions is to say that any one input = a one output.* An equivalent relay circuit for the OR gate is shown in Figure 50–10. Notice in this circuit that if either or both of the relays are energized, there will be an output at Y.

Another gate that is very similar to the OR gate is known as an EXCLUSIVE OR gate. The symbol for an EXCLUSIVE OR gate is shown in Figure 50–11. The EXCLUSIVE OR gate has a high output when either, but not both, of its inputs are high. Refer to the truth table shown in Figure 50–12. An equivalent relay circuit for the EXCLUSIVE OR gate is shown in Figure 50–13. Notice that if both relays are energized or de-energized at the same time, there is no output.

The INVERTER

The simplest of all the gates is the INVERTER. The INVERTER has one input and one output. As its name implies, *the output is inverted, or the opposite of the input.* For example, if the input is high, the output is low, or if the input is low, the output is high. Figure 50–14 shows the computer logic and NEMA symbols for an INVERTER.

In computer logic, a circle drawn on a gate means to invert. Since the “O” appears on the output end of the gate, it means the output is inverted. In NEMA logic an

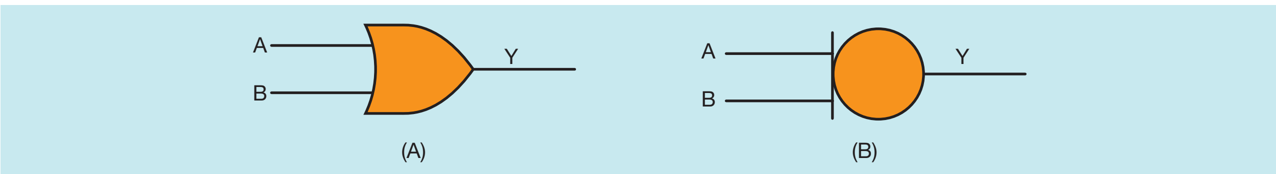


Figure 50–8 (A) Computer logic symbol for an OR gate; (B) NEMA logic symbol for an OR gate. (Source: Delmar/Cengage Learning.)

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

Figure 50–9 Truth table for a two-input OR gate. (Source: Delmar/Cengage Learning.)

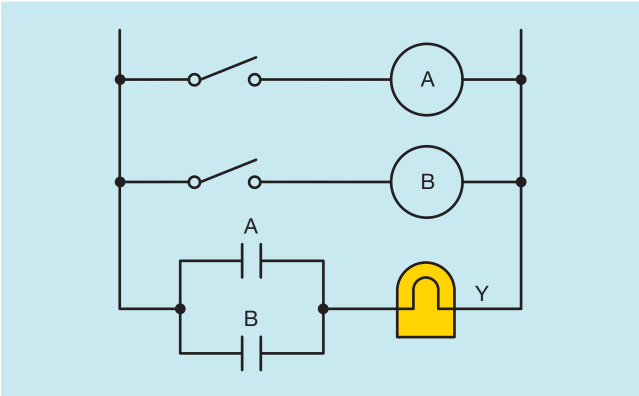


Figure 50–10 Relay equivalent circuit for an OR gate. (Source: Delmar/Cengage Learning.)

X is used to show that a gate is inverted. The truth table for an INVERTER is shown in Figure 50–15. The truth table clearly shows that the output of the INVERTER is the opposite of the input. Figure 50–16 shows an equivalent relay circuit for the INVERTER.

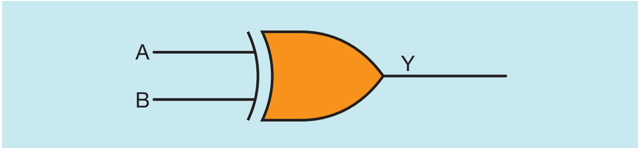


Figure 50–11 Computer logic symbol for an EXCLUSIVE OR gate. (Source: Delmar/Cengage Learning.)

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	0

Figure 50–12 Truth table for an EXCLUSIVE OR gate. (Source: Delmar/Cengage Learning.)

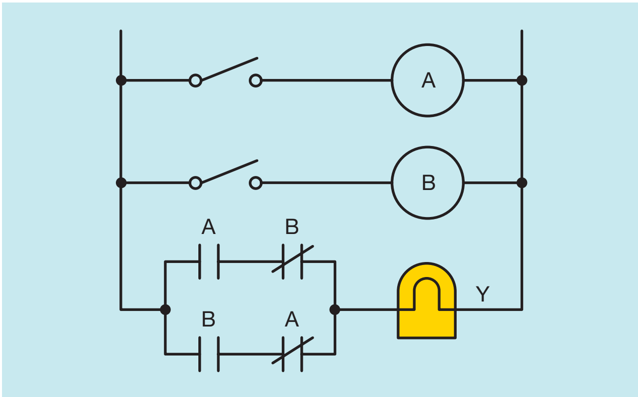


Figure 50–13 Equivalent relay circuit for an EXCLUSIVE OR gate. (Source: Delmar/Cengage Learning.)

The NOR Gate

The NOR gate is the "NOT OR" gate. Referring to the computer logic and NEMA logic symbols for a NOR gate in Figure 50–17, notice that the symbol for the NOR gate is the same as the symbol for the OR gate with an inverted output. A NOR gate can be made by connecting an INVERTER to the output of an OR gate as shown in Figure 50–18.

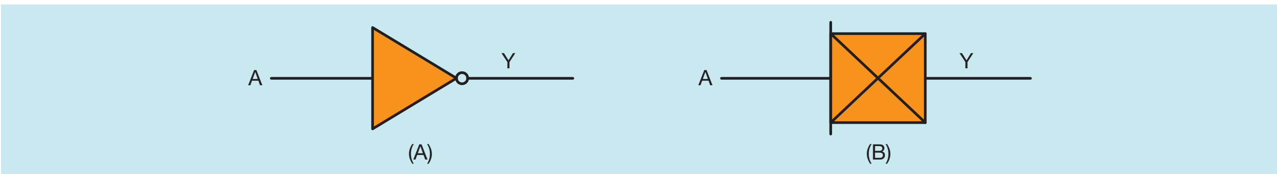


Figure 50–14 (A) Computer logic symbol for an INVERTER; (B) NEMA logic symbol for an INVERTER. (Source: Delmar/Cengage Learning.)

A	Y
0	1
1	0

Figure 50–15 Truth table for an INVERTER. (Source: Delmar/Cengage Learning.)

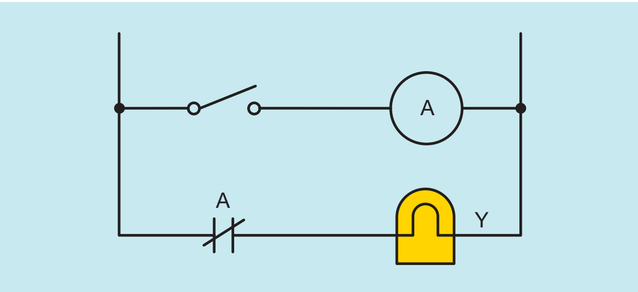


Figure 50–16 Equivalent relay circuit for an INVERTER. (Source: Delmar/Cengage Learning.)

The truth table shown in Figure 50–19 shows that the output of a NOR gate is zero, or low. when any input is high. Therefore, it could be said that *any one input = a zero output for the NOR gate.* An equivalent relay circuit for the NOR gate is shown in Figure 50–20. Notice in Figure 50–20 that if either relay A or B is energized, there is no output at Y.

The NAND Gate

The NAND gate is the "NOT AND" gate. Figure 50–21 shows the computer logic symbol and the NEMA logic symbol for the NAND gate. Notice that these symbols are the same as the symbols for the AND gate with inverted outputs. If any input of a NAND gate is low, the output is high. Refer to the truth table in Figure 50–22. Notice that the truth table clearly indicates that *any zero input = a one output.* Figure 50–23 shows an equivalent relay circuit for the NAND gate. If either relay A or relay B is de-energized, there is an output at Y.

The NAND gate is often referred to as the basic gate because it can be used to make any of the other gates. For instance, Figure 50–24 shows the NAND gate connected to make an INVERTER. If a NAND gate is used as an INVERTER and is connected to the output of another NAND gate, it will become an AND gate, as shown in Figure 50–25. When two NAND gates are connected as INVERTERS, and these INVERTERS are connected to the inputs of another NAND gate, an OR gate is formed (Figure 50–26). If an INVERTER is added to the output of the OR gate shown in Figure 50–26, a NOR gate is formed (Figure 50–27).

Integrated Circuits

Digital logic gates are generally housed in fourteen-pin, IC packages. One of the old reliable types of TTL logic that is frequently used is the 7400 family of devices. For instance, a 7400 IC is a quad, two-input, positive NAND gate. The word quad means that there are four NAND gates contained in the package. Each NAND gate has two inputs, and positive means that a level one is considered to be a positive voltage.

There can, however, be a difference in the way ICs are connected. A 7400 (J or N) IC has a different pin connection than a 7400 (W) package. In Figure 50–28, both ICs contain four two-input NAND gates, but the pin connections are different. For this reason, it is necessary to use a connection diagram when connecting or testing integrated circuits. A fourteen-pin IC is shown in Figure 50–29.

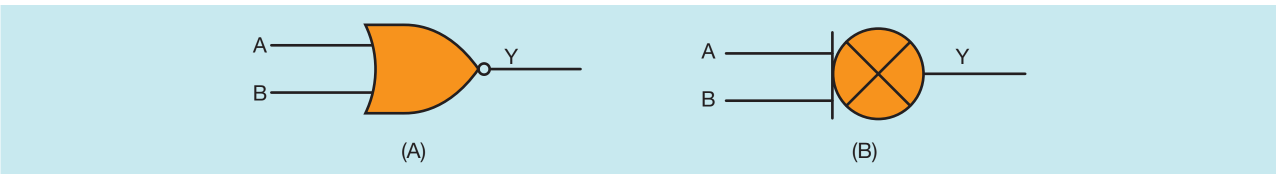


Figure 50–17 (A) Computer symbol for a two-input NOR gate; (B) NEMA logic symbol for a two-input NOR gate. (Source: Delmar/Cengage Learning.)

Figure 50–18 Equivalent NOR gate. (Source: Delmar/Cengage Learning.)

A	B	Y
0	0	1
0	1	0
1	0	0
1	1	0

Figure 50–19 Truth table for a two-input NOR gate. (Source: Delmar/Cengage Learning.)

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

Figure 50–22 Truth table for a two-input NAND gate. (Source: Delmar/Cengage Learning.)

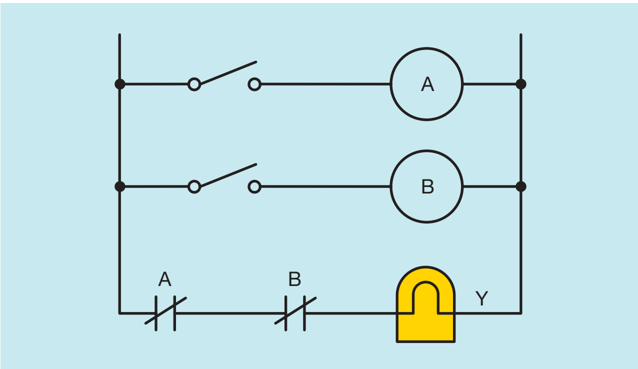


Figure 50–20 Equivalent relay circuit for a two-input NOR gate. (Source: Delmar/Cengage Learning.)

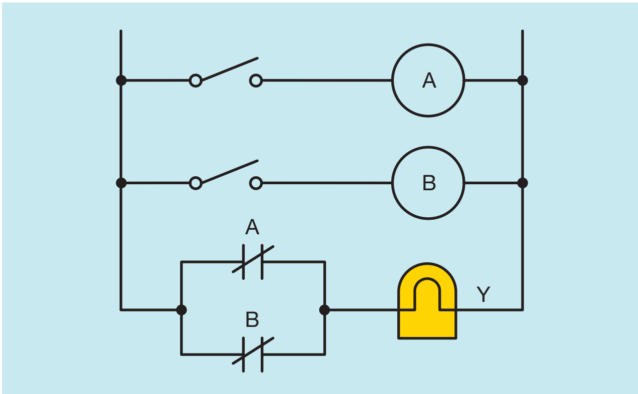


Figure 50–23 Equivalent relay circuit for a two-input NAND gate. (Source: Delmar/Cengage Learning.)

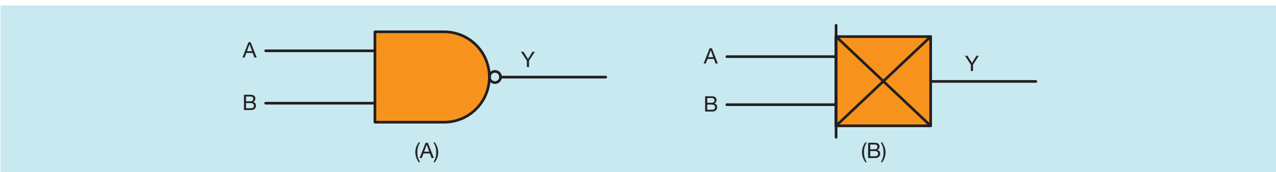


Figure 50–21 (A) Computer logic symbol for a two-input NAND gate (B) NEMA logic symbol for a two-input NAND gate. (Source: Delmar/Cengage Learning.)

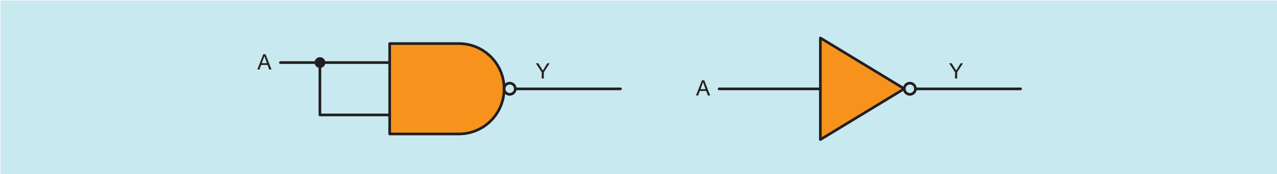


Figure 50–24 NAND gate connected as an INVERTER. (Source: Delmar/Cengage Learning.)

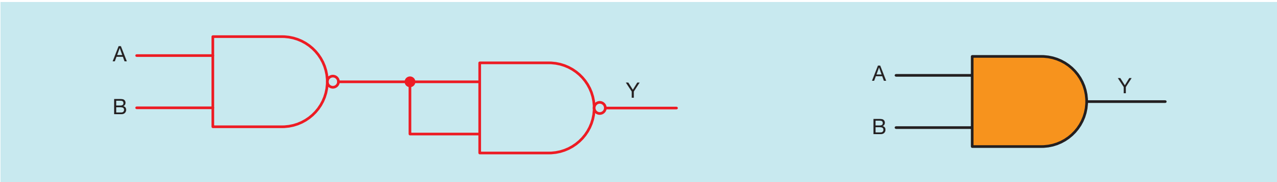


Figure 50–25 NAND gates connected as an AND gate. (Source: Delmar/Cengage Learning.)

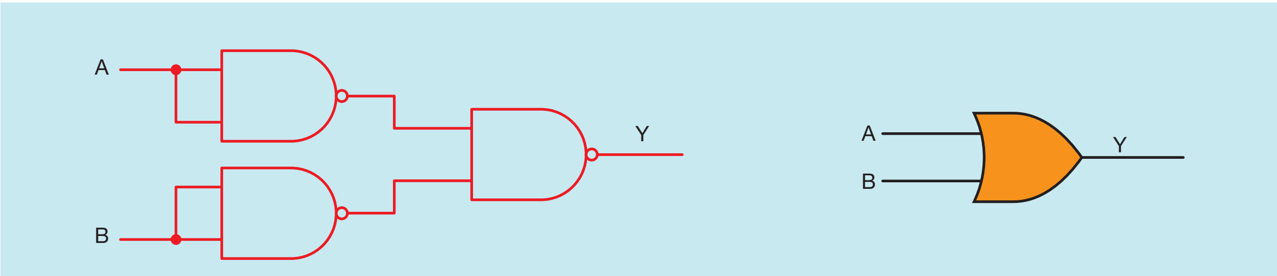


Figure 50–26 NAND gates connected as an OR gate. (Source: Delmar/Cengage Learning.)

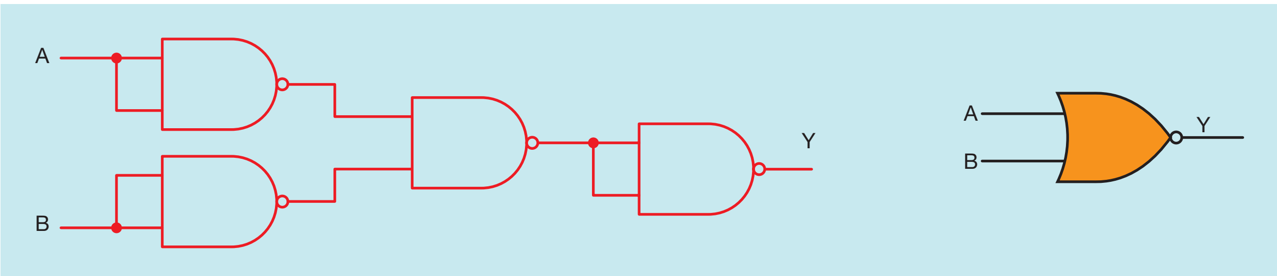


Figure 50–27 NAND gates connected as a NOR gate. (Source: Delmar/Cengage Learning.)

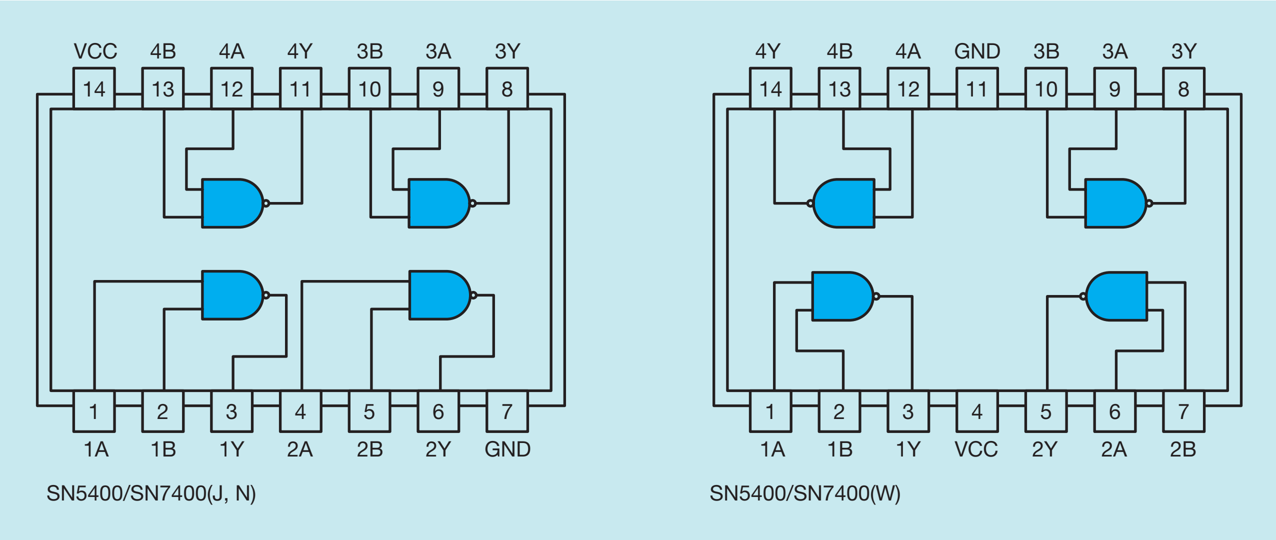


Figure 50–28 Integrated circuit connection of a quad, two-input NAND gate. (Courtesy Tektronix, Inc.)

Testing Integrated Circuits

Integrated circuits cannot be tested with a volt-ohm-milliammeter. Most ICs must be tested by connecting power to them and then testing the inputs and outputs with special test equipment. Most industrial equipment is designed with different sections of the control system built in modular form. The electrician determines which section of the circuit is not operating and replaces that module. The defective module is then sent to the electronics department or to a company outside of the plant for repair.

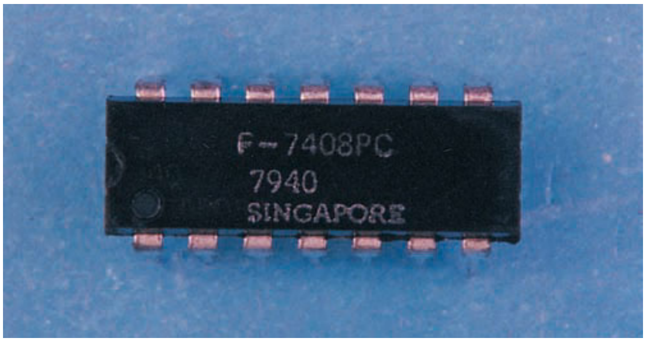


Figure 50–29 Fourteen-pin inline integrated circuit used to house digital logic gates. (Source: Delmar/Cengage Learning.)

Review Questions

1. What type of digital logic operates on 5 volts?
2. What precautions must be taken when connecting CMOS logic?
3. What do the letters COSMOS stand for?
4. When using a two-input AND gate, what conditions of input must be met to have an output?
5. When using a two-input OR gate, what conditions of input must be met to have an output?
6. Explain the difference between an OR gate and an EXCLUSIVE OR gate.
7. When using a two-input NOR gate, what condition of input must be met to have an output?
8. When using a two-input NAND gate, what condition of input must be met to have an output?
9. If an INVERTER is connected to the output of a NAND gate, what logic gate is formed?
10. If an INVERTER is connected to the output of an OR gate, what gate is formed?
11. What symbol is used to represent "invert" when computer logic symbols are used?
12. What symbol is used to represent "invert" when NEMA logic symbols are used?

CHAPTER 51

THE BOUNCELESS SWITCH

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss why mechanical contacts should be spring loaded.
- Discuss problems associated with contact bounce.
- Describe methods of eliminating contact bounce.
- Connect a bounceless switch circuit using digital logic gates.

When a control circuit is constructed, it must have sensing devices to tell it what to do. The number and type of sensing devices used are determined by the circuit. Sensing devices can range from a simple push button to float switches, limit switches, and pressure switches. Most of these sensing devices use some type of mechanical switch to indicate their condition. A float switch, for example, indicates its condition by opening or closing a set of contacts (Figure 51–1). The float switch can "tell" the control circuit that a liquid is either at a certain level or not. Most of the other types of sensing devices use this same method to indicate some condition. A pressure switch indicates that a pressure is either at a certain level or not, and a limit switch indicates if some device has moved a certain distance or if a device is present or absent from some location.

Almost all of these devices employ a snap-action switch. When a mechanical switch is used, the snap action is generally obtained by spring loading the contacts. This snap action is necessary to ensure good contact when the switch operates. Assume that a float switch is used to sense when water reaches a certain level in a tank. If the water rises at a slow rate, the contacts will come together at a slow rate, resulting in a poor connection. However, if the contacts are spring loaded, when the water reaches a certain level, the contacts will snap from one position to another.

Although most contacts have a snap action, they do not generally close with a single action. When the movable contacts meet the stationary contact, there is often a fast bouncing action. This means that the contacts may actually make and break contact three or four times in succession before the switch remains closed. When

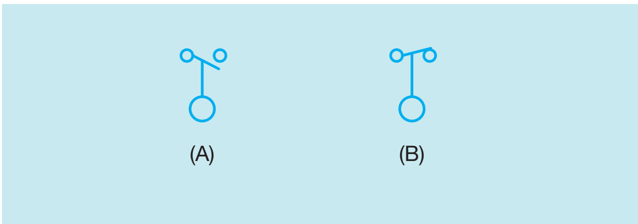


Figure 51–1 (A) Normally open float switch; (B) Normally closed float switch. (Source: Delmar/Cengage Learning.)

this type of switch is used to control a relay, contact bounce does not cause a problem because relays are relatively slow-acting devices (Figure 51–2).

When this type of switch is used with an electronic control system, however, contact bounce can cause a great deal of trouble. Most digital logic circuits are very fast-acting and can count each pulse when a contact bounces. Depending on the specific circuit, each of these pulses may be interpreted as a command. Contact bounce can cause the control circuit to "lose its mind."

Since contact bounce can cause trouble in an electronic control circuit, contacts are debounced before they are permitted to "talk" to the control system. When contacts must be debounced, a circuit called *a bounceless switch* is used. Several circuits can be used to construct a bounceless switch, but the most common construction method uses digital logic gates. Although any of the inverting gates can be used to construct a bounceless switch, in this example only two will be used.

Before construction of the circuit begins, the operation of a bounceless switch circuit should first be discussed. The idea is to construct a circuit that will lock its output either high or low when it detects the first pulse from the mechanical switch. If its output is locked in a position, it will ignore any other pulses it receives from the switch. The output of the bounceless switch is connected to the input of the digital control circuit. The control circuit will now receive only one pulse instead of a series of pulses.

The first gate used to construct a bounceless switch is the INVERTER. The computer symbol and the truth table for the INVERTER are shown in Figure 51–3. The bounceless switch circuit using INVERTERS is shown in Figure 51–4. The output of the circuit should be high, with the switch in the position shown. The

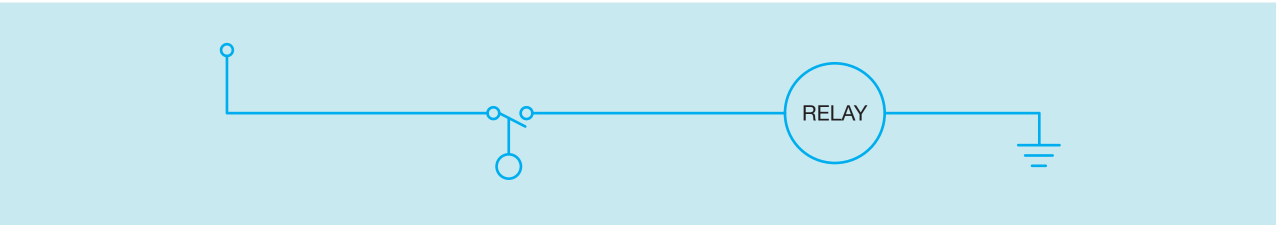


Figure 51–2 Contact bounce does not greatly affect relay circuits. (Source: Delmar/Cengage Learning.)

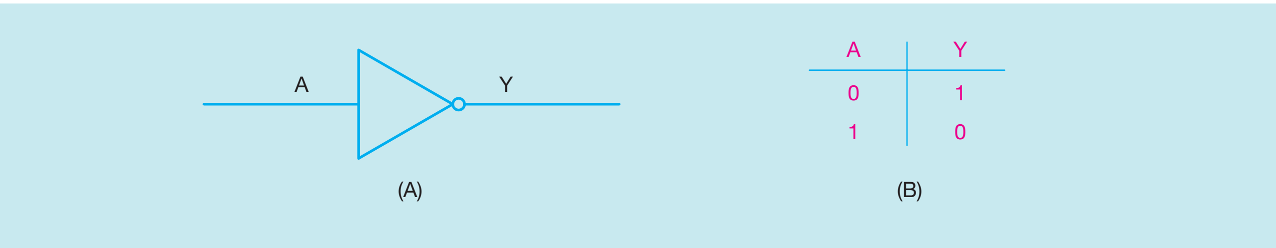


Figure 51–3 (A) Symbol for an INVERTER; (B) Truth table for an INVERTER. (Source: Delmar/Cengage Learning.)

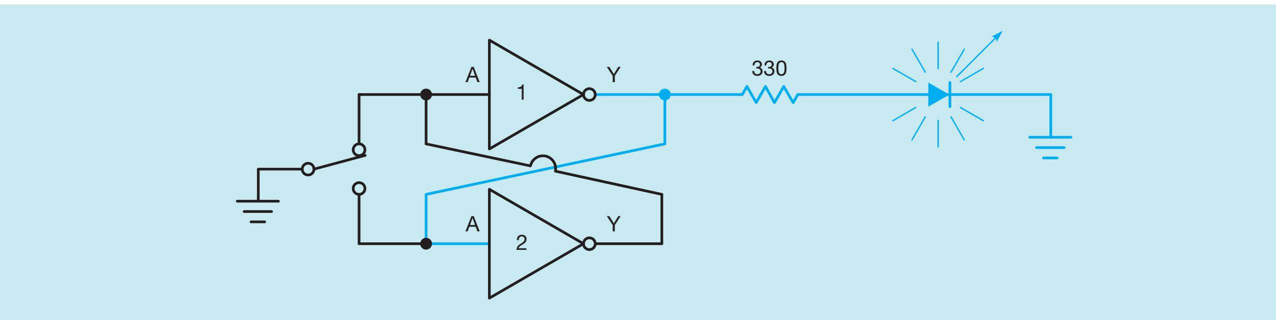


Figure 51–4 High output condition. (Source: Delmar/Cengage Learning.)

switch connects the input of INVERTER #1 directly to ground, or low. This causes the output of INVERTER #1 to be at a high state. The output of INVERTER #1 is connected to the input of INVERTER #2. Since the input of INVERTER #2 is high, its output is low. The output of INVERTER #2 is connected to the input of INVERTER #1. This causes a low condition to be maintained at the input of INVERTER #1.

If the position of the switch is changed as shown in Figure 51–5, the output will change to low. The switch now connects the input of INVERTER #2 to ground, or low. The output of INVERTER #2 is, therefore, high. The high output of INVERTER #2 is connected to the input of INVERTER #1. Since the input connected to INVERTER #1 is now high, its output becomes low. The output of INVERTER #1 is connected to the input of INVERTER #2. This forces a low input to be maintained at INVERTER #2. Notice that the output of one INVERTER is used to lock the input of the other INVERTER.

The second logic gate used to construct a bounceless switch is the NAND gate. The computer symbol and the truth table for the NAND gate are shown in Figure 51–6. The circuit in Figure 51–7 shows the construction of a bounceless switch using NAND gates. In this circuit, the switch has input A of gate #1 connected to low, or ground. Since input A is low, the output is high. The output of gate #1 is connected to input A of gate #2. Input B of gate #2 is connected to a high through the 4.7 kilohm resistor. Since both inputs of gate #2 are high, its output is low. This low output is connected to input B of gate #1. Since gate #1 now has a low connected to input B, its output is forced to remain high even if contact bounce causes a momentary high at input A.

When the switch changes position as shown in Figure 51–8, input B of gate #2 is connected to a low. This forces the output of gate #2 to become high. The high output of gate #2 is connected to input B of gate #1. Input A of gate #1 is connected to a high through a 4.7 kilohm resistor. Since both inputs of gate #1 are

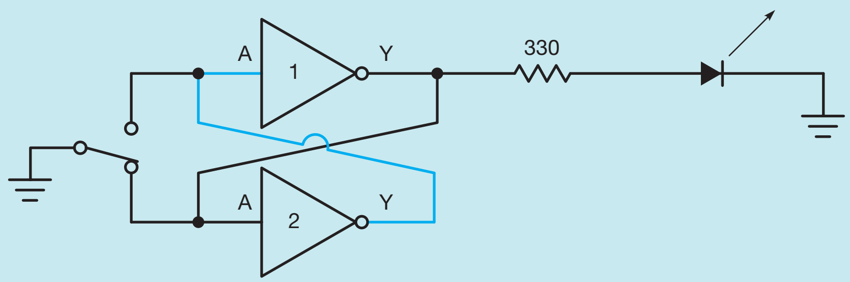


Figure 51–5 Low output condition. (Source: Delmar/Cengage Learning.)

A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

(B)

Figure 51–6 (A) Symbol for a NAND gate; (B) Truth table for a NAND gate. (Source: Delmar/Cengage Learning.)

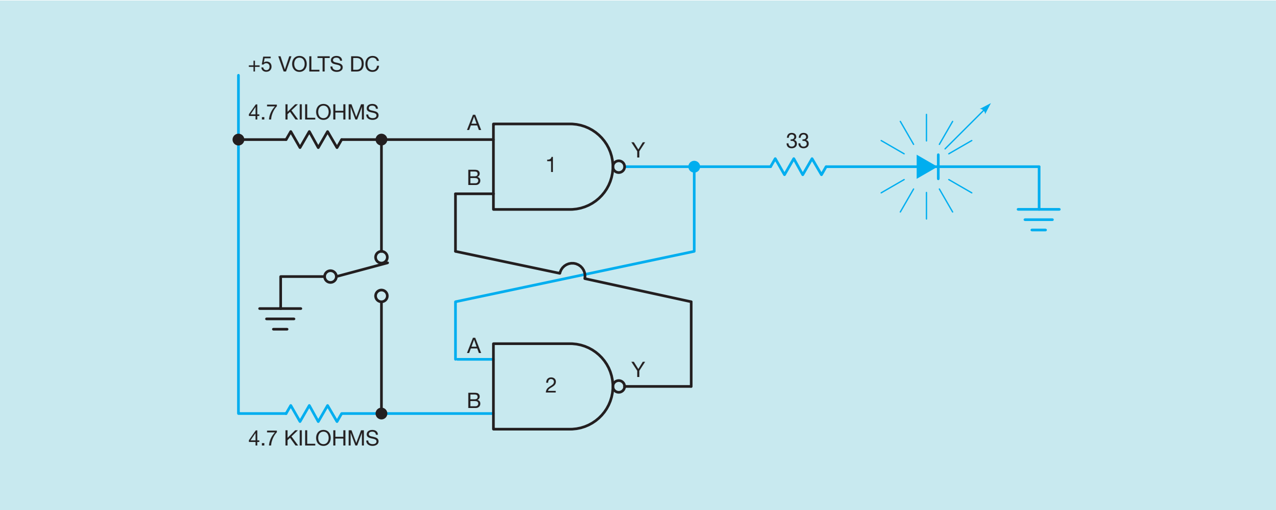


Figure 51–7 High output condition. (Source: Delmar/Cengage Learning.)

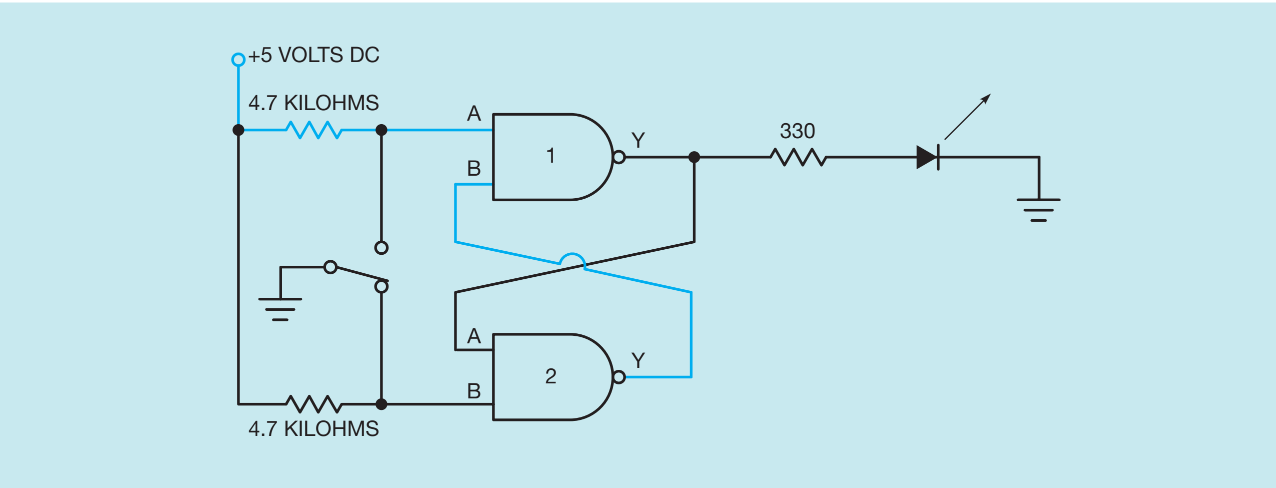


Figure 51–8 Low output condition. (Source: Delmar/Cengage Learning.)

high, its output is low. This low is connected to input A of gate #2, which forces its output to remain high even if contact bounce causes a high to be momentarily connected to input B.

The output of this circuit will remain constant even if the switch contacts bounce. The switch has now been debounced and is ready to be connected to the input of an electronic control circuit.

Review Questions

1. Why should mechanical contacts be spring loaded?
2. Name three examples of sensing devices.
3. Why must contacts be debounced before they are connected to electronic control circuits?
4. What function does a bounceless switch circuit perform?
5. Name two types of logic gates that can be used to construct a bounceless switch circuit.

CHAPTER 52

START-STOP PUSH-BUTTON CONTROL

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of a start-stop relay control circuit.
- Describe the operation of the basic gates used in this chapter.
- Describe the operation of the solid-state control circuit.
- Discuss practical wiring techniques for connecting digital logic circuits.
- Connect a start-stop, push-button control using logic gates.

In this chapter, a digital circuit will be designed to perform the same function as a common relay circuit. The relay circuit is a basic stop-start, push-button circuit with overload protection (Figure 52–1).

Before beginning the design of an electronic circuit that will perform the same function as this relay circuit, the operation of the relay circuit should first be discussed. In the circuit shown in Figure 52–1, no current can flow to relay coil M because the normally open START button and the normally open contact are controlled by relay coil M.

When the START button is pushed, current flows through the relay coil and normally closed overload contact to the power source (Figure 52–2). When current flows through relay coil M, the contacts connected parallel to the START button close. These contacts maintain the circuit to coil M when the START button releases and returns to its open position (Figure 52–3).

The circuit will continue to operate until the STOP button is pushed and breaks the circuit to the coil (Figure 52–4). When the current flow to the coil stops, the relay de-energizes and contact M reopens. Since the START button is now open and contact M is open, there is no complete circuit to the relay coil when the STOP button is returned to its normally closed position. If the relay is to be restarted, the START button must be pushed again to provide a complete circuit to the relay coil.

The only other logic condition that can occur in this circuit is caused by the motor connected to the load contacts of relay M. Assume the motor is connected in series with the heater of an overload relay

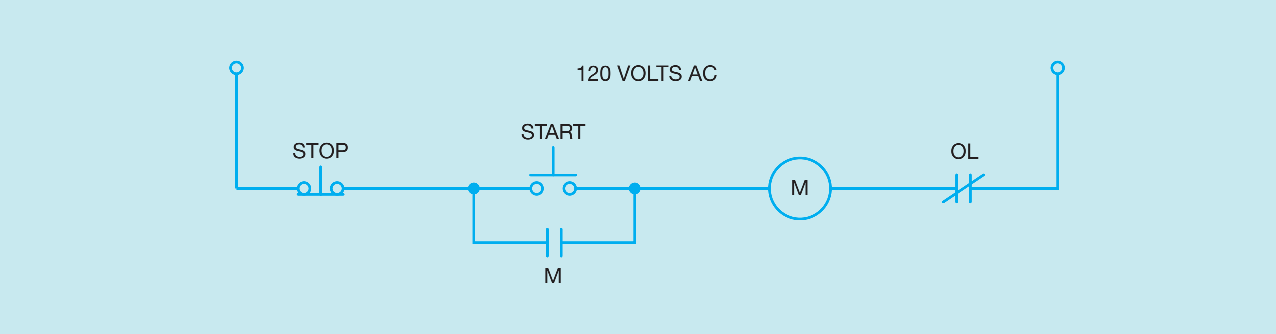


Figure 52–1 Start-stop, push-button circuit. (Source: Delmar/Cengage Learning.)

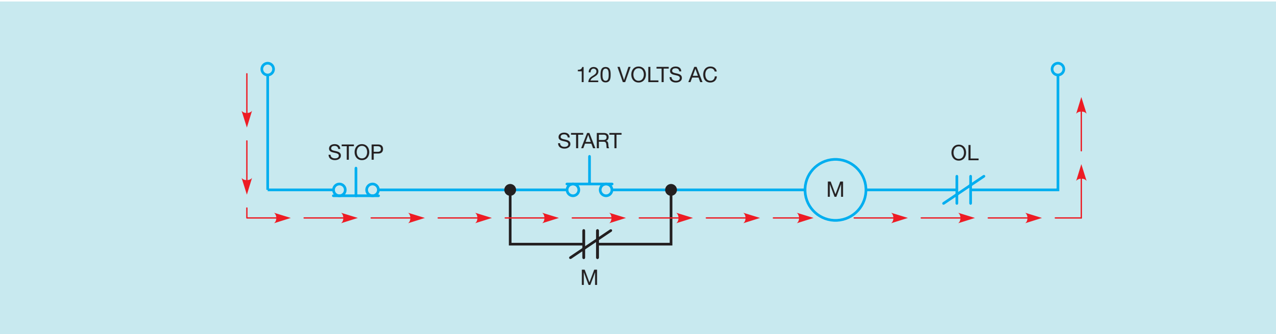


Figure 52–2 START button energizes “M” relay coil. (Source: Delmar/Cengage Learning.)

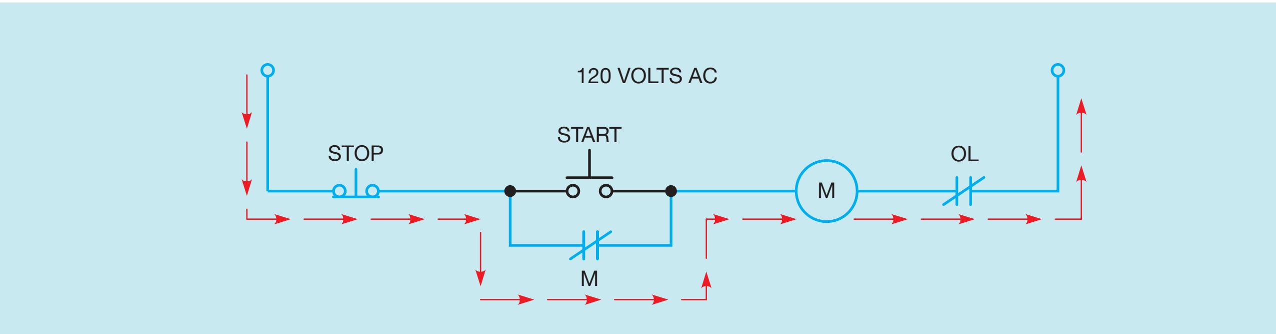


Figure 52–3 “M” contacts maintain the circuit. (Source: Delmar/Cengage Learning.)

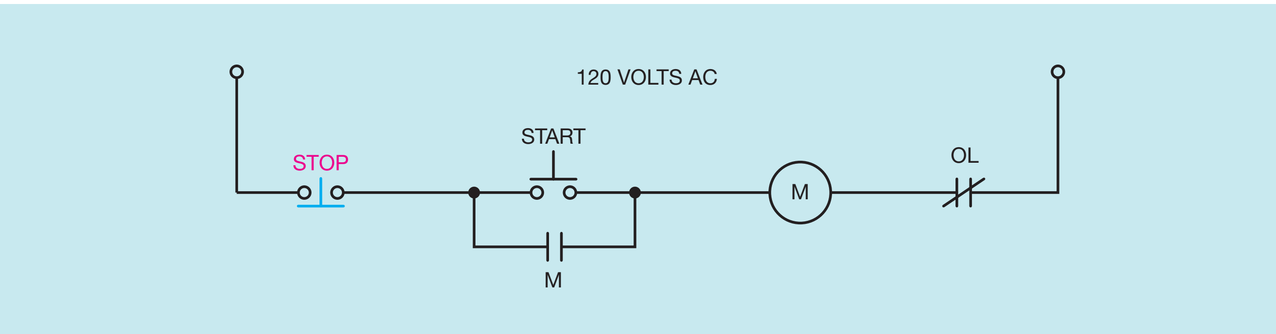


Figure 52–4 STOP button breaks the circuit. (Source: Delmar/Cengage Learning.)

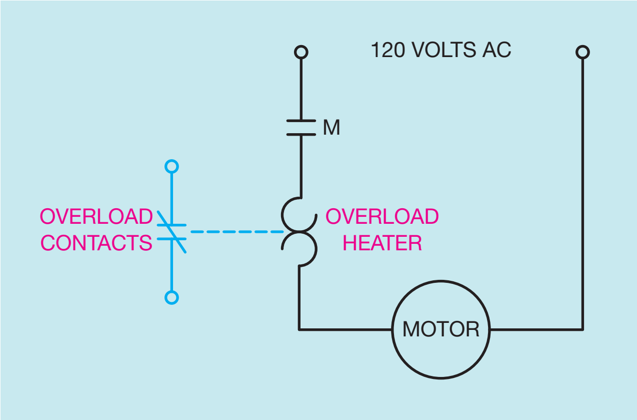


Figure 52–5 (Source: Delmar/Cengage Learning.)

(Figure 52–5). When coil M energizes, it closes the load contact M as shown in Figure 52–6. When the load contact closes, it connects the motor to the 120 volt AC power line.

If the motor is overloaded, it will cause too much current to flow through the circuit. When a current greater than normal flows through the overload heater, the heater produces more heat than it does under normal conditions. If the current becomes high enough, it will cause the normally closed overload contact to open. Notice that the overload contact is electrically isolated from the heater. The contact, therefore, can be connected to a different voltage source than the motor.

If the overload contact opens, the control circuit is broken and the relay de-energizes as if the STOP button had been pushed. After the overload contact has been reset to its normally closed position, the coil will remain de-energized until the START button is again pressed.

Now that the logic of the circuit is understood, a digital logic circuit that will operate in this manner can be designed. The first problem is to find a circuit that can be turned on with one push button and turned off with another. The circuit shown in Figure 52–7 can perform this function. This circuit consists of an OR gate

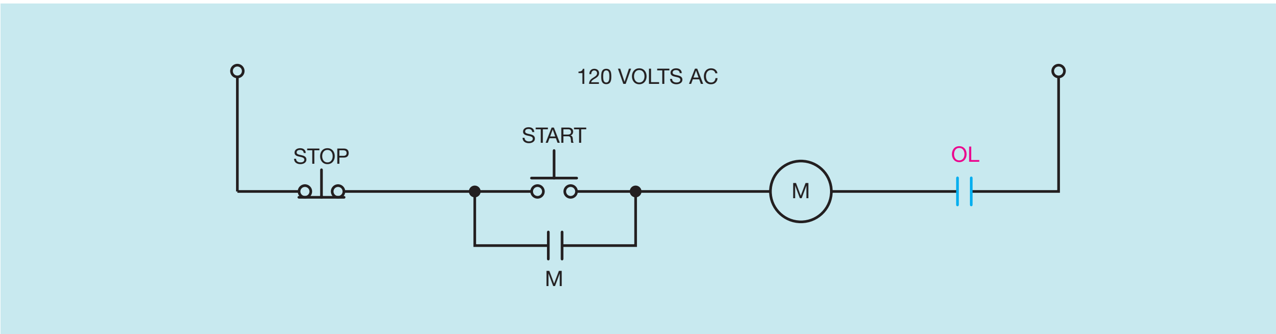


Figure 52–6 Overload contacts break the circuit. (Source: Delmar/Cengage Learning.)

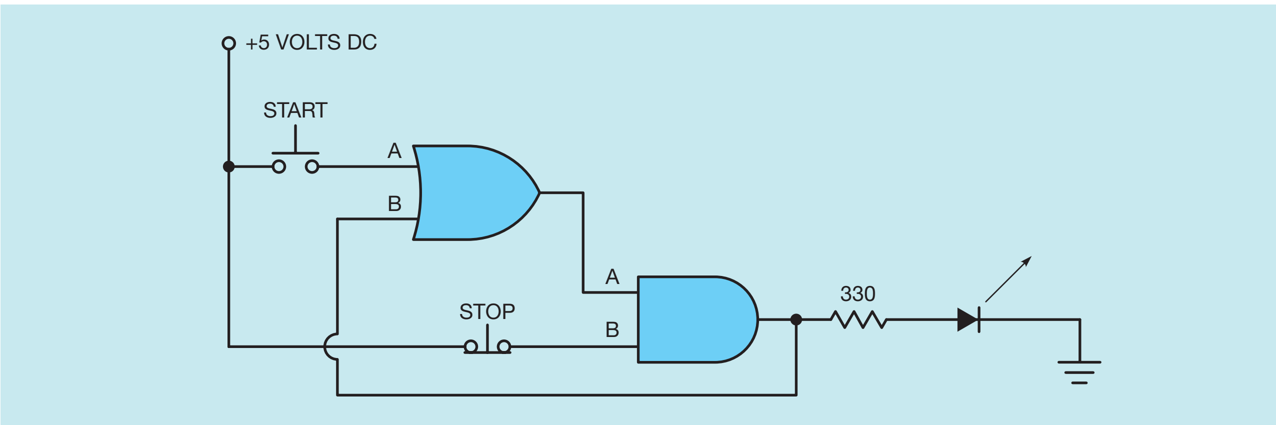


Figure 52–7 (Source: Delmar/Cengage Learning.)

and an AND gate. Input A of the OR gate is connected to a normally open push button, which is connected to 5 volts DC. Input B of the OR gate is connected to the output of the AND gate. The output of the OR gate is connected to input A of the AND gate. Input B of the AND gate is connected through a normally closed push button to +5 volts DC. This normally closed push button is used as the STOP button. The output of the AND gate is the output of the circuit.

To understand the logic of this circuit, assume that the output of the AND gate is low. This produces a low at input B of the OR gate. Since the push button connected to input A is open, a low is produced at this input also. When all inputs of an OR gate are low, its output is also low. The low output of the OR gate is connected to input A of the AND gate. Input B of the AND gate is connected to a high through the normally closed push-button switch. Since input A of the AND gate is low, the output of the AND gate is forced to remain in a low state.

When the START button is pushed, a high is connected to input A of the OR gate. This causes the output of the OR gate to change to high. This high output is connected to input A of the AND gate. The AND gate now has both of its inputs high, so its output changes from a low to a high state. When the output of the AND gate changes to a high state, input B of the OR gate becomes high also. Since the OR gate now has a high connected to its B input, its output will remain high when the push button is returned to its open condition and input A becomes low. Notice that this circuit operates the same as the relay circuit when the START button is pushed. The output changes from a low state to a high state and the circuit locks in this condition so the START button can be reopened.

When the normally closed STOP button is pushed, input B of the AND gate changes from high to low. When input B changes to a low state, the output of the AND gate changes to a low state also. This causes a low to appear at input B of the OR gate. The OR gate now has both of its inputs low, so its output changes from a high state to a low state. Since input A of the AND gate is now low, the output is forced to remain low when the STOP button returns to its closed position and input B becomes high. The circuit designed here can be turned on with the START button and turned off with the STOP button.

The next design task is to connect the overload contact to the circuit. The overload contact must be connected in such a manner that it will cause the output of the circuit to turn off if it opens. One's first impulse might be to connect the overload contact to the circuit as shown in Figure 52–8. In this circuit, the output of AND gate #1 has been connected to input A of AND gate #2. Input B of AND gate #2 has been connected to a high through the normally closed overload contact. If the overload contact remains closed, input B will remain

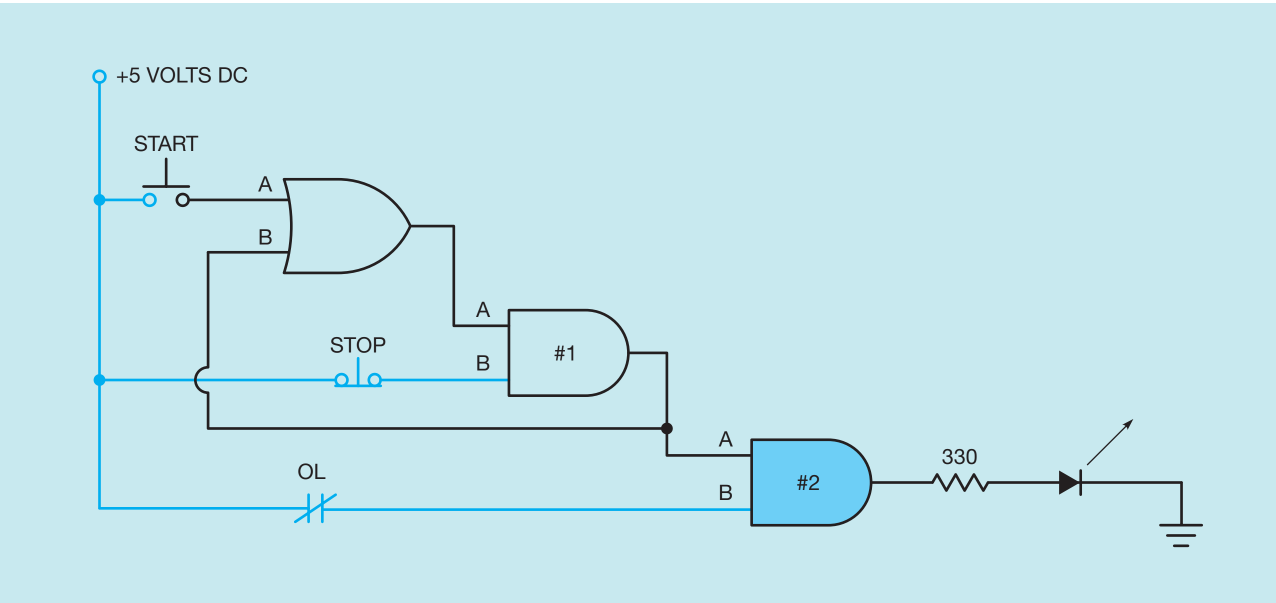


Figure 52–8 (Source: Delmar/Cengage Learning.)

high. The output of AND gate #2 is, therefore, controlled by input A. If the output of AND gate #1 changes to a high state, the output of AND gate #2 will also change to a high state. If the output of AND gate #1 becomes low, the output of AND gate #2 will become low also.

If the output of AND gate #2 is high and the overload contact opens, input B will become low and the output will change from a high to a low state. This circuit appears to operate with the same logic as the relay circuit until the logic is examined closely. Assume that the overload contacts are closed and the output of AND gate #1 is high. Since both inputs of AND gate #2 are high, the output is also high. Now assume that the overload contact opens and causes input B to change to a low condition. This forces the output of AND gate #2 to change to low state also. Input A of AND gate #2 is still high, however. If the overload contact is reset, the output will immediately change back to a high state. If the overload contact opens and is then reset in the relay circuit, the relay will not restart itself. The START button must be pushed to restart the circuit. Although this is a small difference in circuit logic, it could become a safety hazard in some cases.

This fault can be corrected with a slight design change. Refer to Figure 52–9. In this circuit, the normally closed STOP button has been connected to input A of AND gate #2, and the normally closed overload switch has been connected to input B. As long as both of these inputs are high, the output of AND gate #2 will provide a high to input B of AND gate #1. If either the STOP button or the overload contact opens, the output of AND gate #2 will change to a low state. When input B of AND gate #2 changes to a low state, it will cause the output of AND gate #1 to change to a low state and unlock the circuit, just as pushing the STOP button did in the circuit shown in Figure 52–8. The logic of this digital circuit is now the same as the relay circuit.

Although the logic of this circuit is now correct, there are still some problems that must be corrected. When gates are used, their inputs must be connected to a definite high or low. When the START button is in its normal position, input A of the OR gate is not connected to anything. When an input is left in this condition, the gate may not be able to determine if the input should be high or low. The gate could, therefore, assume either condition. To prevent this, inputs must always be connected to a definite high or low.

When using TTL logic, inputs are always pulled high with a resistor as opposed to being pulled low. If a resistor is used to pull an input low as shown in Figure 52–10, it will cause the gate to have a voltage drop at its output. This means that in the high state, the output of the gate may be only 3 or 4 volts instead of 5 volts. If this output is used as the input of another gate, and the other gate has been pulled low with a resistor, the output of the second gate may be only 2 or 3 volts. Notice that each time a gate is pulled through a resistor, its outcome voltage becomes low. It this were done through

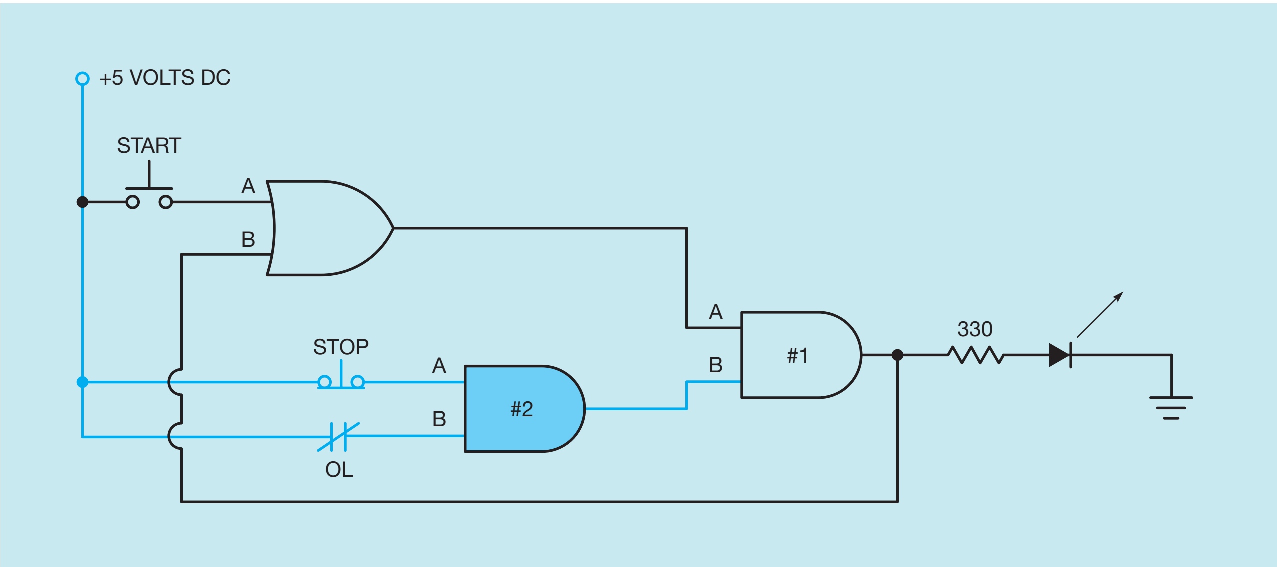


Figure 52–9 (Source: Delmar/Cengage Learning.)

several steps, the output voltage would soon become so low it could not be used to drive the input of another gate.

Figure 52–11 shows a resistor used to pull the input of a gate high. In this circuit, the push button is used to connect the input of the gate to ground, or low.

The push button can be adapted to produce a high at the input instead of a low by adding an INVERTER as shown in Figure 52–12. In this circuit, a pull-up resistor is connected to the input of an INVERTER. Since the input of the INVERTER is high, its output

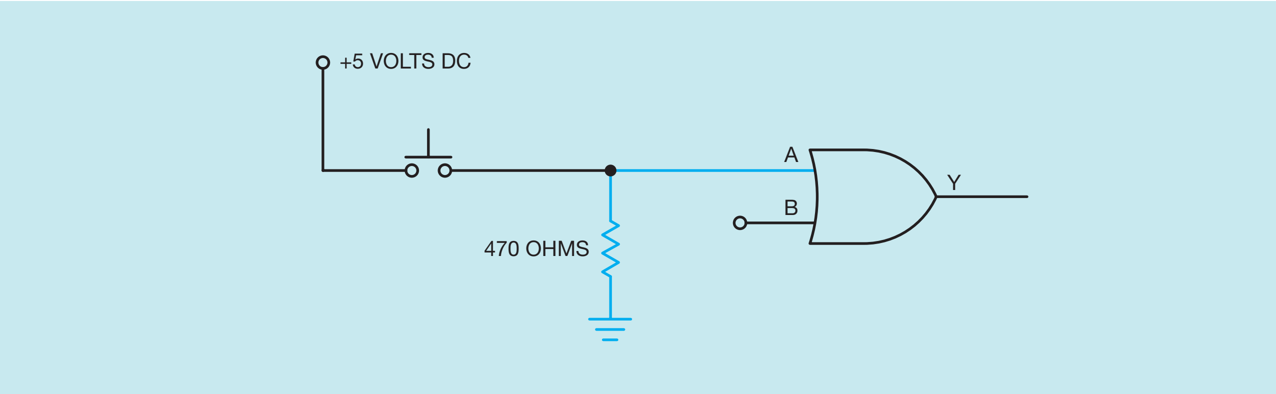


Figure 52–10 Resistor used to lower the input of a gate. (Source: Delmar/Cengage Learning.)

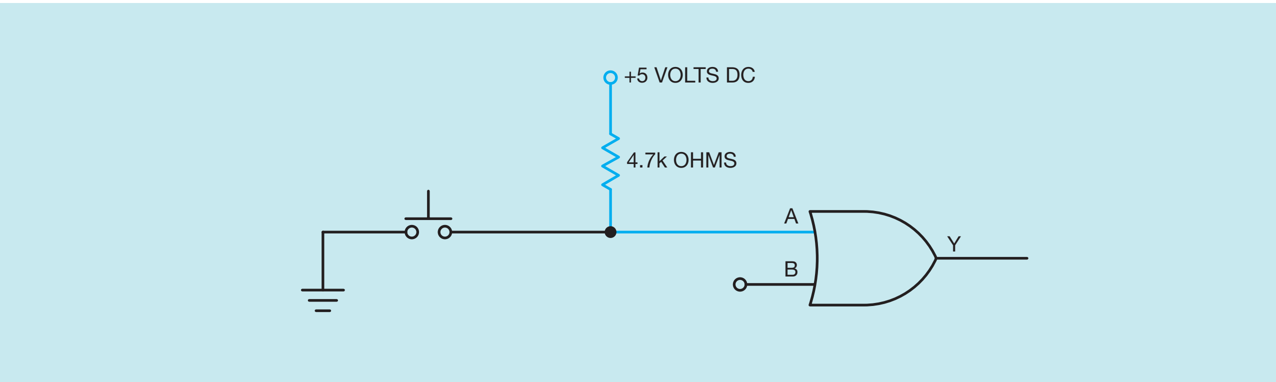


Figure 52–11 Resistor used to raise the input of a gate. (Source: Delmar/Cengage Learning.)

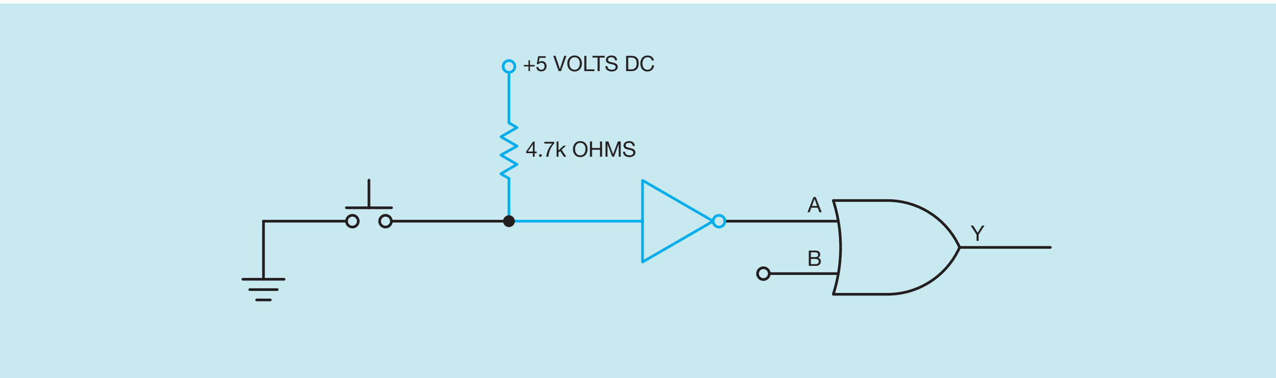


Figure 52–12 Push button produces a high at the input. (Source: Delmar/Cengage Learning.)

will produce a low at input A of the OR gate. When the normally open push button is pressed, a low will be produced at the input of the INVERTER. When the input of the INVERTER becomes low, its output becomes high. Notice that the push button will now produce a high input A of the OR gate when it is pushed.

Since both of the push buttons and the normally closed overload contact are used to provide high inputs, the circuit is changed as shown in Figure 52–13. Notice that the normally closed push button and the normally closed overload switch connected to the inputs of AND gate #2 are connected to ground instead of Vcc. When the switches are connected to ground, a low is provided to the input of the INVERTERS to which they are connected. The INVERTERS, therefore, produce a high at the input of the AND gate. If one of these normally closed switches opens, a high will be provided to the input of the INVERTER. This will cause the output of the INVERTER to become low. If the logic of the circuit shown in Figure 52–13 is checked, it can be seen that it is the same as the logic of the circuit shown in Figure 52–9.

The final design problem for this circuit concerns the output. So far, a light-emitting diode has been used as the load. The LED is used to indicate when the output is high and when it is low. The original circuit, however, was used to control a 120 volt AC motor. This control can be accomplished by connecting a solid-state relay to the output in place of the LED (Figure 52–14). In this circuit, the output of AND gate #1 is connected to the input of an opto-isolated, solid-state relay. When the output of the AND gate changes to a high condition, the solid-state relay turns on and connects the 120 volt AC load to the line.

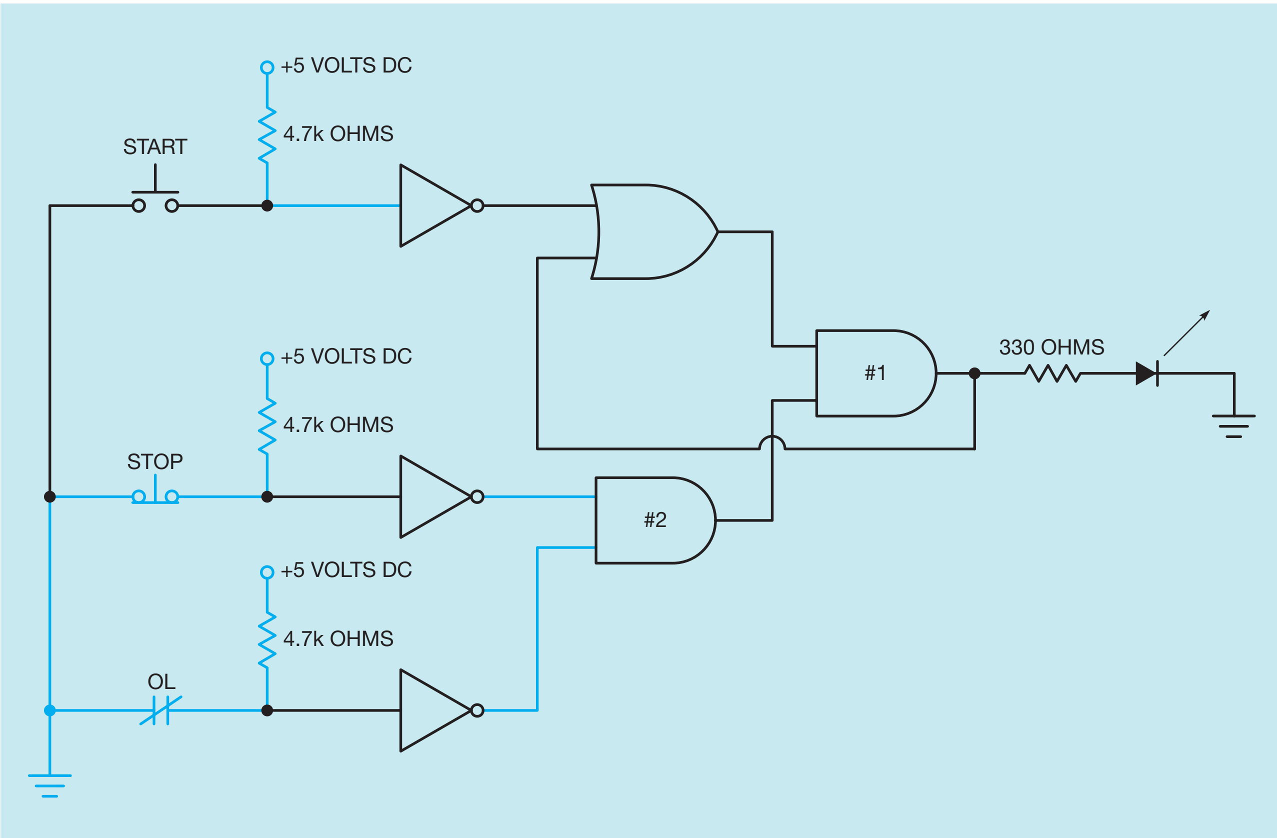


Figure 52–13 (Source: Delmar/Cengage Learning.)

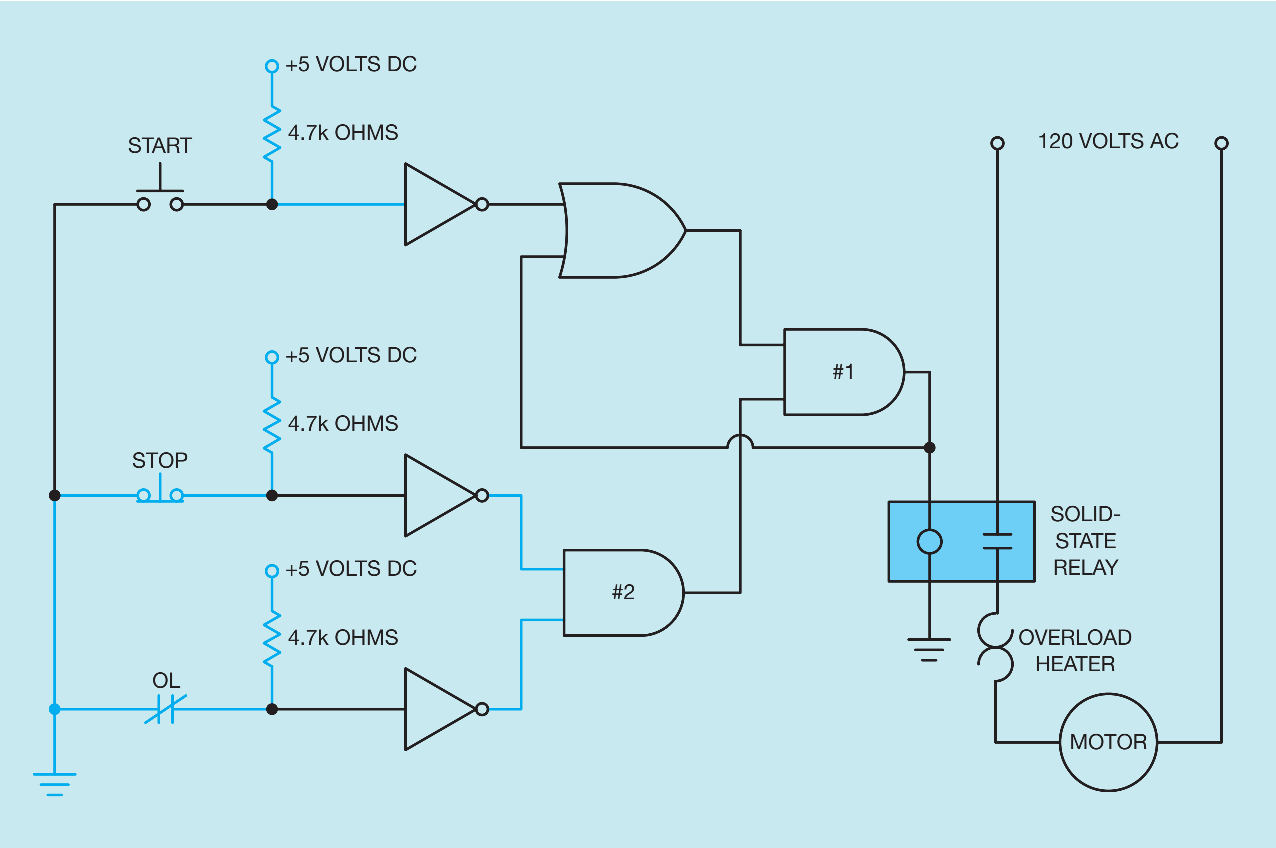


Figure 52–14 Solid-state, start-stop, push-button control. (Source: Delmar/Cengage Learning.)

Review Questions

1. In a relay circuit, what function is served by the holding contacts?
2. What is the function of the overload relay in a motor control circuit?
3. What conditions of input must exist if an OR gate is to produce a high output?
4. What conditions of input must exist if an AND gate is to produce a high output?
5. When connecting TTL logic, why are inputs pulled high instead of low?
6. Referring to Figure 52–9, how would this circuit operate if input B of the OR gate was reconnected to input A of AND gate #1 instead of its output?
7. Referring to Figure 52–12, what function does the INVERTER serve in this circuit?

CHAPTER 53

PROGRAMMABLE LOGIC CONTROLLERS

OBJECTIVES

After studying this chapter, the student will be able to:

- List the principal part of a programmable logic controller.
- Describe differences between programmable logic controllers and other types of computers.
- Discuss differences between the I/O Rack, CPU, and program loader.
- Draw a diagram of how the input and output modules work.

Programmable logic controllers (PLCs) were first used by the automotive industry in the late 1960s. Each time a change was made in the design of an automobile, it was necessary to change the control system operating the machinery. This consisted of physically rewiring the control system to make it perform the new operation. Rewiring the system was, of course, very time consuming and expensive. What the industry needed was a control system that could be changed without the extensive rewiring required to change relay control systems.

Differences Between PLCs and PCs

One of the first questions generally asked is, "Is a programmable logic controller a computer?" The answer to that question is "yes." The PLC is a special type of computer designed to perform a special function. Although the programmable logic controller (PLC) and the personal computer (PC) are both computers, there are some significant differences. Both generally employ the same basic type of computer and memory chips to perform the tasks for which they are intended, but the PLC must operate in an industrial environment. Any computer that is intended for industrial use must be able to withstand extremes of temperature; ignore voltage spikes and drops on the power line; survive in an atmosphere that often contains corrosive vapors, oil, and dirt; and withstand shock and vibration.

Programmable logic controllers are designed to be programmed with schematic or ladder diagrams instead of common computer languages. An electrician that is familiar with ladder logic diagrams can generally learn to program a PLC in a few hours as opposed to the time required to train a person how to write programs for a standard computer.

Basic Components

Programmable logic controllers can be divided into four primary parts:

A. The power supply.

B. The central processing unit (CPU).

C. The programming terminal or program loader.

D. The I/O (pronounced eye-oh) Rack.

The Power Supply

The function of the power supply is to lower the incoming AC voltage to the desired level, rectify it to direct current, and then filter and regulate it. The internal logic of a PLC generally operates on 5 to 24 volts DC, depending on the type of controller. This voltage must be free of voltage spikes and other electrical noise and be regulated to within 5% of the required voltage value. Some manufacturers of PLCs build a separate power supply and others build the power supply into the central processing unit.

Figure 53–1 A central processing unit. (Courtesy Allen-Bradley, a Rockwell International Company.)

The CPU

The CPU, or central processing unit, is the "brains" of the programmable logic controller. It contains the microprocessor chip and related integrated circuits to perform all the logic functions. The microprocessor chip used in most PLCs is the same as that found in most home and business personal computers.

The CPU often has a key located on the front panel (Figure 53–1). This switch must be turned on before the CPU can be programmed. This is done to prevent the circuit from being changed or deleted accidentally. Other manufacturers use a *software switch* to protect the circuit. A software switch is not a physical switch. It is a command that must be entered before the program can be changed or deleted. Whether a physical switch or a software switch is used, they both perform the same function. They prevent a program from being accidentally changed or deleted.

Plug connections on the CPU provide connection for the programming terminal and I/O Racks (Figure 53–2). CPUs are designed so that once a program has been developed and tested, it can be stored on some type of medium such as tape, disc, CD, or other storage device. In this way, if a CPU fails and has to be replaced, the program can be downloaded from the stor-

Figure 53–2 Plug connections located on the CPU. (Courtesy Siemens Energy and Automation, Inc.)

age medium. This eliminates the time consuming process of having to reprogram the unit by hand.

The Programming Terminal

The programming terminal, or loading terminal, is used to program the CPU. The type of terminal used depends on the manufacturer and often the preference of the consumer. Some are small handheld devices that use a liquid crystal display or light-emitting diodes to show the program (Figure 53–3). Some of these small units will display one line of the program at a time and others require the program to be entered in a language called Boolean.

Another type of programming terminal contains a display and keyboard (Figure 53–4). This type of terminal generally displays several lines of the program at a time and can be used to observe the operation of the circuit as it is operating.

Figure 53–3 Hand held programming terminal and small programmable logic controller. (Courtesy Cutler Hammer, Eaton Corp.)

Figure 53–4 Programming terminal. (Courtesy Allen-Bradley, a Rockwell International Company.)

Many industries prefer to use a notebook or laptop computer for programming (Figure 53–5). An interface that permits the computer to be connected to the input of the PLC and software program is generally available from the manufacturer of the PLC.

The terminal is not only used to program the PLC but is also used to troubleshoot the circuit. When the terminal is connected to the CPU, the circuit can be examined while it is in operation. Figure 53–6 illustrates a circuit typical of those that are seen on the display. Notice that this schematic diagram is different from the typical ladder diagram. All of the line components are shown as normally open or normally closed contacts. There are no NEMA symbols for push button, float

Figure 53–5 A notebook computer is often used as the programming terminal for a PLC. (Courtesy Dell Computers.)

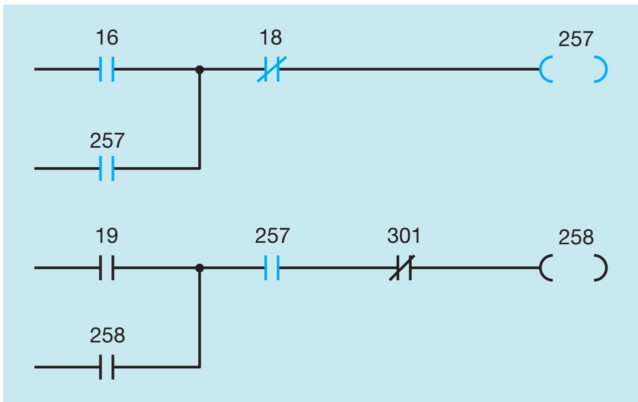


Figure 53–6 Analyzing circuit operation with a terminal. (Source: Delmar/Cengage Learning.)

switch, limit switches, etc. The PLC recognizes only open or closed contacts. It does not know if a contact is connected to a push button, a limit switch, or a float switch. Each contact, however, does have a number. The number is used to distinguish one contact from another.

In this example, coil symbols look like a set of parentheses instead of a circle as shown on most ladder diagrams. Each line ends with a coil and each coil has a number. When a contact symbol has the same number as a coil, it means that the contact is controlled by that coil. The schematic in Figure 53–6 shows a coil numbered 257 and two contacts numbered 257. When coil 257 is energized, the PLC interprets both contacts 257 to be closed.

A characteristic of interpreting a diagram while viewing it on the screen of most loading terminals is that when a current path exists through a contact, or if a coil is energized, it will be highlighted on the display. In the example shown in Figure 53–6, coil 257, both 257 contacts, contact 16, and contact 18 are drawn with dark heavy lines, illustrating that they are highlighted or illuminated on the display. Highlighting a contact does not means that it has changed from its original state. It means that there is a complete circuit through that contact. Contact 16 is highlighted, indicating that coil 16 has energized and contact 16 is closed and providing a complete circuit. Contact 18, however, is shown as normally closed. Since it is highlighted, coil 18 has not been energized, because a current path still exists through contact 18. Coil 257 is shown highlighted, indicating that it is energized. Since coil 257 is energized, both 257 contacts are now closed, providing a current path through them.

When the loading terminal is used to load a program into the PLC, contact and coil symbols on the keyboard are used (Figure 53–7). Other keys permit specific types of relays such as timers, counters, or retentive relays to be programmed into the logic of the circuit. Some keys permit parallel paths, generally referred to as down rungs, to be started and ended. The method employed to program a PLC is specific to the make and model of the controller. It is generally necessary to consult the manufacturer's literature if you are not familiar with the specific PLC.

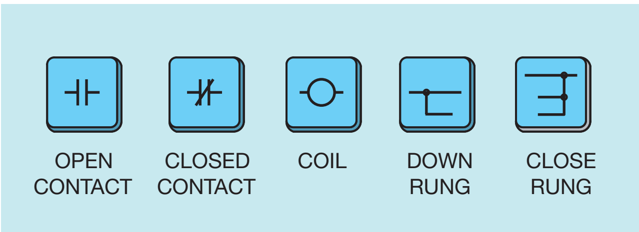


Figure 53–7 Symbols are used to program the PLC. (Source: Delmar/Cengage Learning.)

The I/O Rack

The I/O Rack is used to connect the CPU to the outside world. It contains input modules that carry information from control sensor devices to the CPU and output modules that carry instructions from the CPU to output devices in the field. I/O Racks are shown in Figures 53–8A and B. Input and output modules contain more than one input or output. Any number from 4 to 32 is common, depending on the manufacturer and model of the PLC. The modules shown in Figure 53–8A can

Figure 53–8A I/O Rack with input and output modules. (Courtesy Schneider Automation.)

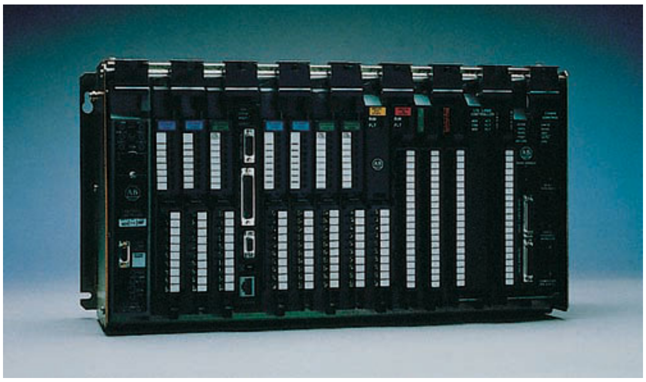


Figure 53–8B I/O Rack with input and output modules. (Courtesy Allen-Bradley Co., Systems Division.)

Figure 53–9 Central processor with I/O Racks. (Courtesy General Electric.)

each handle sixteen connections. This means that each input module can handle 16 different input devices such as push buttons, limit switches, proximity switches, float switches, and so on. The output modules can each handle 16 external devices such as pilot lights, solenoid coils, or relay coils. The operating voltage can be either alternating or direct current, depending on the manufacturer and model of controller, and is generally either 120 or 240 volts. The I/O Rack shown in Figure 53–8A can handle 10 modules. Since each module can handle 16 input or output devices, the I/O Rack is capable of handling 160 input and output devices. Many PLCs are capable of handling multiple I/O Racks.

I/O Capacity

One factor that determines the size and cost of a PLC is its I/O capacity. Many small units may be intended to handle as few as 16 input and output devices. Large PLCs can generally handle several hundred. The number of input and output devices the controller must handle also affects the processor speed and amount of memory the CPU must have. A CPU with I/O Racks is shown in Figure 53–9.

The Input Module

The central processing unit of a programmable logic controller is extremely sensitive to voltage spikes and electrical noise. For this reason, the input I/O uses opto-isolation to electrically separate the incoming signal from the CPU. Figure 53–10 shows a typical circuit used for the input. A metal-oxide-varistor (MOV) is connected across the AC input to help eliminate any voltage spikes that may occur on the line. The MOV is a voltage sensitive resistor. As long as the voltage across its terminals remains below a certain level, it exhibits a very high resistance. If the voltage should become too high, the resistance changes almost instantly to a very low value. A bridge rectifier changes the AC voltage into DC. A resistor is used to limit current to an LED. When power is applied to the circuit, the LED turns on. The light is detected by a phototransistor, which signals the CPU that there is a voltage present at the input terminal.

When the module has more than one input, the bridge rectifiers are connected together on one side to form a common terminal. On the other side, the rectifiers are labeled 1, 2, 3, and 4. Figure 53–11 shows four bridge rectifiers connected together to form a common terminal. Figure 53–12 shows a limit switch connected to input 1, a temperature switch connected to

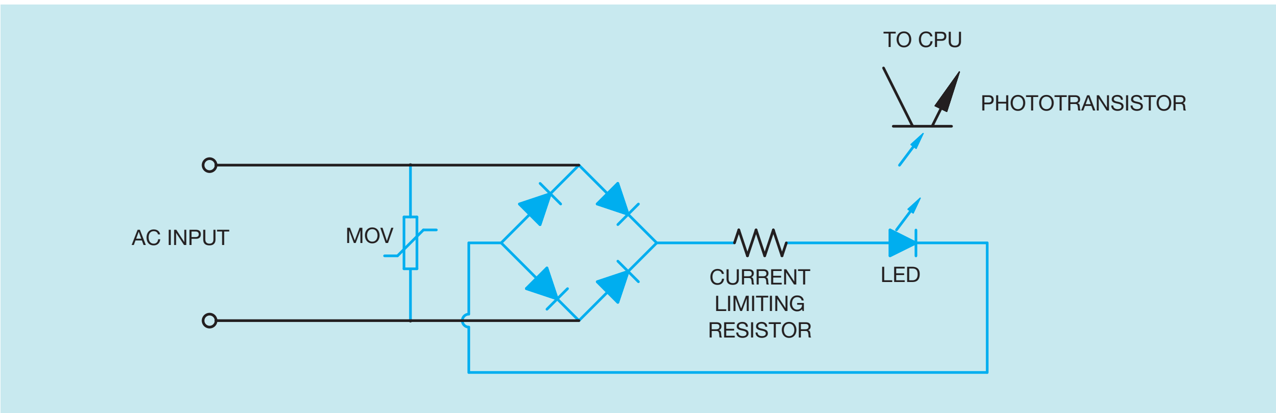


Figure 53–10 Input Circuit. (Source: Delmar/Cengage Learning.)

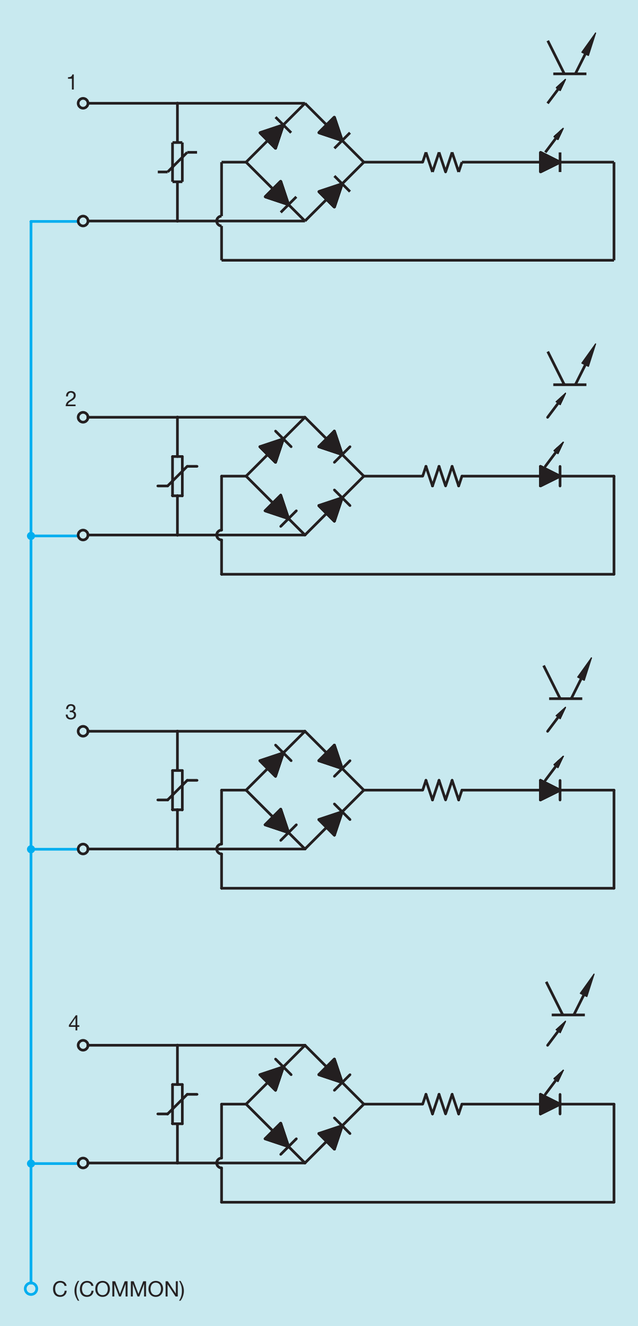


Figure 53–11 Four-input module. (Source: Delmar/Cengage Learning.)

input 2, a float switch connected to input 3, and a normally open push button connected to input 4. Notice that the pilot devices complete a circuit to the bridge rectifiers. If any switch closes, 120 volts AC will be connected to a bridge rectifier, causing the corresponding LED to turn on and signal the CPU that the input has voltage applied to it. When voltage is applied to an input, the CPU considers that input to be at a high level.

The Output Module

The output module is used to connect the CPU to the load. Output modules provide line isolation between the CPU and the external circuit. Isolation is generally provided in one of two ways. The most popular is with optical isolation, very similar to the input modules. In this case, the CPU controls an LED. The LED is used to signal a solid-state device to connect the load to the line. If the load is operated by direct current, a power phototransistor is used to connect the load to the line (Figure 53–13). If the load is an alternating current device, a triac is used to connect the load to the line (Figure 53–14). Notice that the CPU is separated from the external circuit by a light beam. No voltage spikes or electrical noise can be transmitted to the CPU.

The second method of controlling the output is with small relays (Figure 53–15). The CPU controls the relay coil. The contacts connect the load to the line. The advantage of this type of output module is that it is not sensitive to whether the voltage is AC or DC and can control 120 or 240 volt circuits. The disadvantage is that it does contain moving parts that can wear. In this instance, the CPU is isolated from the external circuit by a magnetic field instead of a light beam.

If the module contains more than one output, one terminal of each output device are connected together to form a common terminal similar to a module with multiple inputs (Figure 53–16). Notice that one side of each triac has been connected together to form a common point. The other side of each triac is labeled 1, 2, 3, or 4. If power transistors are used as output devices, the collectors or emitters of each transistor would be connected to form a common terminal. Figure 53–14 shows a relay coil connected to the output of a triac. Notice that the triac is used as a switch to connect the load to the line. The power to operate the load must be provided by an external source. *Output modules **do not** provide power to operate external loads.*

The amount of current an output can control is limited. The current rating of most outputs can range from 0.5 to about 3 amperes, depending on the manufacturer and type of output. Outputs are intended to control loads that draw a small amount of current, such as solenoid coils, pilot lights, and relay coils. Some outputs can control motor starter coils directly and others require an interposing relay. Interposing relays are employed when the current draw of the load is above the current rating of the output. Interposing relays are also employed when the PLC controls starters in a motor control center. This prevents two different power

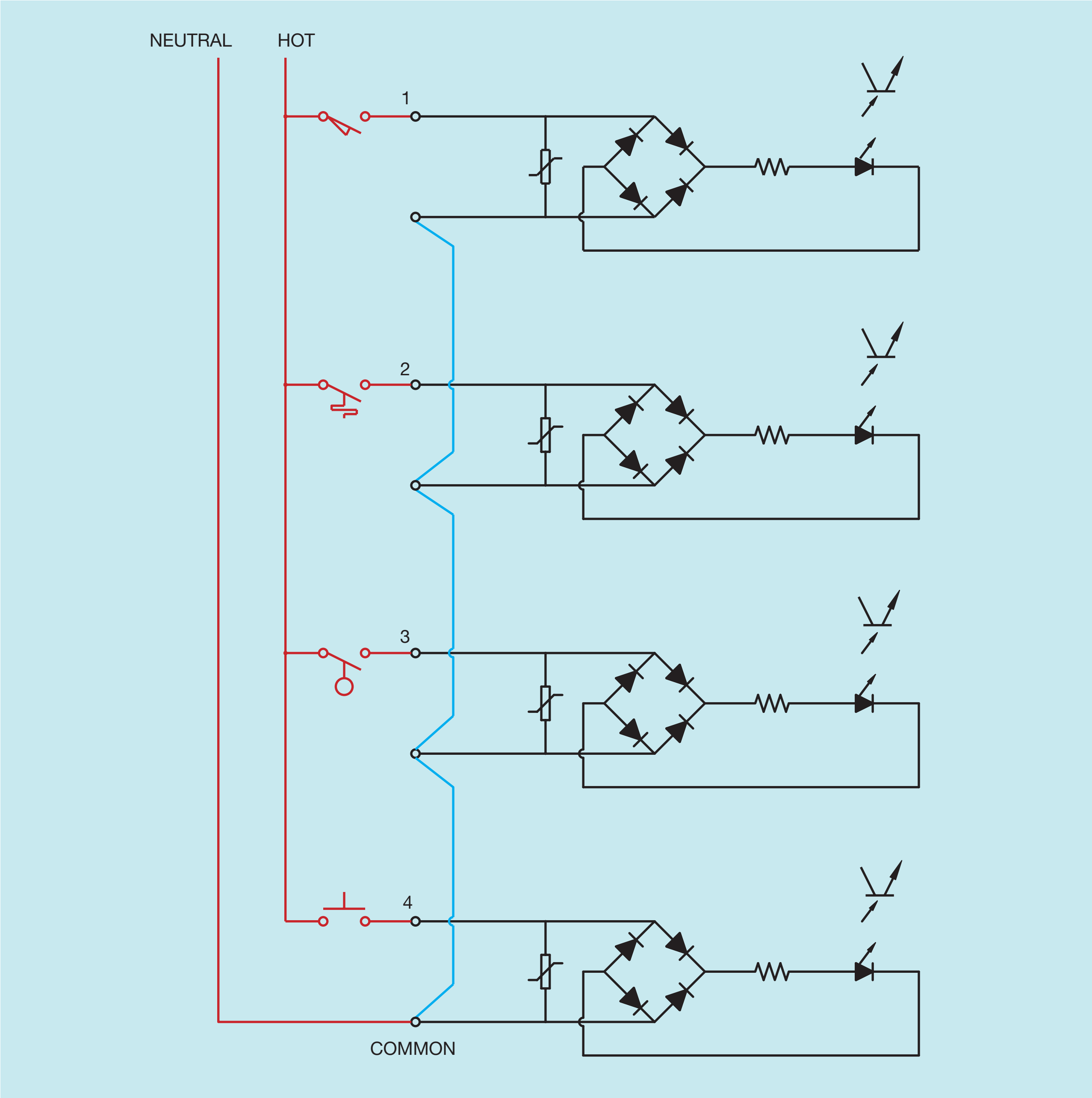


Figure 53–12 Pilot devices connected to input modules. (Source: Delmar/Cengage Learning.)

sources from being present inside an MCC module. Two power sources inside a control module could present a safety hazard (Figure 53–17).

Internal Relays

The actual logic of the control circuit is performed by *internal relays*. An internal relay is an imaginary device that exists only in the logic of the computer. It can have any number of contacts—from one to several hundred—and the contacts can be programmed normally open or normally closed. Internal relays are programmed into the logic of the PLC by assigning them a certain number. Manufacturers provide a chart that lists which numbers can be used to program inputs and outputs, internal relay coils, timers, counters, and so on. When a coil is entered at the end of a line of logic and is given a number that corresponds to an internal relay, it

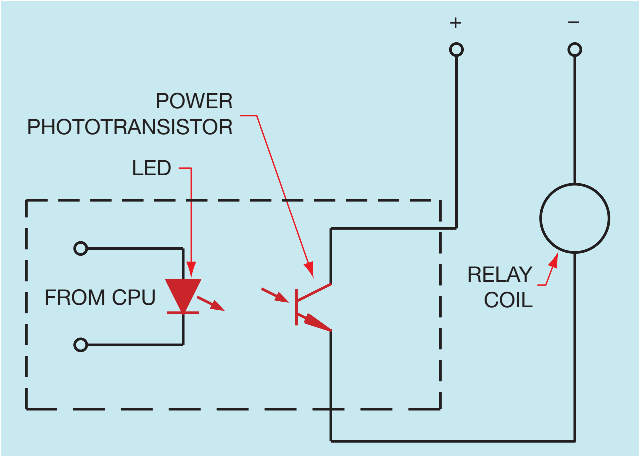


Figure 53–13 A power phototransistor connects a DC load to the line. (Source: Delmar/Cengage Learning.)

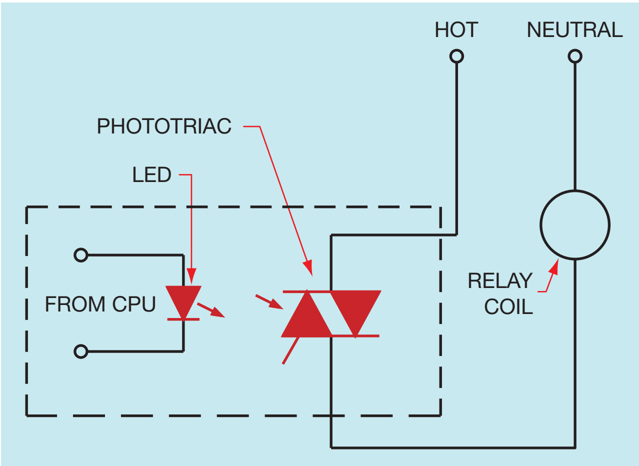


Figure 53–14 A triac connects an AC load to the line. (Source: Delmar/Cengage Learning.)

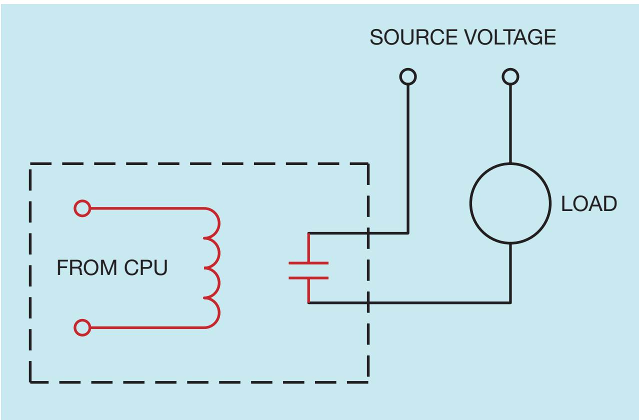


Figure 53–15 A relay connects the load to the line. (Source: Delmar/Cengage Learning.)

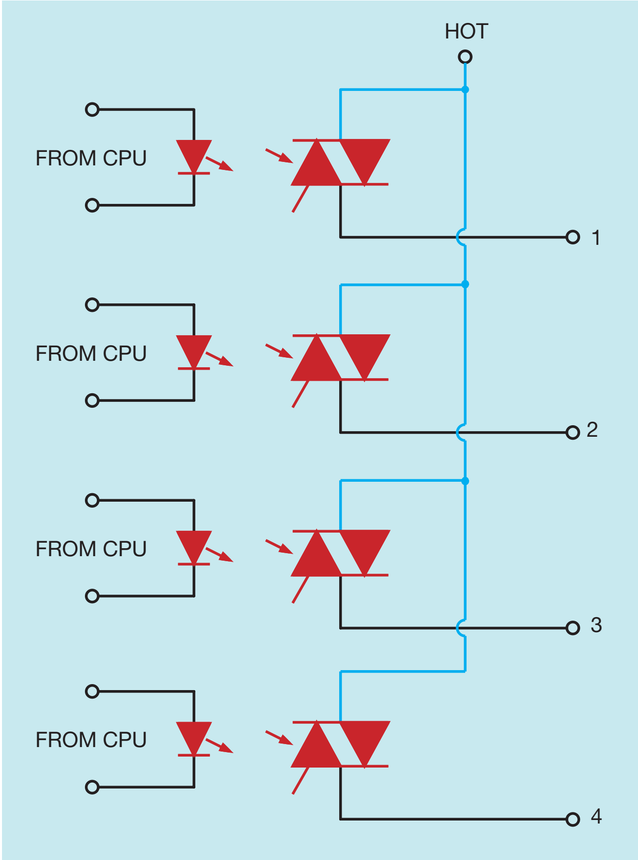


Figure 53–16 Multiple output module. (Source: Delmar/Cengage Learning.)

will act like a physical relay. Any contacts given the same number as that relay will be controlled by that relay.

Timers and Counters

Timers and counters are internal relays, also. There is no physical timer or counter in the PLC. They must be programmed into the logic in the same manner as any other internal relay, by assigning them a number that corresponds to the timer or counter. The difference is that the time delay or number of counts must be programmed when they are inserted into the program. The number of counts for a counter is entered using numbers on the keys on the load terminal. Timers are generally programmed in 0.1 second intervals. Some manufacturers provide a decimal key and others do not. If a decimal key is not provided, the time delay is entered as 0.1 second intervals. If a delay of 10 seconds is desired, for example, the number 100 would be entered, because 100 tenths of a second equals 10 seconds.

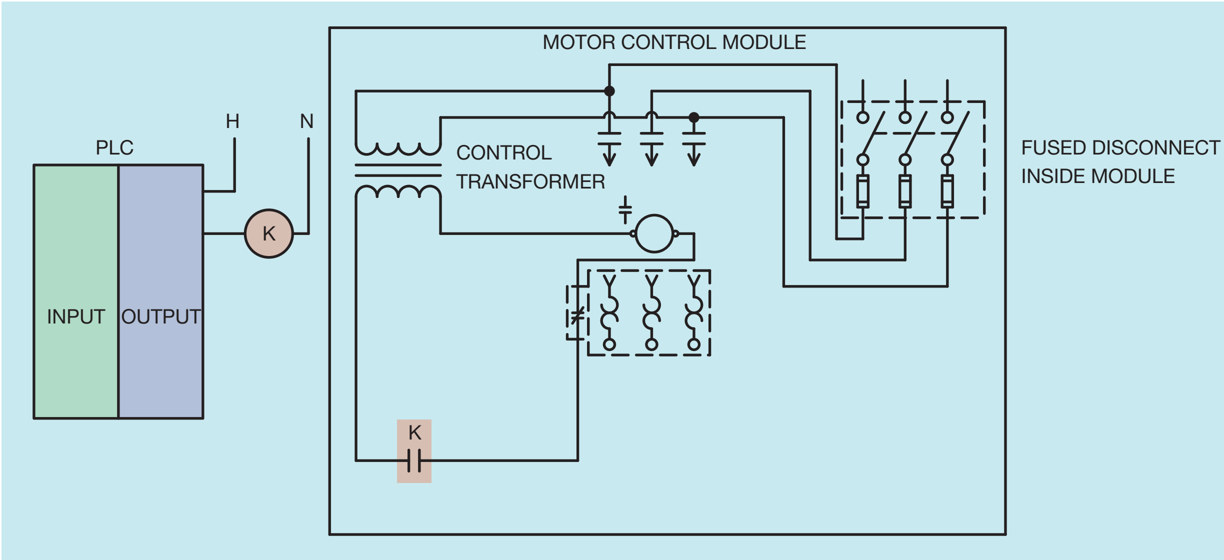


Figure 53–17 An interposing relay is used to operate the starter in a motor control center module. (Source: Delmar/Cengage Learning.)

Off-Delay Circuit

Some PLCs permit a timer to be programmed as on or off delay, but others permit only on-delay timers to be programmed. When a PLC permits only on-delay timers to be programmed, a simple circuit can be used to permit an on-delay timer to perform the function of an off-delay timer (Figure 53–18). To understand the action of the circuit, recall the operation of an off-delay timer. When the timer coil is energized, the timed contacts change position immediately. When the coil is de-energized, the contacts remain in their energized state for some period of time before returning to their normal state. In the circuit shown in Figure 53–18, it is assumed that contact 400 controls the action of the timer. Coil 400 is an internal relay coil located somewhere in the circuit. Coil 12 is an output and controls some external device. Coil TO-1 is an on-delay timer set for 100 tenths of a second. When coil 400 is energized, both 400 contacts change position. The normally open 400 contact closes and provides a current path to coil 12. The normally closed 400 contact opens and prevents a circuit from being completed to coil TO-1 when coil 12 energizes. Note that coil 12 turns on immediately when contact 400 closes. When coil 400 is de-energized, both 400 contacts return to their normal position. A current path is maintained to coil 12 by the now closed 12 contact in parallel with the normally open 400 contact. When the normally closed 400 contact returns to its normal position, a current path is established to coil TO-1 thorough the now closed 12 contact. This starts the time sequence of timer TO-1. After a delay of 10 seconds, the normally closed TO-1 contact opens and de-energizes coil 12, returning the two 12 contacts to their normal position. The circuit is now back in the state shown in Figure 53–16. Note the action of the circuit. When coil 400 is energized, output coil 12 turns on immediately. When coil 400 is de-energized, output 12 remains on for 10 seconds before turning off.

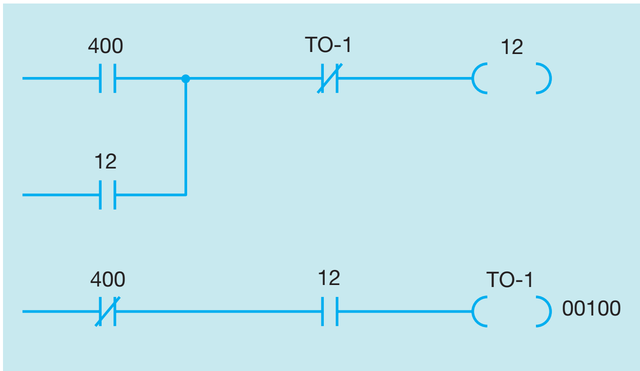


Figure 53–18 Off-delay timer circuit. (Source: Delmar/Cengage Learning.)

The number of internal relays and timers contained in a PLC is determined by the memory capacity of the computer. As a general rule, PLCs that have a large I/O capacity will have a large amount of memory. The use of PLCs has steadily increased since their invention in the late 1960s. A PLC can replace hundreds of relays and occupy only a fraction of space. The circuit logic can be changed easily and quickly without requiring extensive hand rewiring. They have no moving parts or contacts to wear out, and their down time is less than an equivalent relay circuit. When replacement is necessary, they can be reprogrammed from a media storage device.

The programming methods presented in this text are general, because it is impossible to include examples of each specific manufacturer. The concepts presented in this chapter, however, are common to all programmable controllers. A PLC used to control a DC drive is shown in Figure 53–19.

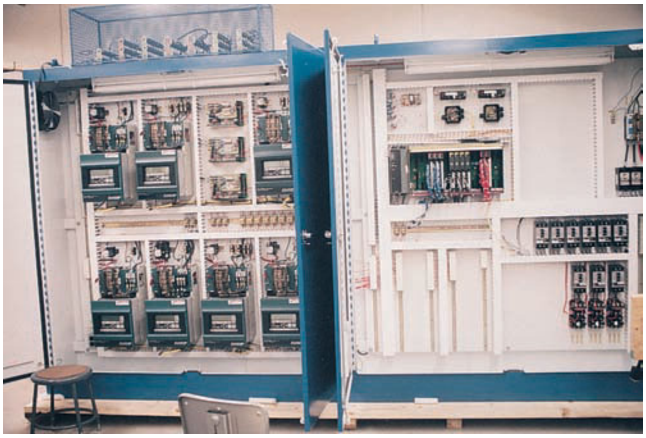


Figure 53–19 DC drive unit controlled by a programmable logic controller. (Courtesy Reliance Electric.)

Review Questions

1. What industry first started using PLCs?
2. Name two differences between PLCs and common home or business computers.
3. Name the four basic sections of a PLC.
4. In what section of the PLC is the actual logic performed?
5. What device is used to program a PLC?
6. What device separates the CPU from the outside world?
7. What is opto-isloation?
8. If an output I/O controls a DC voltage, what solid-state device is used to connect the load to the line?
9. If an output I/O controls an AC voltage, what solid-state device is used to connect the load to the line?
10. What is an internal relay?
11. What is the purpose of the key switch located on the front of the CPU in many PLCs?
12. What is a software switch?

CHAPTER 54
PROGRAMMING A PLC

OBJECTIVES

After studying this chapter, the student will be able to:

- Convert a relay schematic to a schematic used for programming a PLC.
- Enter a program into a programmable controller.

In this chapter, a relay schematic will be converted into a diagram used to program a programmable controller. The process to be controlled is shown in Figure 54–1. A tank is used to mix two liquids. The control circuit operates as follows:

A. When the START button is pressed, solenoids A and B energize. This permits the two liquids to begin filling the tank.

B. When the tank is filled, the float switch trips. This de-energizes solenoids A and B and starts the motor used to mix the liquids together.

C. The motor is permitted to run for 1 minute. After 1 minute has elapsed, the motor turns off and solenoid C energizes to drain the tank.

D. When the tank is empty, the float switch de-energizes solenoid C.

E. A STOP button can be used to stop the process at any point.

F. If the motor becomes overloaded, the action of the entire circuit will stop.

G. Once the circuit has been energized, it will continue to operate until it is manually stopped.

Circuit Operation

A relay schematic that will perform the logic of this circuit is shown in Figure 54–2. The logic of this circuit is as follows:

A. When the START button is pushed, relay coil CR is energized. This causes all CR contacts to close. Contact CR-1 is a holding contact used to maintain the circuit to coil CR when the START button is released.

B. When contact CR-2 closes, a circuit is completed to solenoid coils A and B. This permits the two liquids that are to be mixed together to begin filling the tank.

C. As the tank fills, the float rises until the float switch is tripped. This causes the normally closed float switch contact to open and the normally open contact to close.

D. When the normally closed float switch opens, solenoid coils A and B de-energize and stop the flow of the two liquids into the tank.

E. When the normally open contact closes, a circuit is completed to the coil of a motor starter and the coil of an on-delay timer. The motor is used to mix the two liquids together.

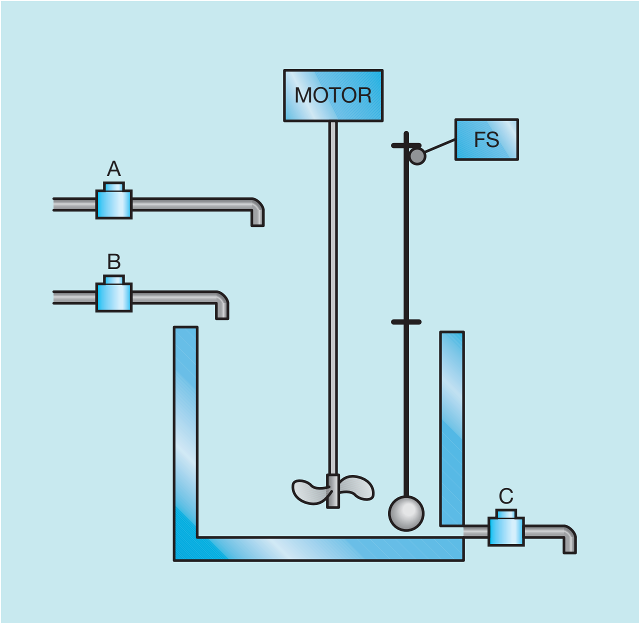


Figure 54–1 Tank used to mix two liquids. (Source: Delmar/Cengage Learning.)

F. At the end of the one minute time period, all of the TR contacts change position. The normally closed TR-2 contact connected in series with the motor starter coil opens and stops the operation of the motor. The normally open TR-3 contact closes and energizes solenoid coil C which permits liquid to begin draining from the tank. The normally closed TR-1 contact is used to assure that valves A and B cannot be re-energized until solenoid C de-energizes.

G. As liquid drains from the tank, the float drops. When the float drops far enough, the float switch trips and its contacts return to their normal positions. When the normally open float switch contact reopens and de-energizes coil TR, all TR contacts return to their normal positions.

H. When the normally open TR-3 contact reopens, solenoid C de-energizes and closes the drain valve. Contact TR-2 recloses, but the motor cannot restart because of the normally open float switch contact.

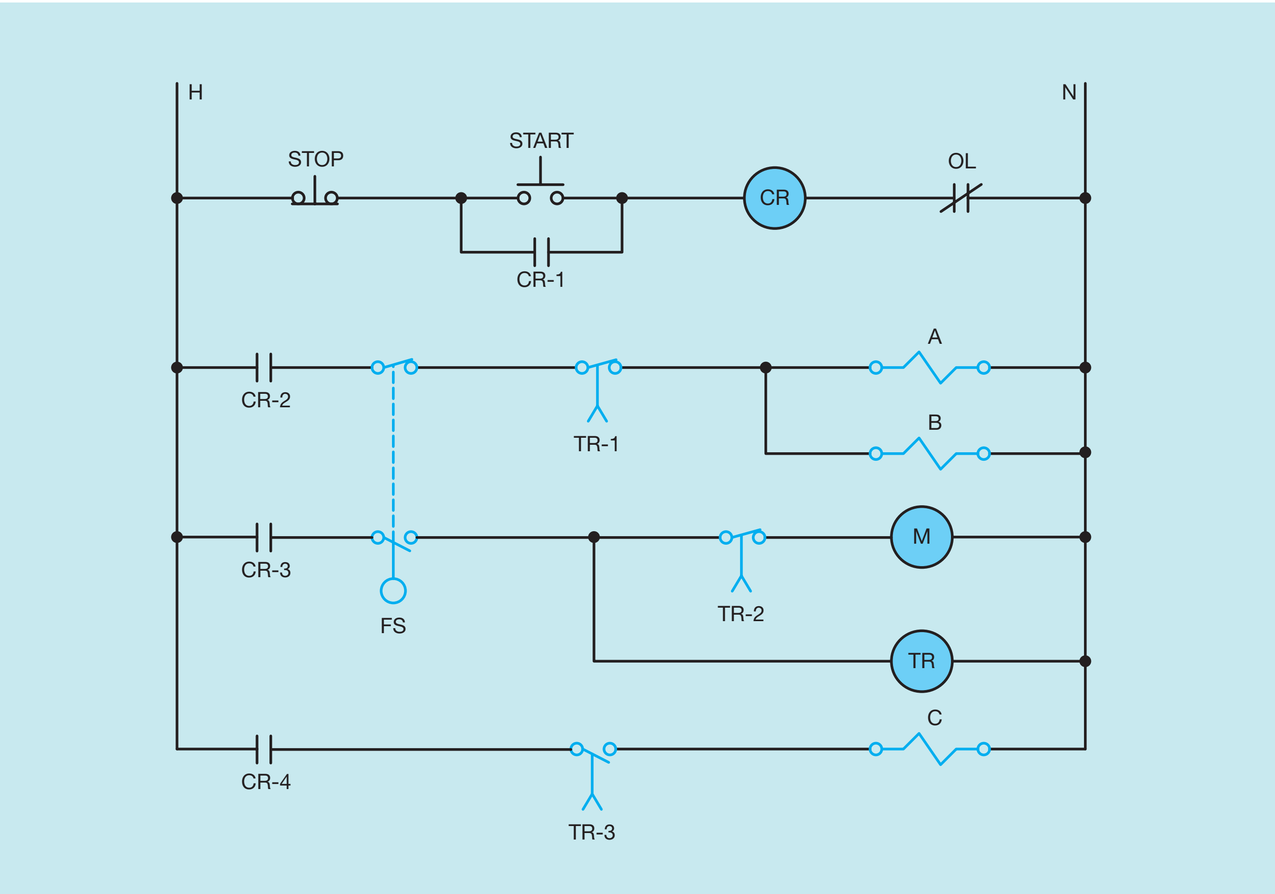


Figure 54–2 Relay schematic. (Source: Delmar/Cengage Learning.)

When contact TR-1 re-closes, a circuit is completed to solenoids A and B. This permits the tank to begin refilling, and the process starts over again.

I. If the STOP button or overload contact opens, coil CR de-energizes and all CR contacts open. This de-energizes the entire circuit.

Developing a Program

This circuit will now be developed into a program that can be loaded into the programmable controller. Figure 54–3 shows a program being developed on a computer. Assume that the controller has an I/O capacity of 32, that I/O terminals 1 through 16 are used as inputs, and that terminals 17 through 32 are used as outputs.

Before a program can be developed for input into a programmable logic controller, it is necessary to assign which devices connect to the input and output terminals. This circuit contains four input devices and four output devices. It is also assumed that the motor starter for this circuit contains an overload relay that contains two contacts instead of one. One contact is normally closed and is connected in series with the coil of the motor starter. The other contact is normally open and is used to supply an input to a programmable logic controller. If the motor becomes overloaded, the normally closed contacts will open and disconnect the motor from the line. The normally open contacts will close and provide a signal to the programmable logic controller that the motor has tripped on overload. The input devices are as follows:

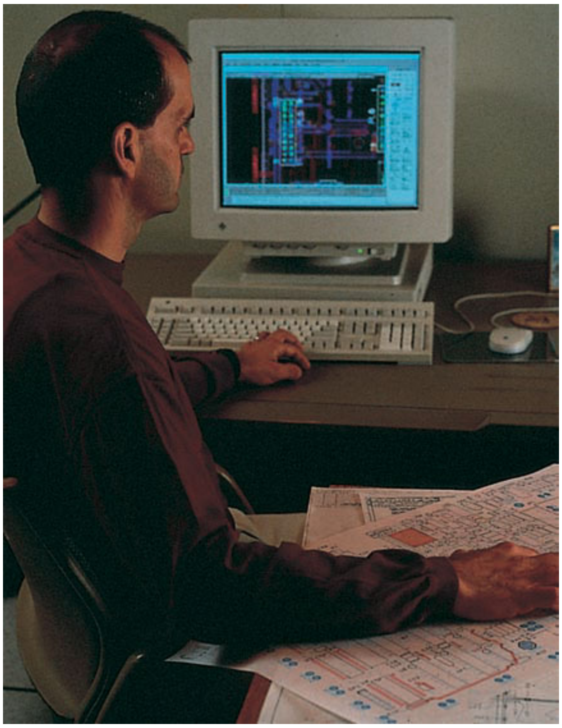


Figure 54–3 A program being developed on a programming terminal. (Courtesy GE Fanuc.)

A. Normally closed STOP push button

B. Normally open START push button

C. Normally open overload contact

D. A float switch that contains both a normally open and normally closed contact.

The four output devices are:

A. Solenoid valve A

B. Solenoid valve B

C. Motor starter coil M

D. Solenoid valve C

The connection of devices to the inputs and outputs is shown in Figure 54–4. The normally closed STOP button is connected to input #1, the normally open START button is connected to input #2, the normally open overload contact is connected to input #3, and the float switch is connected to input #4.

The outputs for this PLC are 17 through 32. Output #17 is connected to solenoid A, output #18 is connected to solenoid B, output #19 is connected to the coil of the motor starter, and output #20 is connected to solenoid C. Note that the outputs ***do not*** supply the power to operate the output devices. The outputs simply complete a circuit. One side of each output device is connected to the ungrounded or hot side of a 120 V AC power line. Neutral is connected to the common terminal of the four outputs. A good way to understand this is to imagine a set of contacts controlled by each output, as shown in Figure 54–5. When programming the PLC, if a coil is given the same number as one of the outputs, it will cause that contact to close and connect the load to the line.

Unfortunately, programmable logic controllers are not all programmed the same way. Almost every manufacturer employs a different set of coil numbers to perform different functions. It is necessary to consult the manual before programming a PLC with which you are not familiar. In order to program the PLC in this

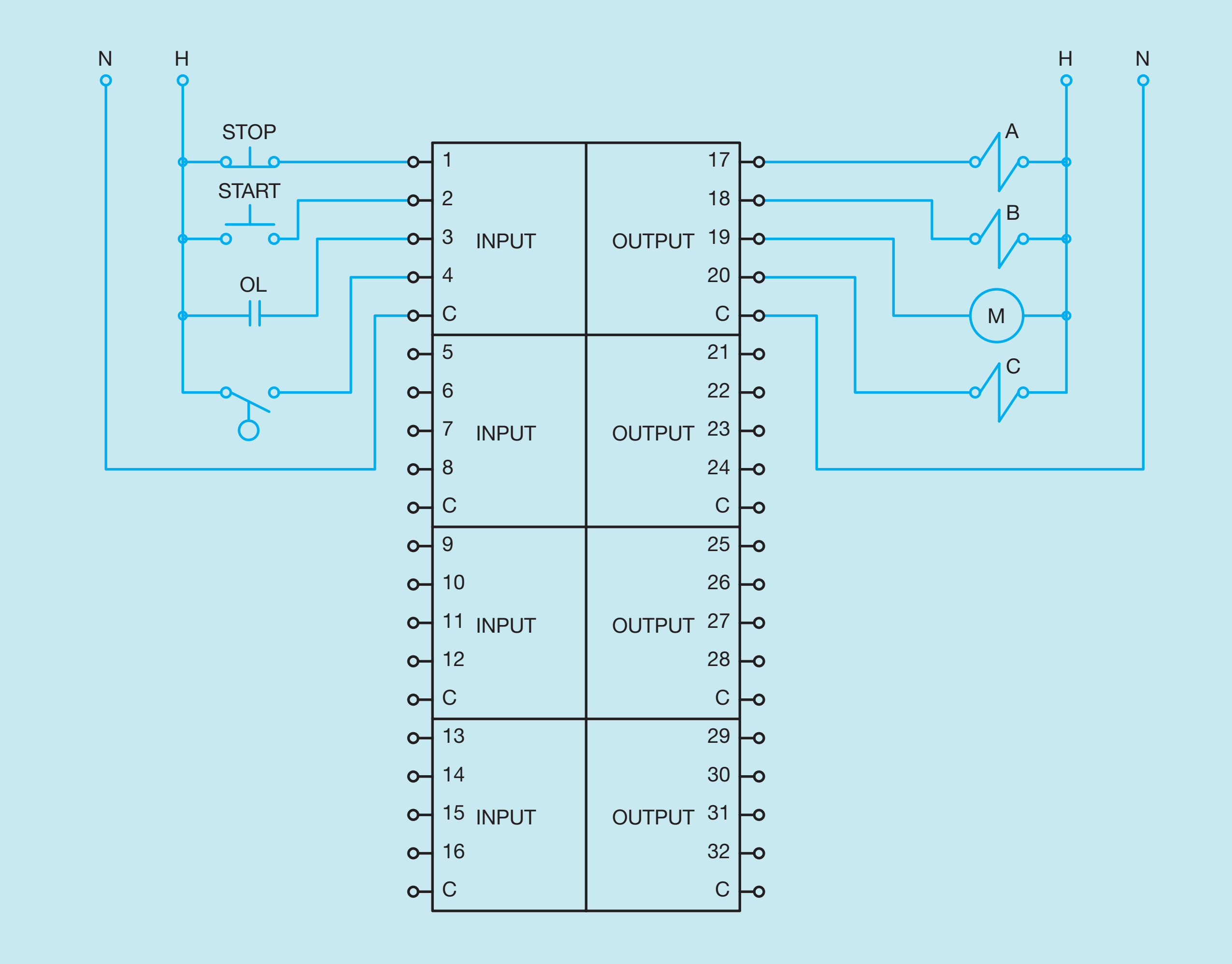


Figure 54–4 Components connected to I/O Rack. (Source: Delmar/Cengage Learning.)

example, refer to the information in Figure 54–6. This chart indicates that numbers 1 through 16 are inputs. Any contact assigned a number between 1 and 16 will be examined each time the programmable logic controller scans the program. If an input has a low (0 V) state, the contact assigned that number will remain in the state it was programmed. If the input has a high (120 V) state, the program will interpret that contact as having changed state. If it was programmed as open, the PLC will now consider it as closed.

Outputs are 17 through 32. Outputs are treated as coils by the PLC. If a coil is given the same number as an output, that output will turn on (close the contact) when the coil is energized. Coils that control outputs can be assigned internal contacts as well. Internal contacts are contacts that exist in the logic of the program only. They do not physically exist. Since they do not physically exist, a coil can be assigned as many internal contacts as desired, and they can be normally open or normally closed.

The chart in Figure 54–6 also indicates that internal relays number from 33 to 103. Internal relays are like internal contacts. They do not physically exist. They exist as part of the program only. They are programmed into the circuit logic by inserting a coil symbol in the program and assigning it a number between 33 and 103.

Timers and counters are assigned coil numbers 200 through 264 and retentive relays are numbered 104 through 134.

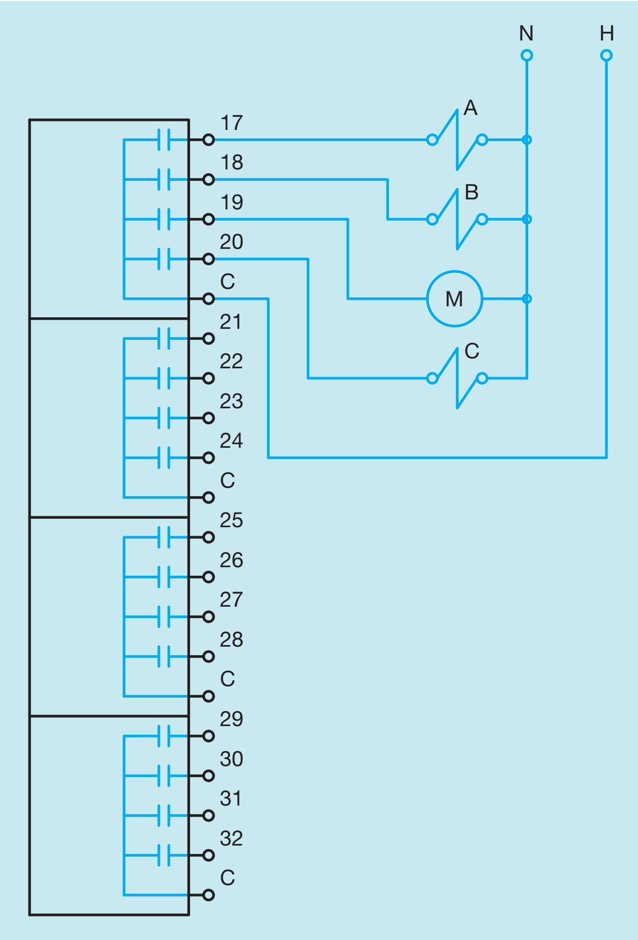


Figure 54–5 Output modules complete a circuit to connect the load to the line. (Source: Delmar/Cengage Learning.)

INPUTS	1 - 16
OUTPUTS	17 - 32
INTERNAL RELAYS	33 - 103
TIMERS AND COUNTERS	200 - 264
RETENTATIVE RELAYS	104 - 134

Figure 54–6 Numbers that correspond to specific PLC functions. (Source: Delmar/Cengage Learning.)

Converting the Program

Developing a program for a programmable logic controller is a little different than designing a circuit with relay logic. There are several rules that must be followed with almost all programmable logic controllers:

1. Each line of logic must end with a coil.
2. Coils cannot be connected in parallel.
3. The program will be scanned in the order that it is entered.
4. Generally, coils cannot be assigned the same number. (Some programmable logic controllers require reset coils to reset counters and timers. These reset coils can be assigned the same number as the counter or timer they reset.)

The first two lines of logic for the circuit shown in Figure 54–2 can be seen in Figure 54–7. Notice that contact symbols are used to represent inputs instead of logic symbols such as push buttons, float switches, etc. The programmable logic controller recognizes all inputs as open or closed contacts. It does not know what device is connected to which input. This is the reason that you must first determine which devices connect to which input before a program can be developed. Also notice that input #1 is shown as a normally open contact. Referring to Figure 54–4, it can be seen that input #1 is connected to a normally closed push button. The input is programmed as normally open because the normally closed push button will supply a high voltage to input #1 in normal operation. Since input #1 is in a high state, the PLC will change the state of the open contact and consider it closed. When the STOP push button is pressed, the input voltage will change to low and the PLC will change the contact back to its original open state and cause coil 33 to de-energize.

Referring to the schematic in Figure 54–2, a control relay is used as part of the circuit logic. Since the control relay does not directly cause any output device to turn on or off, an internal relay will be used. The chart in Figure 54–6 indicates that internal relays number between 33 and 103. Coil #33 is an internal relay and does

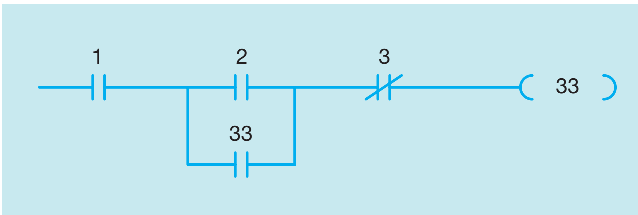


Figure 54–7 Lines 1 and 2 of the program. (Source: Delmar/Cengage Learning.)

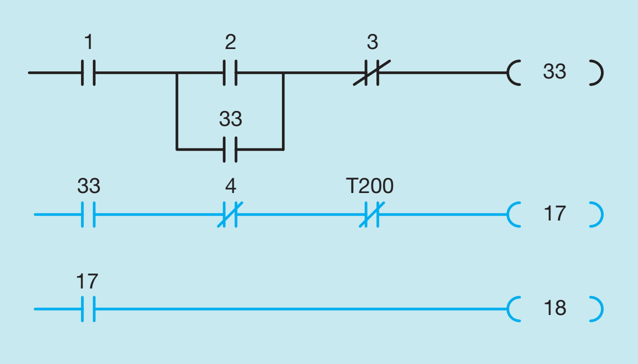


Figure 54–8 Lines 3 and 4 of the circuit are added. (Source: Delmar/Cengage Learning.)

not physically exist. Any number of contacts can be assigned to this relay and they can be open or closed. The #33 contact connected in parallel with input #2 is the holding contact, labeled CR-1 in Figure 54–2.

The next two lines of logic are shown in Figure 54–8. The third line of logic in the schematic in Figure 54–2 contains a normally open CR-2 contact, a normally closed float switch contact, a normally closed on-delay timed contact and solenoid coil A. The fourth line of logic contains solenoid coil B connected in parallel with solenoid coil A. Line 3 in Figure 54–8 uses a normally open contact, assigned the number 33 for contact CR-2. A normally closed contact symbol is assigned the number 4. Since the float switch is connected to input #4, it will control the action of this contact. As long as input #4 remains in a low state, the contact will remain closed. If the float switch should close, input #4 will become high and the number 4 contact will open. The next contact is timed contact TR-1. The chart in Figure 54–6 indicates that timers and counters are assigned numbers 200 through 264. In this circuit, timer TR will be assigned #200. Line 3 ends with coil #17. When coil 17 becomes energized, it will turn on output 17 and connect solenoid coil A to the line.

The schematic in Figure 54–2 shows that solenoid coil B is connected in parallel with solenoid coil A. Programmable logic controllers do not permit coils to be connected in parallel. Each line of logic must end with its own coil. Since solenoid coil B is connected in parallel with A, they both operate at the same time. This logic can be accomplished by assigning an internal contact the same number as the coil controlling output 17. Notice in Figure 54–8 that when coil 17 energizes it will cause contact 17 to close and energize output 18 at the same time.

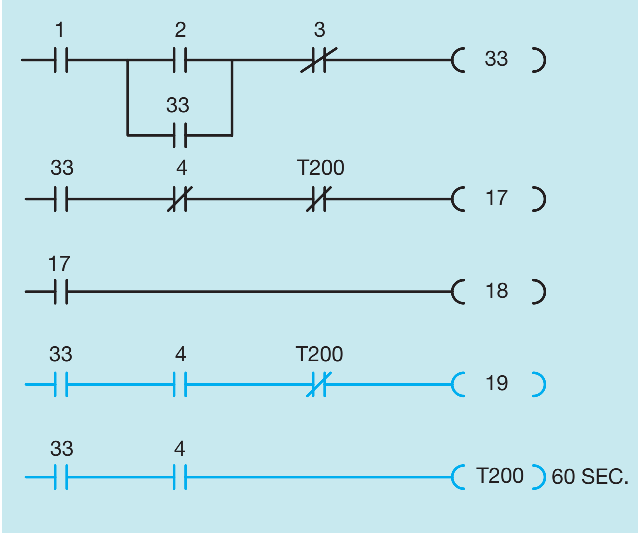


Figure 54–9 Lines 5 and 6 are added to the program. (Source: Delmar/Cengage Learning.)

In Figure 54–9, lines 5 and 6 of the schematic are added to the program. A normally open contact assigned number 33 is used as contact CR-3. A normally open contact assigned the number 4 is controlled by the float switch, and a second normally closed timed contact controlled by timer 200 is programmed in line 5. The output coil is assigned the number 19. When this coil energizes, it turns on output 19 and connects motor starter coil M to the line.

Line 6 contains timer coil TR. Notice in Figure 54–2 that coil TR is connected in parallel with contact TR-2 and coil M. As was the case with solenoid coils A and B, coil TR cannot be connected in parallel with coil M. According to the schematic in Figure 54–2, coil TR is actually controlled by contacts CR-3 and the normally open float switch. This logic can be accomplished as shown in Figure 54–9 by connecting coil T200 in series with contacts assigned the numbers 33 and 4. float switches do not normally contain this many contacts, but since the physical float switch is supplying a high or low voltage to input 4, any number of contacts assigned the number 4 can be used.

The last line of the program is shown in Figure 54–10. A normally open contact assigned the number 33 is used for contact CR-4, and a normally open contact controlled by timer T200 is used for the normally open timed contact labeled TR-3. Coil 20 controls the operation of solenoid coil C.

The circuit shown in Figure 54–2 has not been converted to a program that can be loaded into a pro-

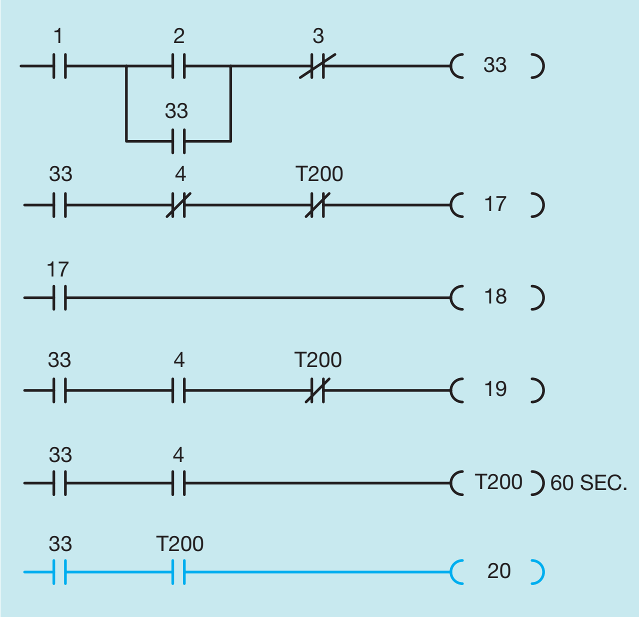


Figure 54–10 Line 7 of the program. (Source: Delmar/Cengage Learning.)

grammable logic controller. The process is relatively simple if the rules concerning PLCs are followed.

Programming in Boolean

The preceding example circuit was developed for one specific type of programmable controller. It was intended as an example of how to develop and enter a program into the logic of the CPU using a programmable terminal similar to the one shown in Figure 54–4. There may be times when it is necessary to use a small programming device that is hand held or that attaches directly to the CPU when entering a program. A unit of this type is shown in Figure 54–11. This programming unit can be used with the SERIES ONE group of programmable controllers manufactured by GE Fanuc Automation. The following program will be developed for entry into the SERIES ONE using the handheld programmer.

Developing the Program

The following program will be used as a trouble annunciator: A pressure switch is to be connected to the input of a programmable controller. When the pressure rises to a preset point, an audible alarm will be sounded and a warning light will flash off and on. When the operator acknowledges the trouble, the audible alarm will be silenced, but the warning light will continue to flash on and off until the pressure returns to a safe level.

Parameters of the Programmable Controller

Before the program can be developed, the parameters of the programmable controller being used must be known. Because the SERIES ONE programmable controller is being used in this example, its parameters will be discussed. An operations and programming guide for the SERIES ONE is shown in Figure 54–12. All coil and I/O references must be entered in *OCTAL*. *OCTAL* is a number system that contains only eight digits, 0 through 7. The numbers 8 and 9 are not used because they do not exist as far as the computer is concerned. This does not mean that the numbers 8 and 9 cannot be used when entering times for a timer, it applies only to the way inputs, outputs, and internal relays are identified. For example, any programmable controller that is octal base will not use the numbers 8 or 9. The I/O points for this unit are 000 through 157. Assume the first I/O module used with this controller contains eight units, and these eight units are inputs. The inputs will number from 0 to 7. Now, assume the next set of I/Os is an output module. Numbers 10 through 17 can be used as an output. Notice that numbers 8 and 9 are omitted. The programming guide indicates that a total of 144 internal coils exists. Coils 160 through 337 are nonretentive and coils 340 through 373 are retentive. There are a total of 64 timers and counters, which begin with 600 and go through 677. Remember that there are no 8s or 9s. After timer 607 is used, the next timer will be 610.

The circuit shown in Figure 54–13 will be programmed into the controller using the small programming unit. The contacts labeled 0 and 1 are inputs. Contact 0 is connected to the normally open pressure switch, which is used to sense the high pressure condition. Contact 1 is connected to the normally open push button used to acknowledge the fault and to turn off the audible alarm. Coils 10 and 11 are outputs. Coil 10 is connected to the warning light and coil 11 is connected to the audible alarm. Coils T600 and T601 are timers used to produce the flashing action of the warning light. In this circuit, the warning light will be on for 0.5 second and off for 0.5 second. Coil 160 is an internal relay.

Figure 54–11 Small programming unit attaches directly to the PLC. (Source: Delmar/Cengage Learning.)

Operation of the Circuit

The circuit operates in the following manner: When the pressure switch closes, all 0 inputs change position. This provides a current path to timer T600, which begins timing. A current path is provided to output 10, which turns on the warning light, and a current path is provided to the audible alarm, turning it on. The normally open 0 contact connected in series with coil 160 closes. At the end of a half second, timer T600 times out and changes the position of all T600 contacts. The normally closed contact connected in series with the warning light opens and turns off output 10. The normally open T600 contact closes and permits timer T601 to begin timing. At the end of a half second, timer T601 opens its normally closed contact connected in series with timer T600. This causes timer T600 to reset and return all of its contacts to their

MEMORY TYPE	VALID REFERENCES (OCTAL)	QUANTITY (DECIMAL)
	SERIES ONE	
I/O Points	000-157	112 total
Internal Coils		144 total
Non-Retentive	160-337	112
Retentive Coils	340-373	28
Initial Reset	374	1
O.I. Second Clock	375	1
Disable All Outputs	376	1
Back-Up Battery Status	377	1
Shift Registers	400-577	128 steps
Timer/Counters	600-677	64 (1)
Sequencers	600-677	64 (1000 steps)
	SERIES ONE PLUS	
I/O Points	000-157 700-767	168 total
Internal Coils		144 total
Non-Retentive	160-337	112
Retentive Coils	340-373	28
Initial Reset	374	1
O.I. Second Clock	375	1
Disable All Outputs	376	1
Back-Up Battery Status	377	1
Shift Registers	400-577 (2)	128 steps
Timer/Counters	600-677	64 (1)
Sequencers	600-677	64 (1000 steps)
Data Registers	400-577 (2)	64 (16-bit)

(1) Total maximum number of Timers and/or Counters
(2) Shift register and data register references are identical, however, shift registers operate on bits, while data registers (located in a totally different area of memory) operate on bytes

MODE SWITCH	
POSITION	FUNCTION
RUN	CPU scans logic, outputs enabled
PROG	Enter/Edit logic, no scanning
LOAD	Controls transfer to and from external device (recorder, printer, PROM writer)

STATUS INDICATORS	
ON/OFF	Operating state of I.O. internal coils or shift registers.
RUN	ON=CPU in RUN mode
BATT	ON=Lithium battery voltage low
PWR	ON=Power supply DC voltage normal
CPU	ON=CPU internal fault Watchdog timer timed out low DC voltage

LOGIC AND EDITING KEYS

KEY	DESCRIPTION
F	(Series One Plus Only) Entered before a 2-digit number to select a data operation.
R	(Series One Plus Only) Entered before a 3-digit data register or 2-digit group reference when programming data operations.
AND	Places logic in series with previous logic.
OR	Places logic in parallel with previous logic.
STR	Starts a new line or group of logic.
NOT	Specifies a normally closed contact when used with AND/OR.
OUT	Ends line of logic with a coil, can be an output.
TMR	Specifies a timer function.
CNT	Specifies a counter function.
SR	Specifies a shift register function.
MCS	Begins a master control relay function.
MCR	Ends a master control relay function.
SET	Specifies a latched coil or used to force an I/O reference on.
RST	Turns off a latched coil or forces an I/O reference off.
DEL	Included in sequence for removing (deleting) an instruction from program memory.
INS	Included in sequence for adding (inserting) an instruction in program memory.
ENT	Causes logic to be placed in program memory.
CLR	Removes (clears) previous logic entry, acknowledges error codes, causes memory address to be displayed when monitoring a program.
SHF	Selects shifted functions (upper label above keys).
SCH	Used when initiating a search function.
PRV	Selects previous logic or function, and when monitoring, selects the previous group of 8 references.
NXT	Selects the next logic function. When monitoring, selects the next group of 8 references.
0 to 9	SHIFTED FUNCTION. Selects numerical values.
•	SHIFTED FUNCTION. Selects decimal point when entering numerical values, (timers using XXX.X seconds).
MON	SHIFTED FUNCTION. Selects monitor operation.
CHECK	SHIFTED FUNCTION. Initiates verify operation with peripheral.
READ	SHIFTED FUNCTION. Initiates loading of CPU memory from a peripheral.
WRITE	SHIFTED FUNCTION. Initiates writing (recording) program in CPU memory to a peripheral.

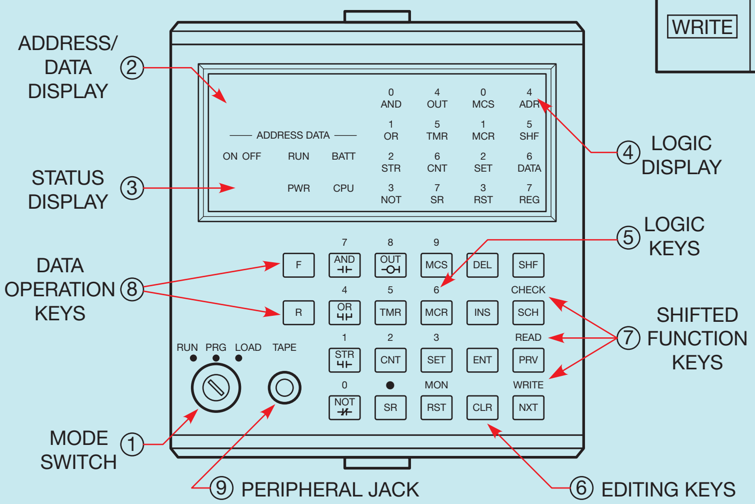


Figure 54–12 Programming guide for a SERIES ONE programmable controller. (Courtesy GE Fanuc Automation North America Inc.)

PROGRAMMER OPERATION

OPERATION	KEYSTROKES	MODE* R	P	L
Clear all memory.	CLR SHF 0 0 0 DEL NXT		X	
Display present address.	CLR	X	X	
Display present function.	NXT	X	X	
Next function.	NXT	X	X	
Previous function.	PRV	X	X	
Go to first function in program memory (address 0000).	SHF NXT	X	X	
Go to specific memory address.	SHF (Address) NXT	X	X	
Search for a specific function.	(Function) SHF (Ref.No.) SCH NXT	X	X	
Search for a specific reference number.	SHF (Ref. No.) SCH NXT	X	X	
Insert function before the displayed function (or address).	(Function) SHF (Ref.No.) INS NXT		X	
Delete function.	(Address) DEL PRV		X	
Edit a program.	(Address) (Function) SHF (Ref.No.) ENT		X	
Check program for errors. If none, next empty address is displayed.	CLR SCH	X	X	
Change T/C preset.	(Address) SHF (preset) ENT	X		
Mon. ON/OFF state of contact or coil.	Observe ON/OFF LED when coil or contact is selected.	X		
Monitor group of 8 consecutive references (I/O, internal coils, SR coils).	SHF (Beginning Ref.No.) MON	X		
Monitor timer or counter accumulate register.	SHF (T/C No.) MON	X		
Force a reference ON (will be overridden by user logic).	SET SHF (Ref.No.) ENT	X		
Force a reference OFF (will be overridden by user logic).	RST SHF (Ref.No.) ENT	X		
Enter a function into program memory.	(Function) SHF (Ref.No.) ENT		X	
Write to tape, printer, or PROM writer.	(Optional Program ID) WRITE			X
Load program memory from tape.	(Optional Program ID) READ			X
Verify data on tape or in PROM writer RAM against program memory.	(Optional Program ID) WRITE			X

*R=RUN, P=PROGRAM, L=LOAD

Figure 54–12 *continued*

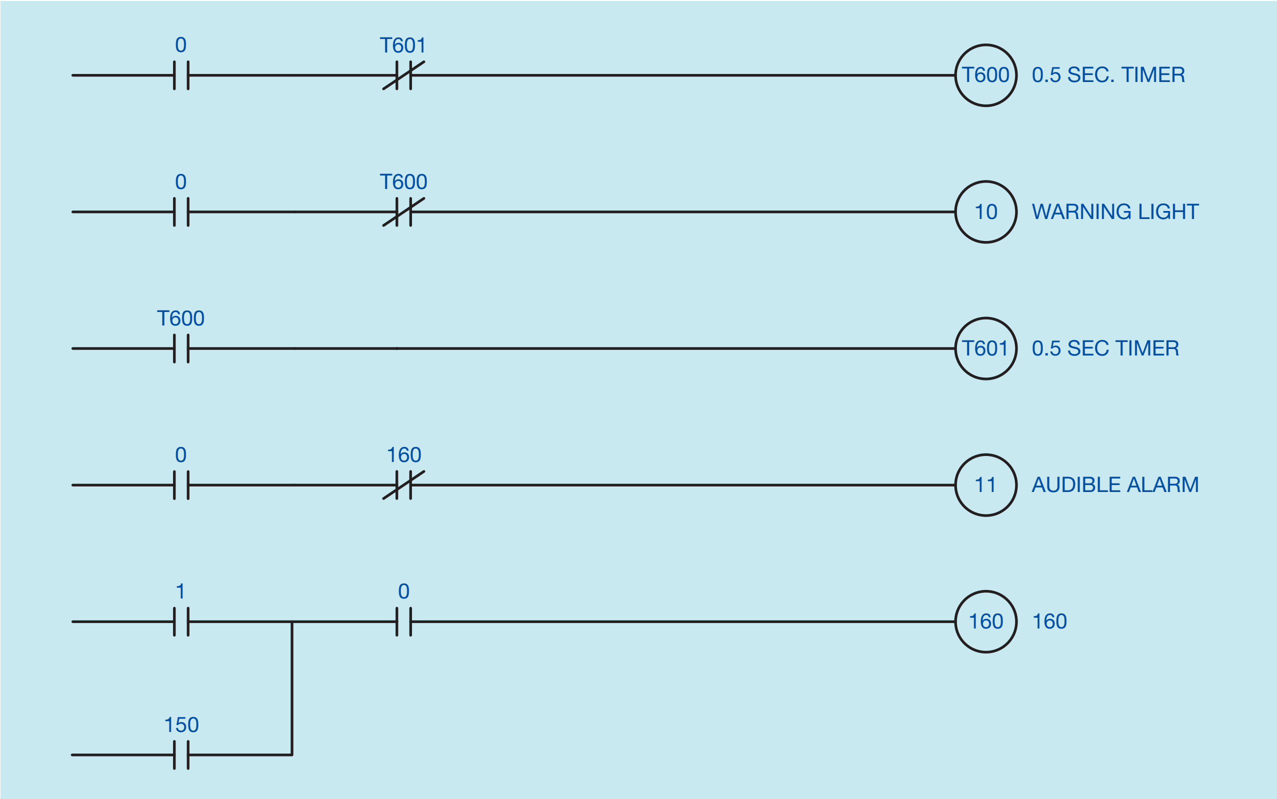


Figure 54–13 Warning light and alarm circuit. (Source: Delmar/Cengage Learning.)

normal position. The normally closed T600 contact permits output 10 to turn on again, and the normally open T600 contact resets timer T601. When timer T601 resets, its contact returns to its normal position, and timer T600 begins timing again.

This condition continues until the operator presses the acknowledge button, causing input contact 1 to close. Contact 1 completes a current path to internal relay 160. When internal relay 160 energizes, the normally open 160 contact closes and seals the circuit around contact 1. The normally closed 160 contact opens and turns off the audible alarm. At this time in the circuit, the audible alarm has been turned off, but the warning light is flashing on and off at half-second intervals. This will continue until the pressure drops to a safe level and input 0 reopens all of its contacts, causing the circuit to reset to its normal position.

Entering the Program

Now that the circuit has been developed, it must be entered into the memory of the CPU. When using a small programming terminal as shown in Figure 54–11, the program must be entered in a language called *Boolean.* When programming in Boolean, to connect one contact in series with another, the AND function must be used. To connect a contact in parallel with another, the OR function is used. To change a contact from open to closed, the NOT function is used. To start a line of the program, the STR function must be used. To end a line of the program, the OUT function is used except when programming a special function such as a timer or counter. When ending a line of the program with a timer, the TMR function is used; when ending the line with a counter, the CNT function is used. Each component of the program must be entered into memory using the ENT key. Some of the keys on this programming unit use serve two functions. The AND key, for example, is also used to enter the number 7 into the program. The NOT key is also used to enter the number 0 into the program. The second function keys are very similar to the dual purpose keys on a typewriter where the shift key is used to access the second function of a key. The same is true for this unit. The SHF key is used to cause the keys to perform their second function.

Once the SHF key has been pressed, it will remain in effect until the ENT key is pressed. There is no need to hold the SHF key down when entering more than one digit into the program.

The first line of logic will be entered as follows:

STR SHF 0 ENT
AND NOT TMR SHF 601 ENT
TMR SHF 600 ENT
SHF .5 ENT

Notice that the STR command is used to start the line of logic. The SHF key must be pressed in order to permit the number 0 to be entered. The ENT command causes that instruction to be entered into the logic of the CPU. The AND function causes the next contact entered to be connected in series with the first contact, and the NOT command instructs the CPU that the contact is to be normally closed instead of normally open. The TMR command instructs the programmable controller that the contact is to be controlled by a timer. Since this line of logic is ended with a timer instead of a normal output or internal relay, the TMR command is used again to instruct the CPU that the last coil is a timer and not an internal relay or output. The CPU can interpret this last timer command to be a coil instead of a contact because directly following this command, the time of the timer had been entered instead of a tie command such as AND or OR. The time is entered with the use of a decimal point in this controller instead of assuming each time interval to be 0.1 second. Different programmable controllers use different methods to enter the time.

The second line of logic is entered as follows:

STR SHF 0 ENT
AND NOT TMR SHF 600 ENT
OUT SHF 10 ENT

The third line of logic is entered as follows:

STR TMR SHF 600 ENT
TMR SHF 601 ENT
SHF .5 ENT

The fourth line of logic is entered as follows:

STR SHF 0 ENT
AND NOT SHF 160 ENT
OUT SHF 11 ENT

The fifth and sixth lines of logic will be entered together because the sixth line of logic is connected in parallel with the fifth:

STR SHF 1 ENT
OR SHF 160 ENT
AND SHF 0 ENT
OUT SHF 160 ENT

This completes the programming of the circuit into the CPU.

Review Questions

1. Why are NEMA symbols representing such components as push buttons, limit switches, and float switches not used in a programmable controller schematic?
2. Explain how to program an internal relay into the controller.
3. Why are the contacts used to represent stop buttons and overload contacts programmed normally open?
4. Why is the output I/O used to energize a motor starter instead of energizing the motor directly?
5. A timer is to be programmed for a delay of 3 minutes. What number is used to set this timer?
6. When programming in Boolean, what command is used to connect two circuit components together in series?
7. When programming in Boolean, what command is used to connect two circuit components together in parallel?
8. When programming in Boolean, what command is used to change a contact from normally open to normally closed?
9. Why are the numbers 8 and 9 not used in an *OCTAL* based system?

CHAPTER 55

ANALOG SENSING FOR PROGRAMMABLE CONTROLLERS

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the differences between analog and digital inputs.
- Discuss precautions that should be taken when using analog inputs.
- Describe the operation of a differential amplifier.

Many of the programmable controllers found in industry are designed to accept analog as well as digital inputs. Analog means continuously varying. These inputs are designed to sense voltage, current, speed, pressure, temperature, humidity, etc. When an analog input is used, a special module mounts on the I/O Rack of the PLC. An analog sensor may be designed to operate between a range of settings, such as 50 to 300 C°, or 0 to 100 psi. These sensors are used to indicate between a range of values instead of merely operating in an on or off mode. An analog pressure sensor designed to indicate pressures between 0 and 100 psi would have to indicate when the pressure was 30 psi, 50 psi, or 80 psi. It would not just indicate whether the pressure had or had not reached 100 psi. A pressure sensor of this type can be constructed in several ways. One of the most common methods is to let the pressure sensor operate a current generator which produces currents between 4 and 20 milliamperes. It is desirable for the sensor to produce a certain amount of current instead of a certain amount of voltage because it eliminates the problem of voltage drop on lines. For example, assume a pressure sensor is designed to sense pressures between 0 and 100 psi. Also assume that the sensor produces a voltage output of 1 volt when the pressure is 0 psi and a voltage of 5 volts when the pressure is 100 psi. Since this is an analog sensor, when the pressure is 50 psi, the sensor should produce a voltage of 3 volts. This sensor is connected to the analog input of a programmable controller (Figure 55–1). The analog input has a sense resistance of 250 ohms. If the wires between the sensor and the input of the programmable controller are short enough (so that there is almost no wire resistance), the circuit will operate without a problem. Because the sense

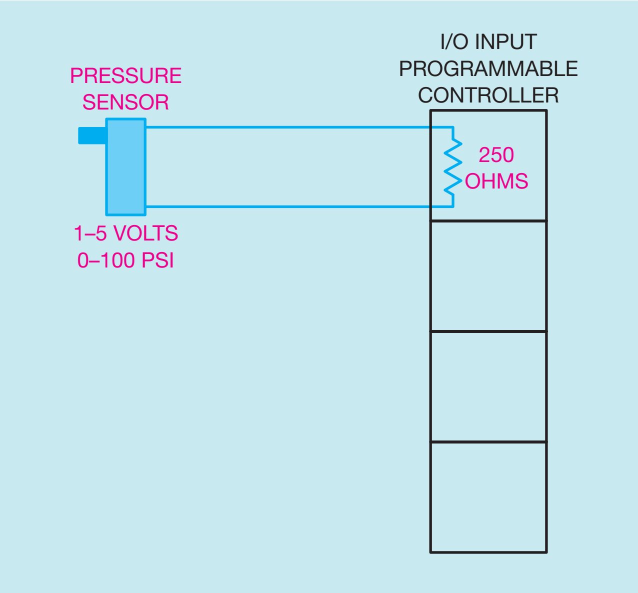


Figure 55–1 The pressure sensor produces one to five volts. (Source: Delmar/Cengage Learning.)

resistor in the input of the programmable controller is the only resistance in the circuit, all of the output voltage of the pressure sensor will appear across it. If the pressure sensor produces a 3 volt output, 3 volts will appear across the sense resistor.

If the pressure sensor is located some distance away from the programmable controller, however, the resistance of the two wires running between the pressure sensor and the sense resistor can cause inaccurate readings. Assume that the pressure sensor is located far enough from the programmable controller so that the two conductors have a total resistance of 50 ohms (Figure 55–2). This means that the total resistance of the circuit is now 300 ohms (250 + 50 = 300). If the pressure sensor produces an output voltage of 3 volts when the pressure reaches 50 psi, the current flow in the circuit will be 0.010 ampere (3/300 = 0.010). Since there is a current flow of 0.010 through the 250 ohms sense resistor, a voltage of 2.5 volts will appear across it. This is substantially less than the 3 volts being produced by the pressure sensor.

If the pressure sensor is designed to operate a current generator with an output of 4 to 20 milliamperes, the resistance of the wires will not cause an inaccurate reading at the sense resistor. Since the sense resistor and the resistance of the wire between the pressure sensor and the programmable controller form a series circuit, the current must be the same at the point in the circuit. If the pressure sensor produces an output current of 4 milliamperes when the pressure is 0 psi and a current of 20 milliamperes when the pressure is 100 psi, at 50 psi it will produce a current of 12 milliamperes. When a current of 12 milliamperes flows through the 250 sense resistor, a voltage of 3 volts will be dropped across it (Figure 55–3). Because the pressure sensor

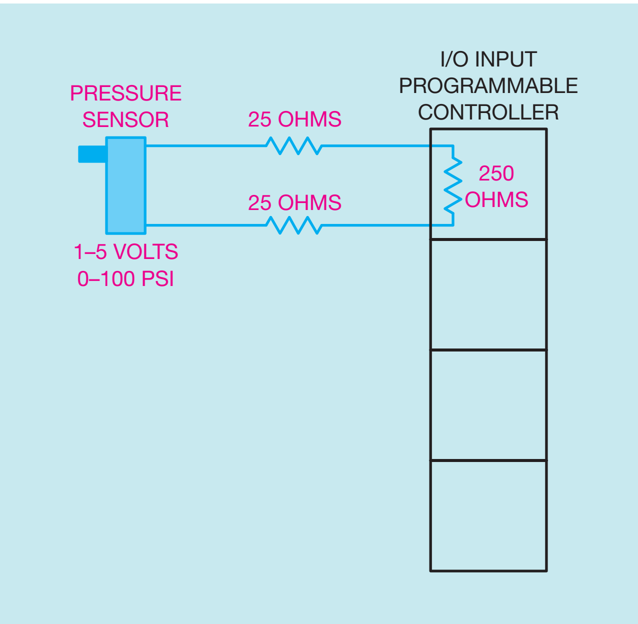


Figure 55–2 Resistance in the lines can cause problems. (Source: Delmar/Cengage Learning.)

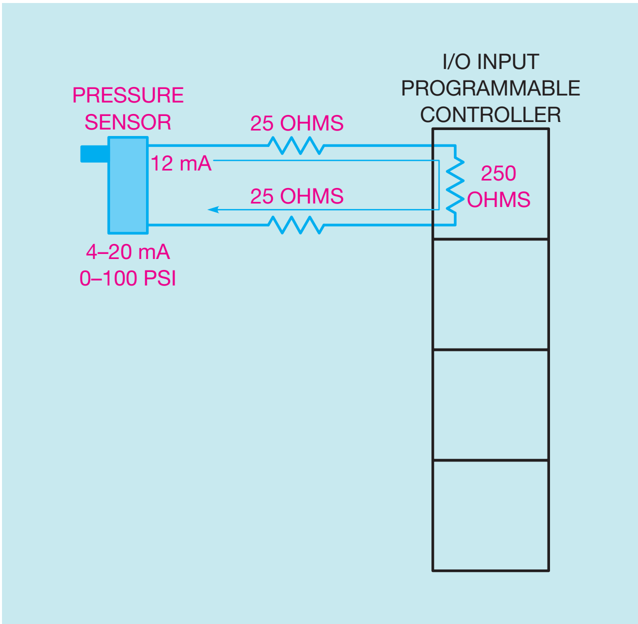


Figure 55–3 The current must be the same in a series circuit. (Source: Delmar/Cengage Learning.)

produces a certain amount of current instead of a certain amount of voltage with a change in pressure, the amount of wire resistance between the pressure sensor and programmable controller is of no concern.

Installation

Most analog sensors can produce only very weak signals—0 to 10 volts or 4 to 20 milliamperes are common. In an industrial environment where intense magnetic fields and large voltage spikes abound, it is easy to lose the input signal in the electrical noise. For this reason, special precautions should be taken when installing the signal wiring between the sensor and the input module. These precautions are particularly important when using analog inputs, but they should also be followed when using digital inputs.

Keep Wire Runs Short

Try to keep wire runs as short as possible. A long wire run has more surface area of wire to pick up stray electrical noise.

Plan the Route of the Signal Cable

Before starting, plan how the signal cable should be installed. *Never run signal wire in the same conduit with power wiring.* Try to run signal wiring as far away from power wiring as possible. When it is necessary to cross power wiring, install the signal cable so that it crosses at a right angle as shown in Figure 55–4.

Use Shielded Cable

Shielded cable is used for the installation of signal wiring. One of the most common types, shown in Figure 55–5, uses twisted wires with a Mylar foil shield. The ground wire must be grounded if the shielding is to operate properly. This type of shielded cable can provide a noise reduction ratio of about 30,000:1.

Another type of signal cable uses a twisted pair of signal wires surrounded by a braided shield. This type of cable provides a noise reduction of about 300:1.

Common coaxial cable should be avoided. This cable consists of a single conductor surrounded by a braided shield. This type of cable offers very poor noise reduction.

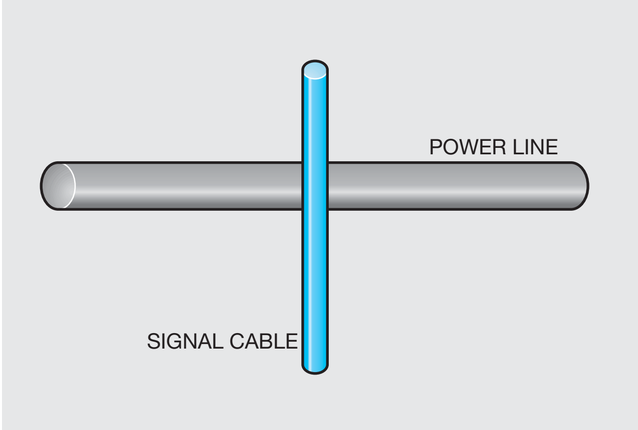


Figure 55–4 Signal cable crosses power line at right angle. (Source: Delmar/Cengage Learning.)

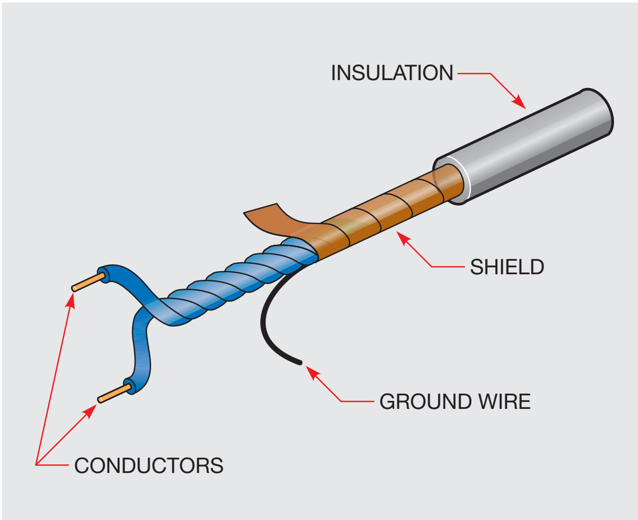


Figure 55–5 Shielded cable. (Source: Delmar/Cengage Learning.)

Grounding

Ground is generally thought of as being electrically neutral, or zero at all points. However, this may not be the case in practical application. It is not uncommon to find that different pieces of equipment have ground levels that are several volts apart (Figure 55–6).

To overcome this problem, large cable is sometimes used to tie the two pieces of equipment together. This forces them to exist at the same potential. This method is sometimes referred to as the brute-force method.

Where the brute-force method is not practical, the shield of the signal cable is grounded at only one end. The preferred method is generally to ground the shield at the sensor.

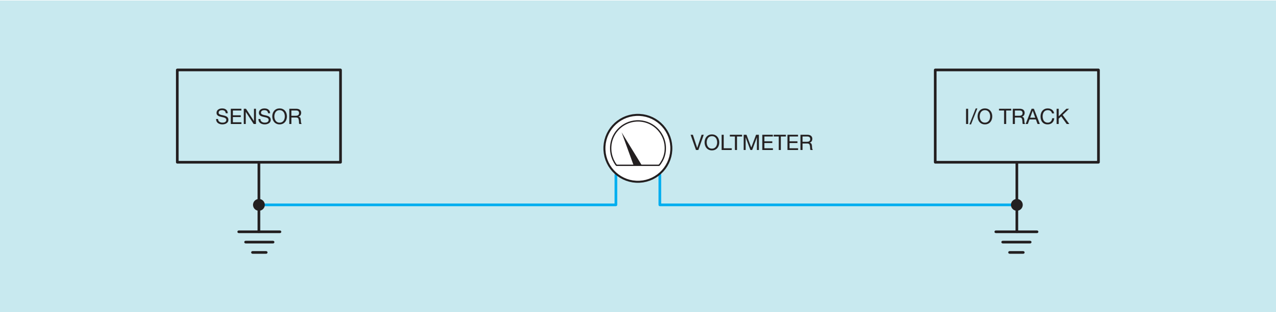


Figure 55–6 All grounds are not equal. (Source: Delmar/Cengage Learning.)

The Differential Amplifier

An electronic device that is often used to help overcome the problem of induced noise is the differential amplifier (Figure 55–7). This device detects the voltage difference between the pair of signal wires and amplifies this difference. Since the induced noise level should be the same in both conductors, the amplifier will ignore the noise. For example, assume an analog sensor is producing a 50 millivolt signal. This signal is applied to the input module, but induced noise is at a level of 5 volts. In this case, the noise level is 100 times greater than the signal level. The induced noise level, however, is the same for both of the input conductors. Therefore, the differential amplifier ignores the 5 volt noise and amplifies only the voltage difference, which is 50 millivolts.

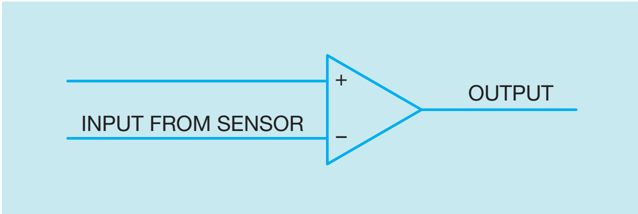


Figure 55–7 Differential amplifier detects difference in signal level. (Source: Delmar/Cengage Learning.)

Review Questions

1. Explain the difference between digital inputs and analog inputs.
2. Why should signal wire runs be kept as short as possible?
3. When signal wiring must cross power wiring, how should the wires be crossed?
4. Why is shielded wire used for signal runs?
5. What is the brute-force method of grounding?
6. Explain the operation of the differential amplifier.

CHAPTER 56
SEMICONDUCTORS

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the atomic structure of conductors, insulators, and semiconductors.
- Discuss how a P-type material is produced.
- Discuss how an N-type material is produced.

Many of the control systems used in today's industry are operated by solid-state devices as well as magnetic and mechanical devices. To install and troubleshoot control systems, an electrician must have an understanding of electronic control devices as well as relays and motor starters. Solid-state devices, such as diodes and transistors, are often called *semiconductors.* The word *semiconductor* refers to the type of material used to make solid-state devices. To understand how solid-state devices operate, one must first study the atomic structure of conductors, insulators, and semiconductors.

Conductors

Conductors are materials that provide easy paths for the flow of electrons. Conductors are generally made from materials that have large, heavy atoms. For this reason, most conductors are metals. The best electrical conductors are silver, copper and aluminum.

Conductors are also made from materials that have only one or two valence electrons in their atoms. (*Valence electrons* are the electrons in the outer orbit of an atom, Figure 56–1). An atom that has only one valence electron makes the best electrical conductor because the electron is held loosely in orbit and is easily given up for current flow.

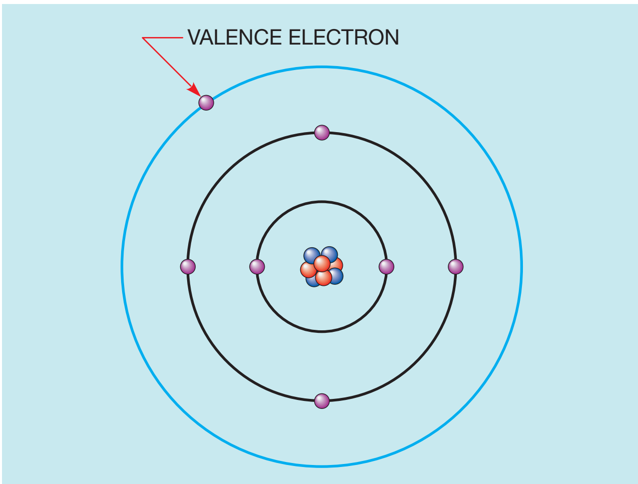


Figure 56–1 Atom of a conductor. (Source: Delmar/Cengage Learning.)

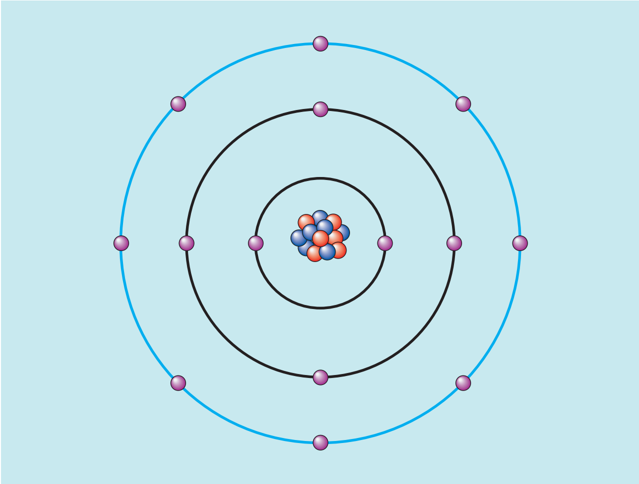


Figure 56–2 Atom of an insulator. (Source: Delmar/Cengage Learning.)

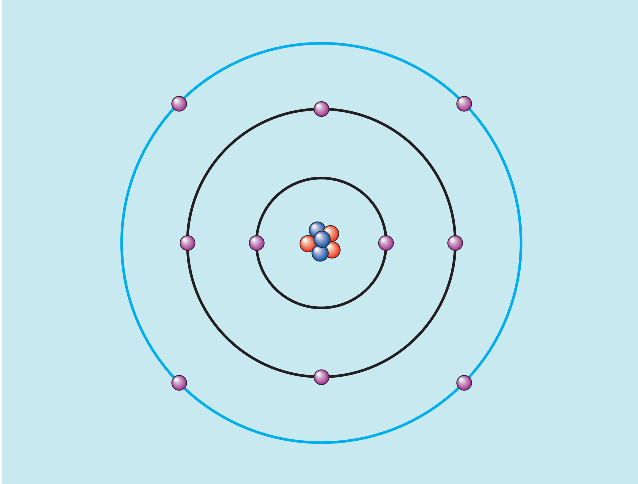


Figure 56–3 Atom of a semiconductor. (Source: Delmar/Cengage Learning.)

Insulators

Insulators are generally made from lightweight materials that have small atoms. The outer orbits of the atoms of insulating materials are filled or almost filled with valence electrons. This means an insulator will have seven or eight valence electrons as in the example in Figure 56–2. Since an insulator has its outer orbit filled or almost filled with valence electrons, the electrons are held tightly in orbit and are not easily given up for current flow.

Semiconductors

Semiconductors, as the word implies, are materials that are neither good conductors nor good insulators. Semiconductors are made from materials that have four valence electrons in their outer orbits (Figure 56–3). Germanium and silicon are the most common semiconductor materials used in the electronics field. Of these materials, silicon is used more often because of its ability to withstand heat.

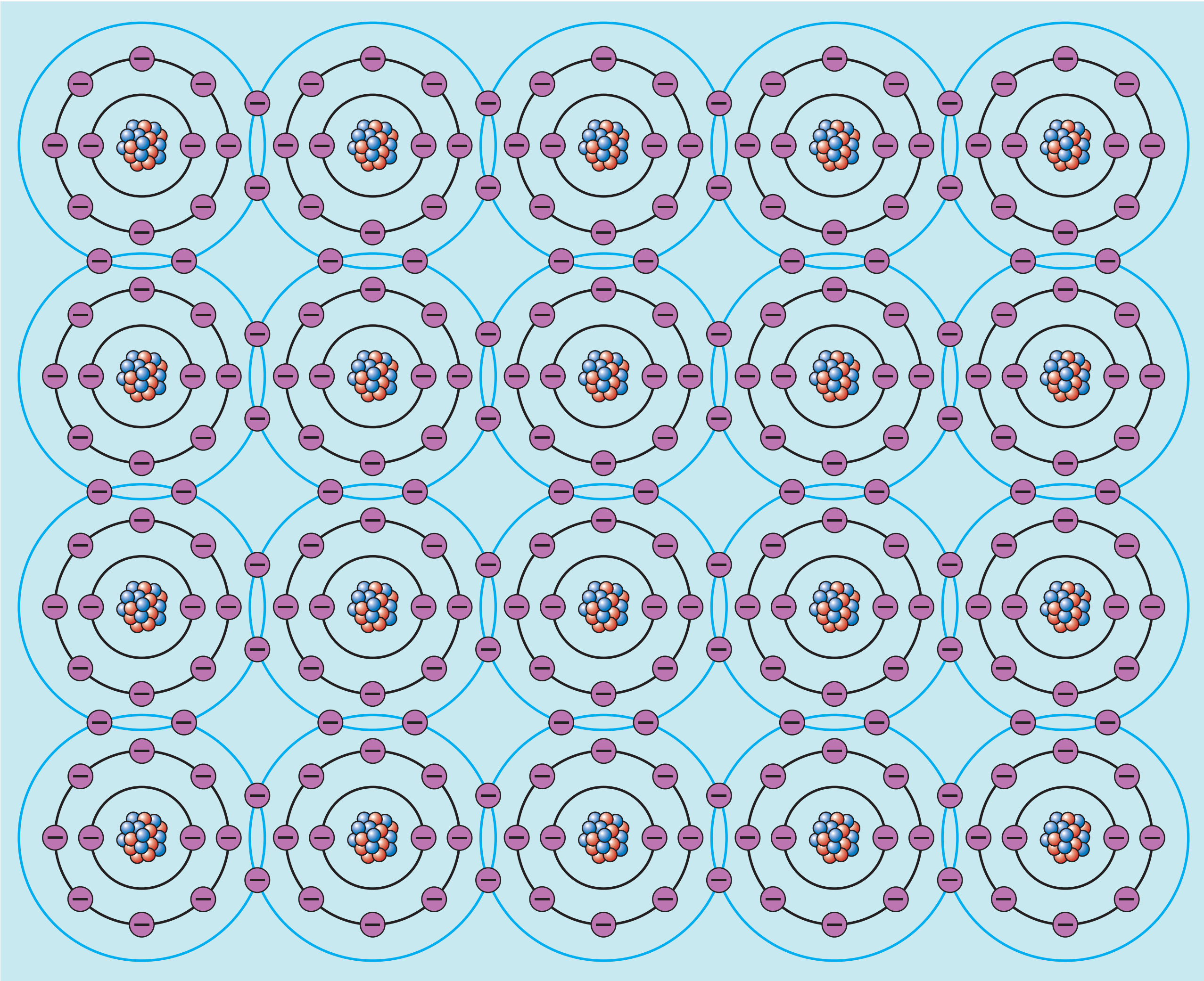


Figure 56–4 Lattice structure of a pure semiconductor material. (Source: Delmar/Cengage Learning.)

When semiconductor materials are refined into a pure form, the molecules arrange themselves into a crystal structure with a definite pattern (Figure 56–4). This type of pattern is called a *lattice structure.* A pure semiconductor material such as silicon has no special properties and will do little more than make a poor conductive material. To make semiconductor material useful in the production of solid-state components, it is

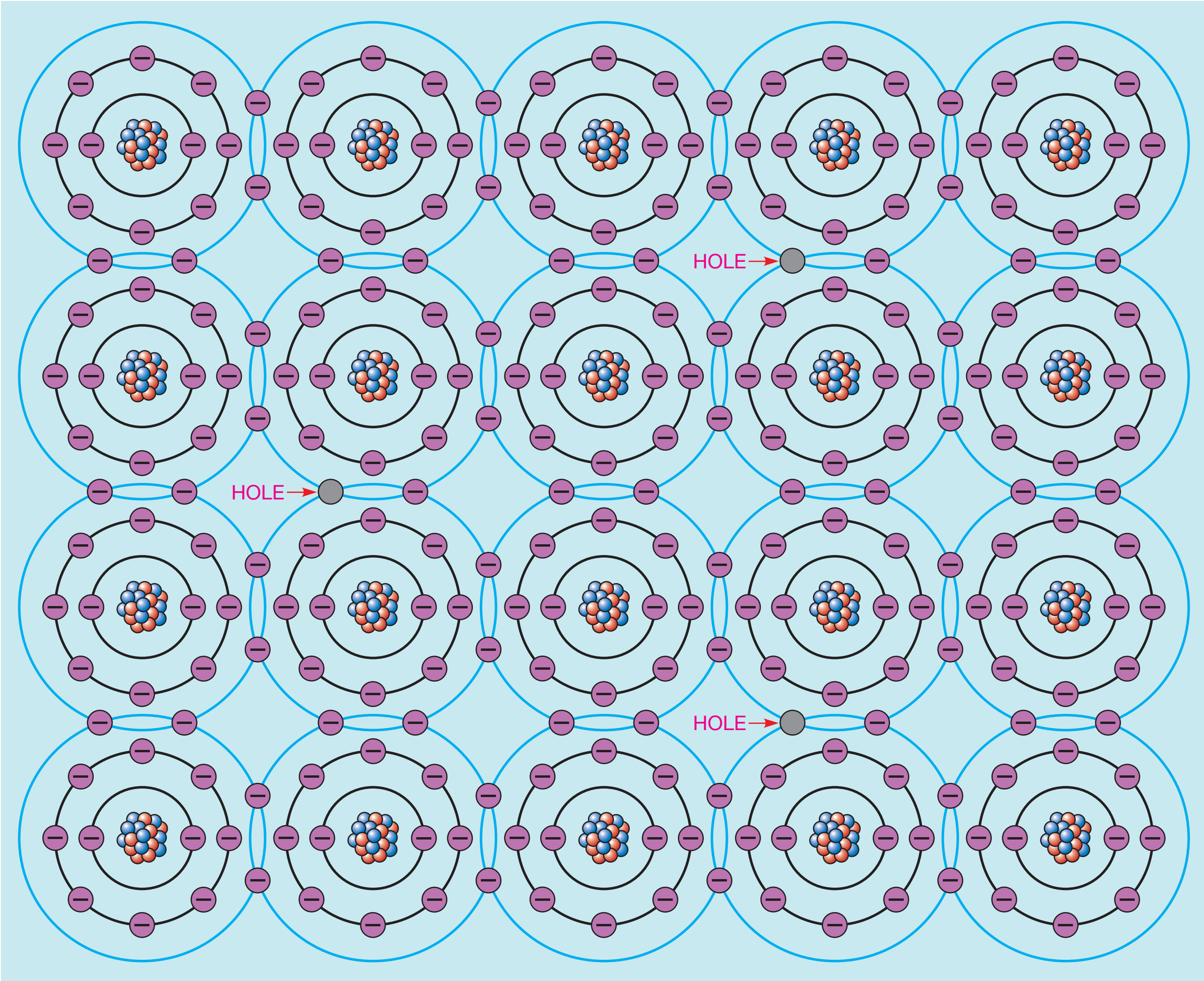


Figure 56–5 Lattice structure of a P-type material. (Source: Delmar/Cengage Learning.)

mixed with an impurity. When pure semiconductor material is mixed with an impurity that has only three valence electrons, such as indium or gallium, the lattice structure changes, leaving a hole in the material (Figure 56–5). This hole is caused by a missing electron. Since the material now lacks an electron, it is no longer electrically neutral. Electrons are negative particles. The hole, which has taken the place of an electron, has a positive charge; therefore, the semiconductor material now has a net positive charge and is called a P-type material.

When a semiconductor material is mixed with an impurity that has five valence electrons, such as arsenic or antimony, the lattice structure has an excess of electrons (Figure 56–6). Since electrons are negative particles, and there are more electrons in the material

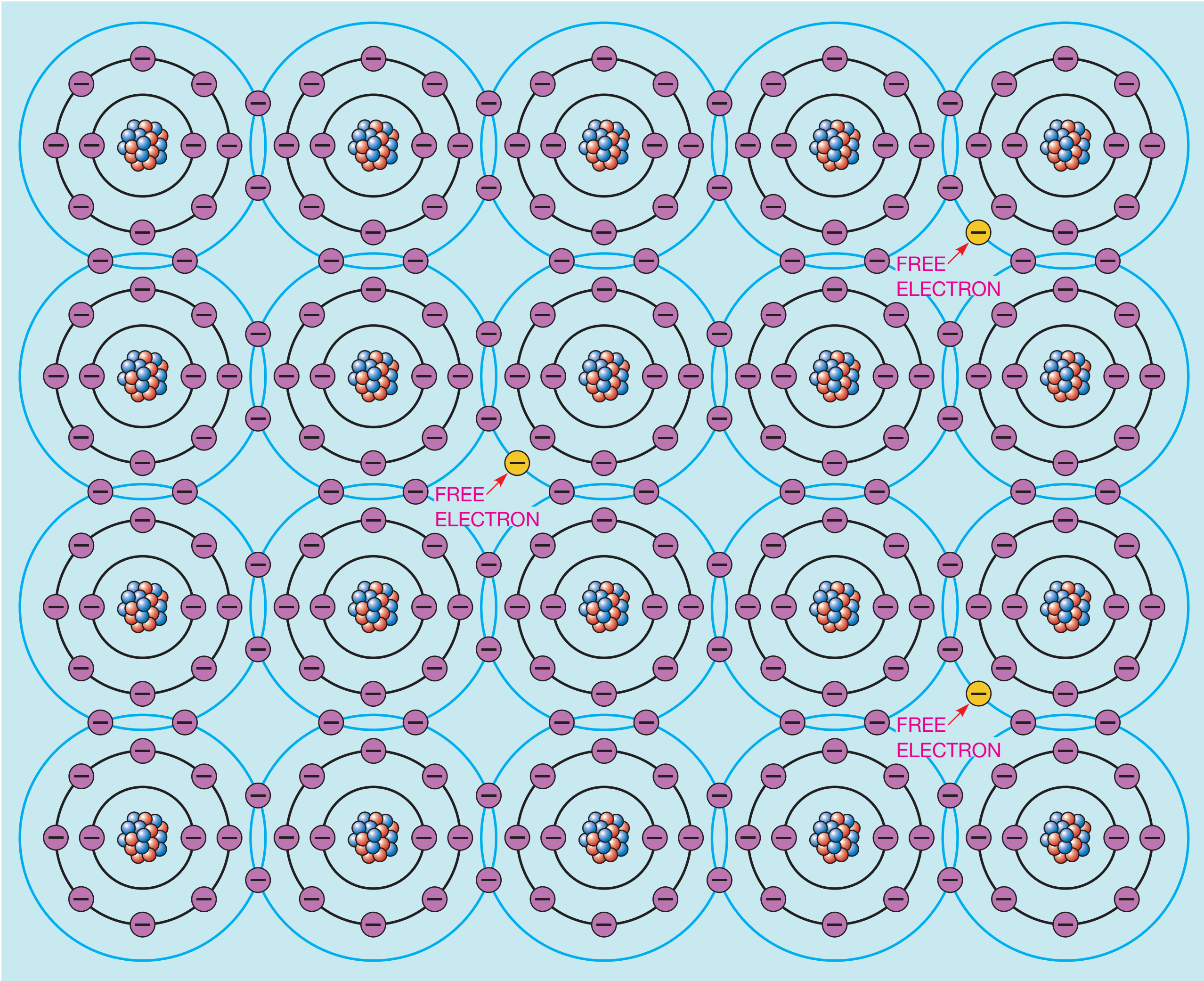


Figure 56–6 Lattice structure of an N-type material. (Source: Delmar/Cengage Learning.)

than there should be, the material has a net negative charge. This material is called an N-type material because of its negative charge.

All solid-state devices are made from combinations of P- and N-type materials. The type of device formed is determined by how the P- and N-type materials are connected. The number of layers of material and the thickness of each layer play an important part in determining what type of device is formed. For example, the diode is often called a PN junction because it is made by joining a piece of P-type material and a piece of N-type material (Figure 56–7). The transistor, on the other hand, is made by joining three layers of semiconductor materials (Figure 56–8).

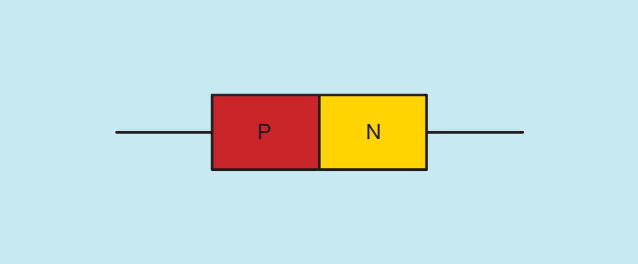


Figure 56–7 The PN junction. (Source: Delmar/Cengage Learning.)

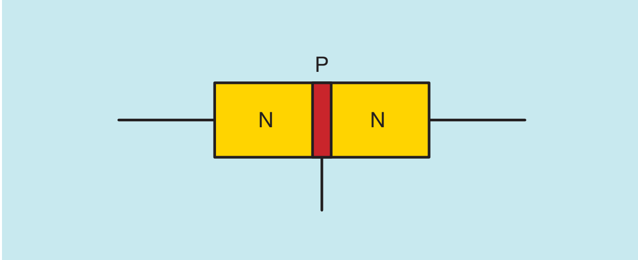


Figure 56–8 The transistor. (Source: Delmar/Cengage Learning.)

Review Questions

1. The atoms of a material used as a conductor generally contain ___________________ valence electrons.
2. The atoms of a material used as an insulator generally contain _____________________ valence electrons.
3. The two materials most often used to produce semiconductor devices are ___________________ and ____________________.
4. What is a lattice structure?
5. How is a P-type material made?
6. How is an N-type material made?
7. Which type of semiconductor material can withstand the greatest amount of heat?
8. All electronic components are formed from P-type and N-type materials. What factors determine the kind of components formed?

CHAPTER 57
THE PN JUNCTION

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss how the PN junction is produced.
- Recognize the schematic symbol for a diode.
- Discuss the differences between the conventional current flow theory and the electron flow theory.
- Discuss how the diode operates in a circuit.
- Identify the anode and cathode leads of a diode.
- Properly connect the diode in an electric circuit.
- Discuss the differences between a half-wave rectifier and a full-wave rectifier.
- Test the diode with an ohmmeter.

The PN Junction

Hundreds of different electronic devices have been produced since the invention of solid-state components. Solid-state devices are made by combining P-type and N-type materials. The device produced is determined by the number of layers of material used, the thickness of the layers of material, and the manner in which the layers are joined.

It is not within the scope of this text to cover even a small portion of these devices. The devices that are covered have been selected because of their frequent use in industry as opposed to communications or computers. These devices are presented in a straightforward, practical manner, and mathematical explanation is used only when necessary.

The PN junction is often called the *diode*. The diode is the simplest of all electronic devices. It is made by joining a piece of P-type material and a piece of N-type material (Figure 57–1). The schematic symbol for a diode is shown in Figure 57–2. The diode operates like an electric check valve in that it permits current to flow through it in only one direction. If the diode is to conduct current, it must be forward biased. The diode is forward biased only when a positive voltage is connected to the anode and a negative voltage is connected to the cathode. If the diode is reverse biased, the negative voltage connected to the anode and the

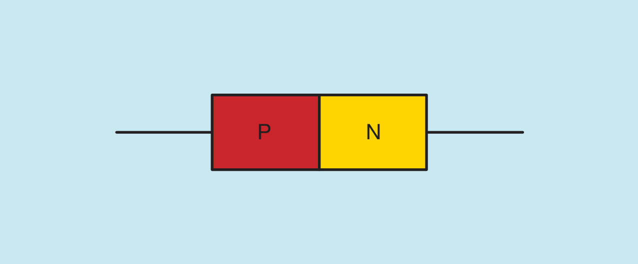


Figure 57–1 The PN junction, or diode. (Source: Delmar/Cengage Learning.)

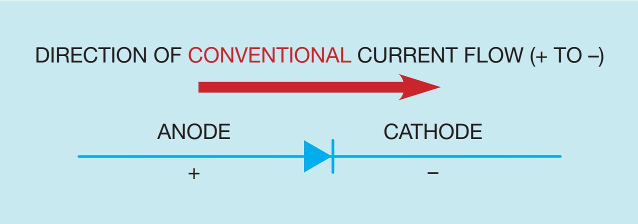


Figure 57–2 Schematic symbol for a diode. (Source: Delmar/Cengage Learning.)

positive voltage connected to the cathode, it will act like an open switch and no current will flow through the device.

When working with solid-state circuits, it is important to realize that circuits are often explained assuming conventional current flow as opposed to electron flow. *The conventional current flow theory assumes that current flows from positive to negative, while the electron flow theory states that current flows from negative to positive.* Although it has been known for many years that current flows from negative to positive, many electronic circuit explanations assume a positive to negative current flow. There are several reasons for this assumption. One reason is that ground is generally negative and is considered to be 0 volts in an electronic circuit. Any voltage above, or greater, than ground is positive. Most people find it is easier to think of something flowing downhill or from some point above to some point below. Another reason is that all of the arrows in an electronic schematic are pointed in the direction of conventional current flow. The diode shown in Figure 57–2 is forward biased only when a positive voltage is applied to the anode and a negative voltage is applied to the cathode. If the conventional current flow theory is used, current will flow in the direction the arrow is pointing. If the electron theory of current flow is used, current must flow against the arrow.

A common example of the use of the conventional current flow theory is the electrical system of an automobile. Most automobiles use a negative ground system, which means that the negative terminal of the battery is grounded. The positive terminal of the battery is considered to be the "hot" terminal, and it is generally assumed that current flows from the "hot" terminal to ground.

The diode can be tested with an ohmmeter (see Procedure 1 in the Appendix). When the leads of an ohmmeter are connected to a diode, the diode should show continuity in only one direction. For example, assume that when the leads of an ohmmeter are connected to a diode, it shows continuity. If the leads are reversed, the ohmmeter should indicate an open circuit. If the diode shows continuity in both directions, it is shorted. If the ohmmeter indicates no continuity in either direction, the diode is open.

The diode can be used to perform many jobs, but it is most commonly used in industry to construct a *rectifier.* A rectifier is a device that changes, or converts, AC voltage into DC voltage. The simplest type of rectifier is the half-wave rectifier (Figure 57–3). The half-wave rectifier can be constructed using only one diode. It gets its name from the fact that it will rectify only half of the AC waveform applied to it. When the voltage applied to the anode is positive, the diode is forward biased and current flows through the diode, the load resistor, and back to the power supply. When the voltage applied to the anode is negative, the diode is reverse biased and no current will flow. Since the diode permits current to flow through the load resistor in only one direction, the current is direct current.

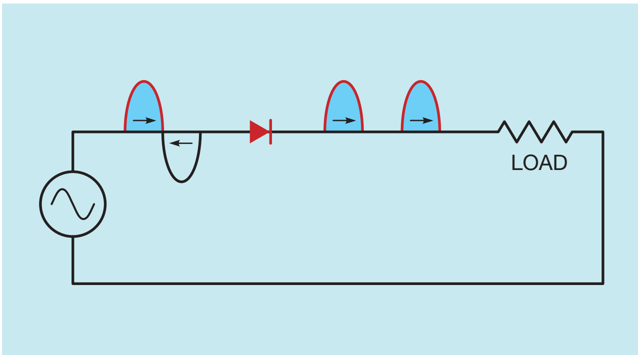


Figure 57–3 Half-wave rectifier. (Source: Delmar/Cengage Learning.)

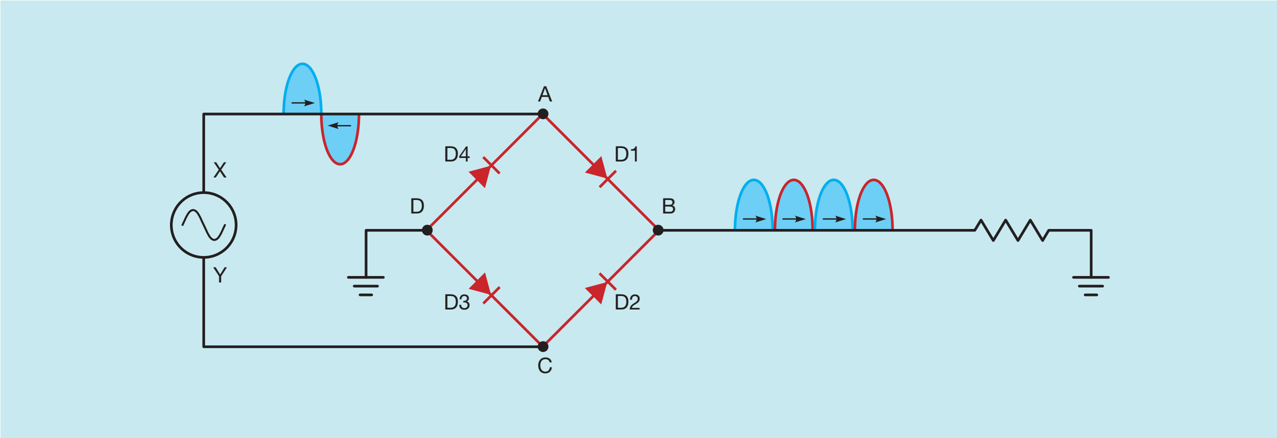


Figure 57–4 Bridge rectifier. (Source: Delmar/Cengage Learning.)

Diodes can be connected to produce full-wave rectification, which means that both halves of the AC waveform are made to flow in the same direction. One type of full-wave rectifier is the bridge rectifier (Figure 57–4). Notice that four diodes are required to construct the bridge rectifier.

To understand the operation of the bridge rectifier shown in Figure 57–4, assume that point X of the AC source is positive and point Y is negative. Current flows to point A of the rectifier. At point A, diode D4 is reverse biased and D1 is forward biased; therefore, the current flows through diode D1 to point B of the rectifier. At point B, diode D2 is reverse biased, so the current must flow through the load resistor to ground. The current returns through ground to point D of the rectifier. At point D, both diodes D3 and D4 are forward biased, but current will not flow from positive to positive. Therefore, the current flows through diode D3 to point C of the bridge, and then to point Y of the AC source, which is negative at this time. Since current flowed through the load resistor during this half cycle, a voltage developed across the resistor.

Now assume that point Y of the AC source is positive and point X is negative. Current flows from point Y to point C of the rectifier. At point C, diode D3 is reverse biased and diode D2 is forward biased. The current flows through diode D2 to point B of the rectifier. At point B, diode D1 is reverse biased, so the current must flow through the load resistor to ground. The current flows from ground to point D of the bridge. At point D, both diodes D3 and D4 are forward biased. Since current will not flow from positive to positive, the current flows through diode D4 to point A of the bridge and then to point X, which is now negative. Current flowed through the load resistor during this half cycle, so a voltage developed across the load resistor. Notice that the current flowed in the same direction through the resistor during both half cycles. Bridge rectifiers in single cases are shown in Figure 57–5.

In industry three-phase power is used more often than single-phase power. Six diodes can be connected to form a three-phase bridge rectifier that will change three-phase AC voltage into DC voltage (Figure 57–6).

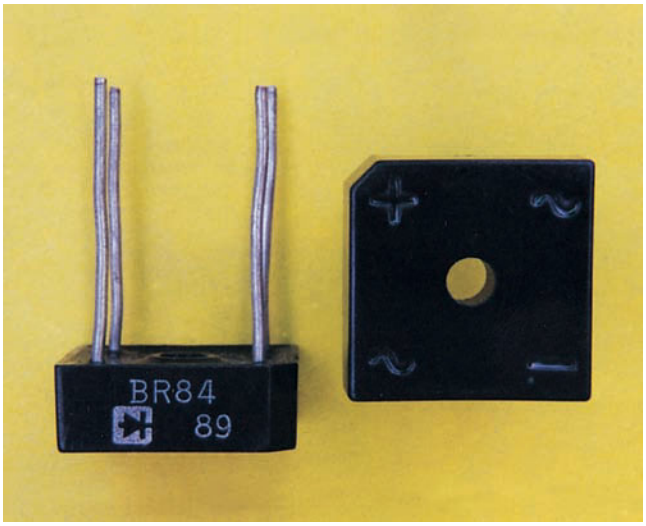


Figure 57–5 Bridge rectifiers in a single case. (Source: Delmar/Cengage Learning.)

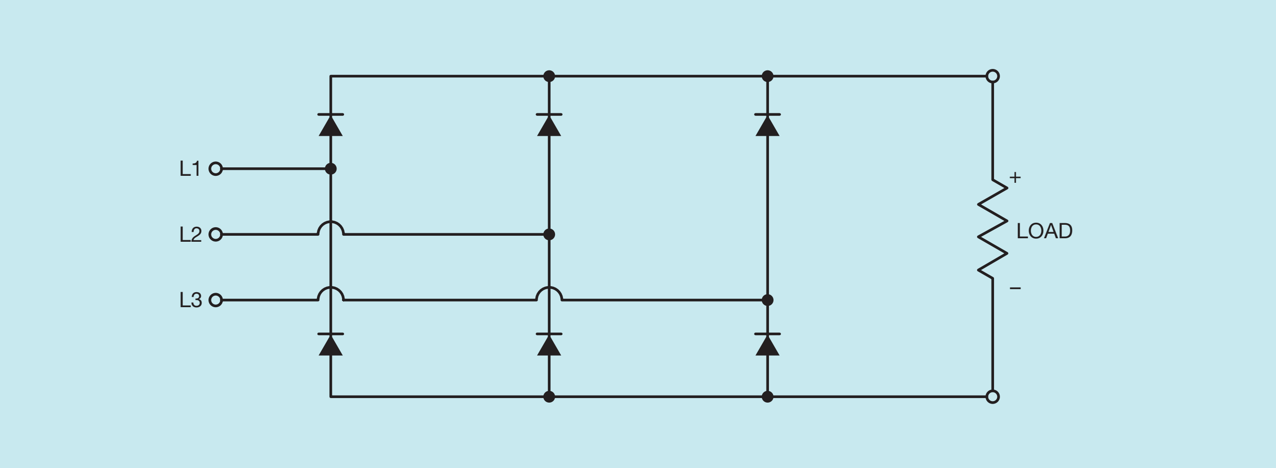


Figure 57–6 Three-phase bridge rectifier. (Source: Delmar/Cengage Learning.)

When the diode is to be connected in a circuit, there must be some means of identifying the anode and the cathode. Diodes are made in different case styles, as shown in Figure 57–7, so there are different methods of identifying the leads. Large stud mounted diodes often have the diode symbol printed on the case to show proper lead identification. Small plastic case diodes often have a line or band around one end of the case (Figure 57–8). This line or band represents the line in front of the arrow on the schematic symbol of the diode. An ohmmeter can always be used to determine the proper lead identification if the polarity of the ohmmeter leads is known. The positive lead of the ohmmeter must be connected to the anode to make the diode forward biased.

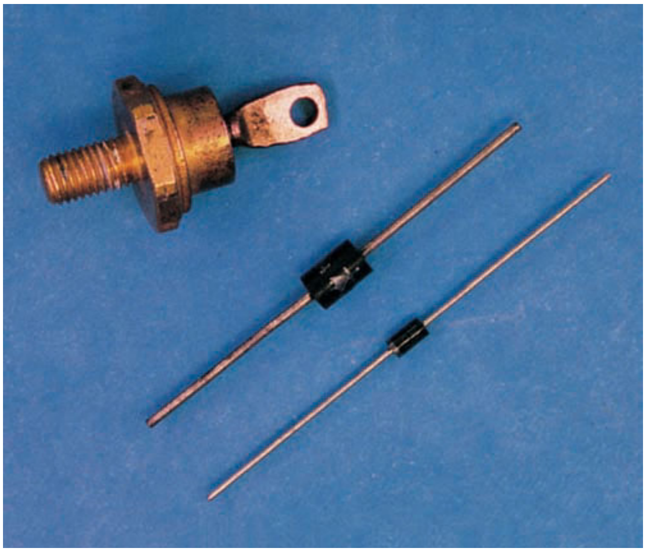


Figure 57–7 Diodes shown in various case styles. (Source: Delmar/Cengage Learning.)

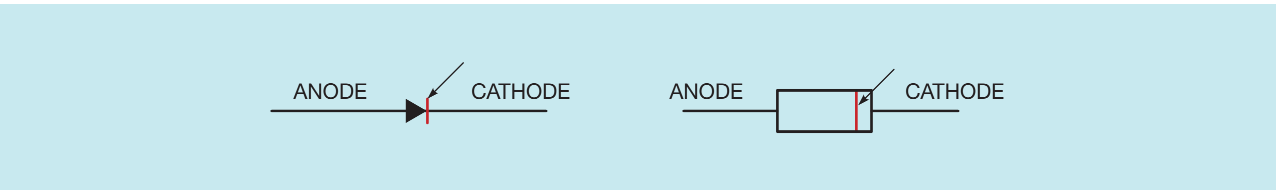


Figure 57–8 Lead identification of a plastic case diode. (Source: Delmar/Cengage Learning.)

Review Questions

1. The PN junction is more commonly known as the ____________________.
2. Draw the schematic symbol for a diode.
3. Explain how a diode operates.
4. Explain the difference between the conventional current flow theory and the electron flow theory.
5. Explain the difference between a half-wave rectifier and a full-wave rectifier.
6. Explain how to test a diode with an ohmmeter.

CHAPTER 58
THE ZENER DIODE

OBJECTIVES

After studying this chapter, the student will be able to:

- Explain the difference between a junction diode and a zener diode.
- Discuss common applications of the zener diode.
- Connect a zener diode in a circuit.

The Zener Diode

The zener diode is a special device designed to be operated with reverse polarity applied to it. When a diode is broken down in the reverse direction, it enters what is known as the *zener region.* Usually, when a diode is broken down into the zener region, it is destroyed; the zener diode, however, is designed to be operated in this region without harming the device.

When the reverse breakdown voltage of a zener diode is reached, the voltage drop of the device remains almost constant regardless of the amount of current flowing in the reverse direction (Figure 58–1). Since the voltage drop of the zener diode is constant, any device connected parallel to the zener will have a constant voltage drop even if the current through the load is changing.

In Figure 58–2, resistor R1 is used to limit the total current of the circuit. Resistor R2 is used to limit the current in the load circuit. Note that the value of R1 is less than the value of R2. This is to ensure that the supply can furnish enough current to operate the load. Note also that the supply voltage is greater than the zener voltage. The supply voltage must be greater than the voltage of the zener diode or the circuit cannot operate.

Resistor R1 and the zener diode form a series circuit to ground. Since the zener diode has a voltage drop of 12 volts, resistor R1 has a voltage drop of 8 volts: (20 V − 12 V = 8 V). Therefore, resistor R1 will permit a maximum current flow in the circuit of 0.08 amperes or 80 milliamperes:

$$\frac{8}{100} = 0.08$$

The load circuit, which is a combination of R2 and R3, is connected parallel to the zener diode. Therefore, the voltage applied to the load circuit must be the same as the voltage dropped by the zener. If the zener diode maintains a constant 12 volt drop, a constant voltage of 12 volts must be applied to the load circuit.

The maximum current that can flow through the load circuit is 0.06 amperes or 60 milliamperes:

$$\frac{12\ \text{V}}{200\ \Omega} = 0.06\ \text{A}$$

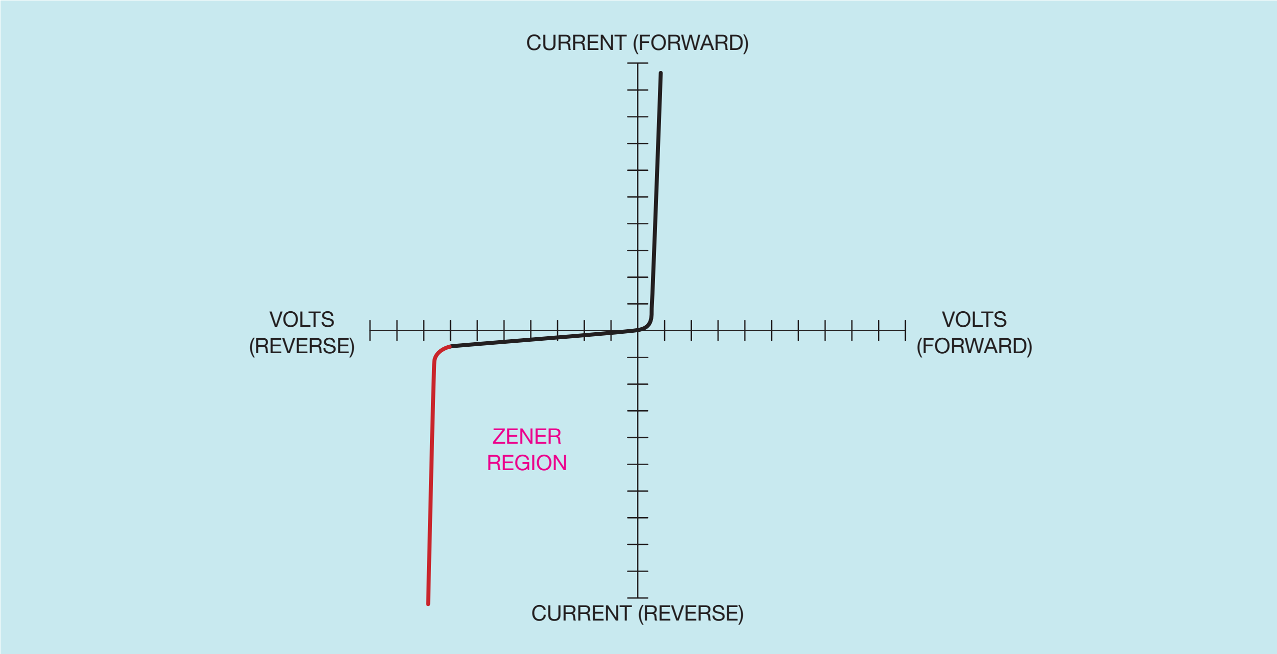


Figure 58–1 (Source: Delmar/Cengage Learning.)

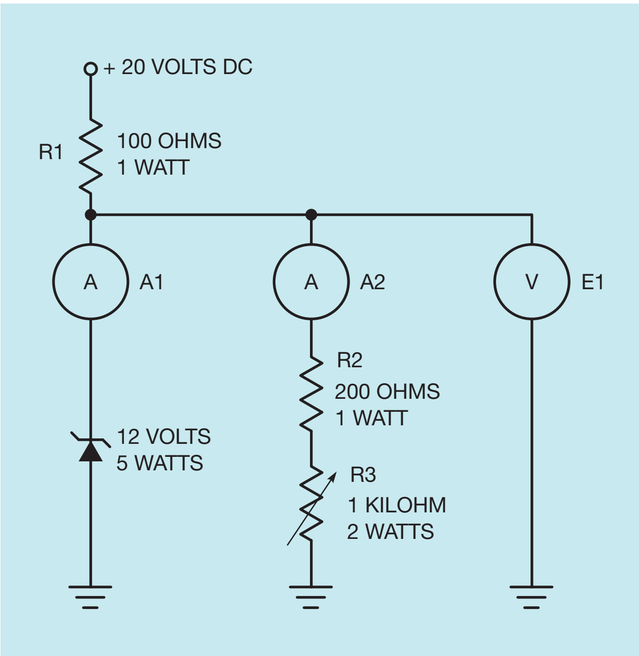


Figure 58–2 (Source: Delmar/Cengage Learning.)

Notice that the value of R2 (200 ohms) is used to ensure that there is enough current available to operate the load.

The maximum current allowed into the circuit by resistor R1 is always equal to the sum of the currents passing through the zener diode and the load. For example, when the load is connected parallel to the zener diode as shown in Figure 58–2, and resistor R3 is adjusted to 0 ohms, meter A1 will indicate a current of 20 milliamperes, and meter A2 will indicate a current of 60 milliamperes. Therefore, the maximum current allowed into the circuit by resistor R1 will be 80 milliamperes (20 mA + 60 mA = 80 mA). The voltage value indicated by meter E1 will be the same as the zener voltage value.

If resistor R3 is increased in value to 200 ohms, the resistance of the load will increase to 400 ohms (200 + 200 = 400). Meter A1 will indicate a current of 50 milliamperes and meter A2 will indicate a current of 30 milliamperes. The voltage value indicated by meter E1 will still be the same as the zener voltage value.

The zener diode, therefore, makes a very effective voltage regulator for the load circuit. Although the current through the load circuit changes, the zener diode forces the voltage across the load circuit to remain at a constant value, and conducts the current not used by the load circuit to ground.

The schematic symbol for a zener diode is shown in Figure 58–3. The zener diode can be tested with an ohmmeter in the same manner as a common junction diode is tested, provided the zener voltage is greater than the battery voltage of the ohmmeter.

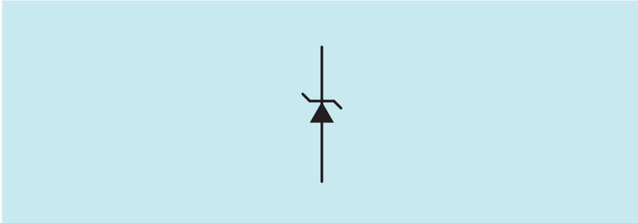


Figure 58–3 Schematic symbol for the zener diode. (Source: Delmar/Cengage Learning.)

Review Questions

1. How is a zener diode connected in a circuit as compared to a common junction diode?
2. What is the primary use of a zener diode?
3. A 5.1 volt zener diode is to be connected to an 8 volt power source. The current must be limited to 50 milliamperes. What value of current-limiting resistor must be connected in series with the zener diode?
4. How is a zener diode tested?
5. In a zener diode circuit, the current limiting resistor limits the total circuit current to 150 milliamperes. If the load circuit is drawing a current of 90 milliamperes, how much current is flowing through the zener diode?

CHAPTER 59
THE TRANSISTOR

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the differences between PNP and NPN transistors.
- Test transistors with an ohmmeter.
- Identify the leads of standard, case-style transistors.
- Discuss the operation of a transistor.
- Connect a transistor in a circuit.

The Transistor

Transistors are made by connecting three pieces of semiconductor material. There are two basic types of transistors: the NPN and the PNP (Figure 59–1). The schematic symbols for these transistors are shown in Figure 59–2. These transistors differ in the manner in which they are connected in a circuit. The NPN transistor must have a positive voltage connected to the collector and a negative voltage connected to the emitter. The PNP must have a positive voltage connected to the emitter and a negative voltage connected to the collector. The base must be connected to the same polarity as the collector to forward bias the transistor. Notice that the arrows on the emitters point in the direction of conventional current flow.

An ohmmeter can be used to test a transistor, which will appear to the ohmmeter to be two joined diodes (Figure 59–3). (For an explanation of how to test a transistor, see Procedure 2 in the Appendix.) If the polarity of the output of the ohmmeter leads is known, the transistor can be identified as NPN or PNP. An NPN transistor will appear to an ohmmeter to be two diodes with their anodes connected. If the positive lead of the ohmmeter is connected to the base of the transistor, a diode junction should be seen between the base-collector and the base-emitter. If the negative lead of

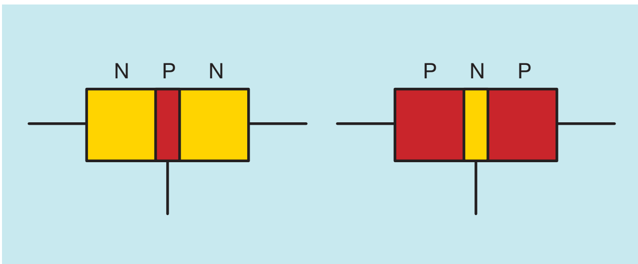


Figure 59–1 Two basic types of transistors. (Source: Delmar/Cengage Learning.)

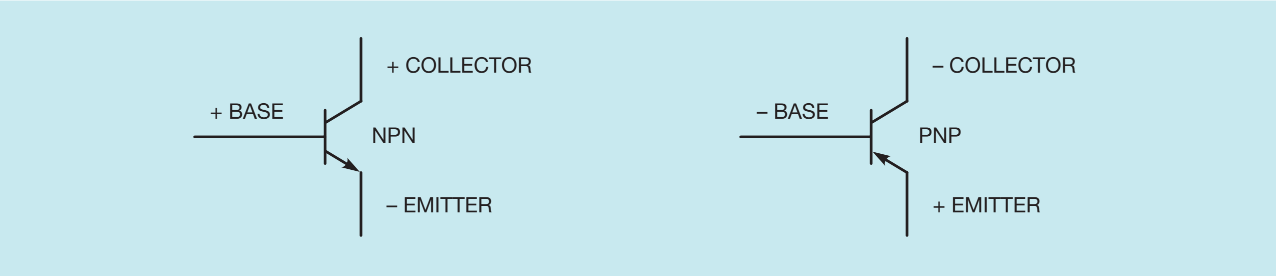


Figure 59–2 Schematic symbols for transistors. (Source: Delmar/Cengage Learning.)

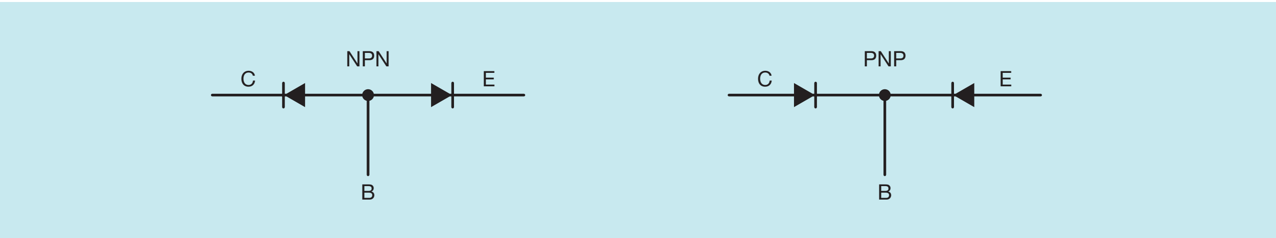


Figure 59–3 Ohmmeter test for transistors. (Source: Delmar/Cengage Learning.)

the ohmmeter is connected to the base of an NPN transistor, there should be no continuity between the base-collector and the base-emitter junction.

A PNP transistor will appear to an ohmmeter to be two diodes with their cathodes connected. If the negative lead of the ohmmeter is connected to the base of the transistor, a diode junction should be seen between the base-collector and the base-emitter. If the positive ohmmeter lead is connected to the base, there should be no continuity between the base-collector or the base-emitter.

The simplest way to describe the operation of a transistor is to say that it operates like an electric valve. Current will not flow through the collector-emitter until current flows through the base-emitter. The amount of base-emitter current, however, is small when compared to the collector-emitter current (Figure 59–4). For example, assume that when 1 milliamperes of current flows through the base-emitter junction, 100 mA of current flow through the collector-emitter junction. If this transistor is a linear device, an increase or decrease of base current will cause a similar increase or decrease of collector current. Therefore, if the base current is increased to 2 milliamperes, the collector current will increase to 200 milliamperes. If the base current is decreased to 0.5 milliamperes, the collector current will decrease to 50 milliamperes. Notice that a small change in the amount of base current can cause a large change in the amount of collector current. This permits a small amount of signal current to operate a larger device such as the coil of a control relay.

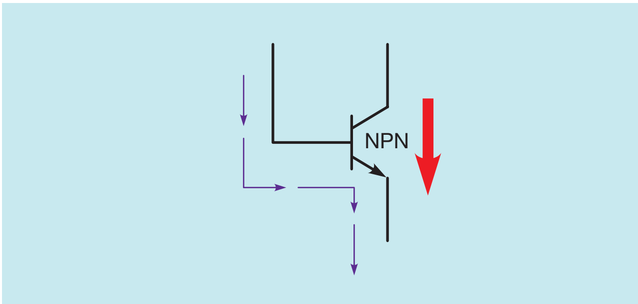


Figure 59–4 A small base current controls a large collector current. (Source: Delmar/Cengage Learning.)

One of the most common applications of the transistor in industry is that of a switch. When used in this manner, the transistor operates like a *digital* device instead of an *analog* device. The term *digital* means a device that has only two states, such as on and off. An *analog* device can be adjusted to different states. An example of this control can be seen in a simple switch connection. A common wall switch is a digital device. It can be used to turn a light on or off. If the simple toggle

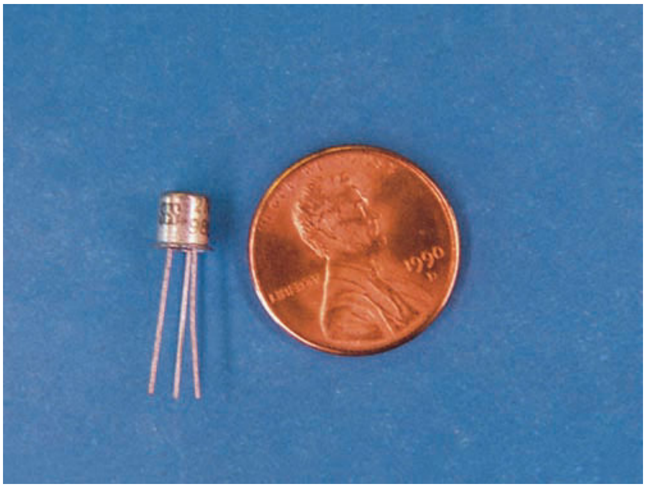


Figure 59–5 TO 18 case transistor. (Source: Delmar/Cengage Learning.)

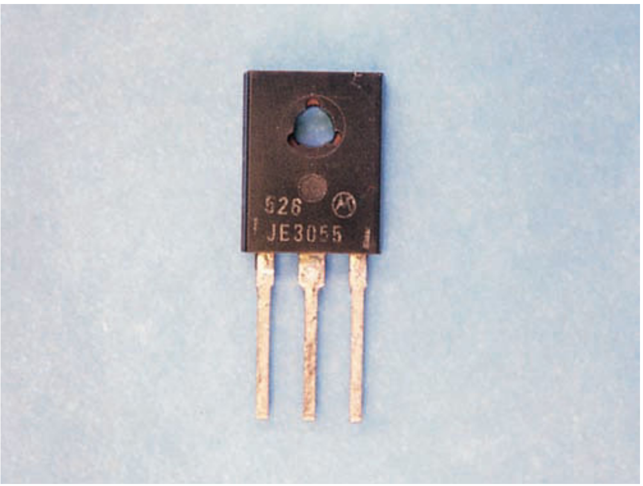


Figure 59–6 TO 220 case transistor. (Source: Delmar/Cengage Learning.)

Figure 59–7 TO 3 case transistor. (Source: Delmar/Cengage Learning.)

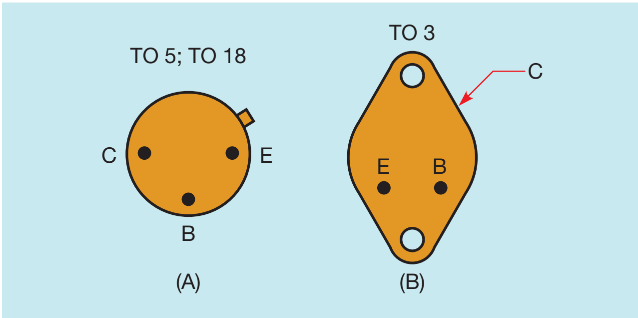


Figure 59–8 Lead identification of transistors. (Source: Delmar/Cengage Learning.)

switch is replaced with a dimmer control, the light can be turned on, off, or it can be adjusted to any position between on and off. The dimmer is an example of analog control.

If no current flows through the base of the transistor, the transistor acts like an open switch and no current can flow through the collector-emitter junction. If enough base current is applied to the transistor to turn it completely on, it acts like a closed switch and permits current to flow through the collector-emitter junction. This is the same action produced by the closing contacts of a relay or motor starter, but, unlike a transistor, a relay or motor starter cannot turn on and off several thousand times a second.

Some case styles of transistors permit the leads to be quickly identified (Figures 59–5, 59–6, and 59–7). The TO 5 and TO 18 cases, and the TO 3 case are in this category. The leads of the TO 5 and TO 18 case transistors can be identified by holding the case of the transistor with the leads facing you as shown in Figure 59–8A. The metal tab on the case of the transistor is closest to the emitter lead. The base and collector leads are positioned as shown.

The leads of a TO 3 case transistor can be identified as shown in Figure 59–8B. When the transistor is held with the leads facing you and down, the emitter is the left lead and the base is the right lead. The case of the transistor is the collector.

Review Questions

1. What are the two basic types of transistors?
2. Explain how to test an NPN transistor with an ohmmeter.
3. Explain how to test a PNP transistor with an ohmmeter.
4. What polarity must be connected to the collector, base, and emitter of an NPN to make it forward biased?
5. What polarity must be connected to the collector, base, and emitter of a PNP transistor to make it forward biased?
6. Explain the difference between an analog device and a digital device.

CHAPTER 60

THE UNIJUNCTION TRANSISTOR

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the differences between junction transistors and unijunction transistors.
- Describe the operation of the unijunction transistor (UJT).
- Identify the leads of a UJT.
- Draw the schematic symbol for a UJT.
- Test a UJT with an ohmmeter.
- Connect a UJT in a circuit.

The Unijunction Transistor

The *unijunction transistor (UJT)* is a special transistor that has two bases and one emitter. The unijunction transistor is a digital device because it has only two states, on and off. It is generally classified with a group of devices known as *thyristors.* Thyristors are devices that are turned completely on or completely off. Thyristors include such devices as the SCR, the triac, the diac and the UJT.

The unijunction transistor is made by combining three layers of semiconductor material as shown in Figure 60–1. Figure 60–2 shows the schematic symbol of the UJT with polarity connections and the base diagram.

Current flows in two paths through the UJT. One path is from base #2 to base #1. The other path is through the emitter and base #1. In its normal state,

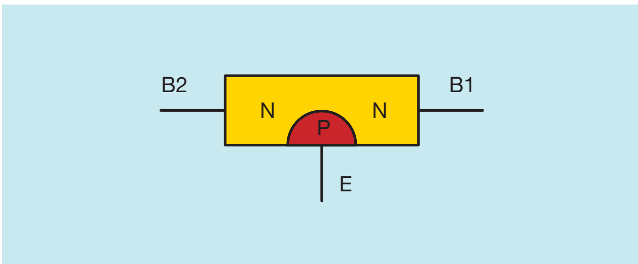


Figure 60–1 The unijunction transistor. (Source: Delmar/Cengage Learning.)

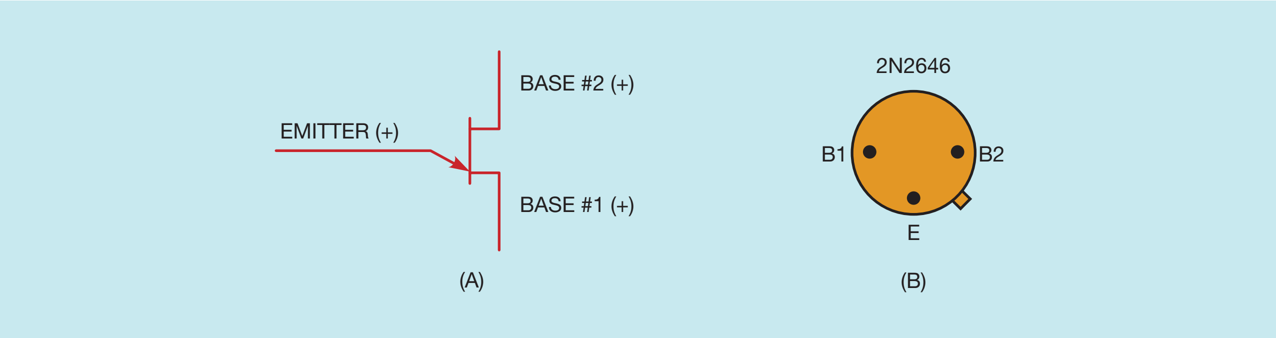


Figure 60–2 The schematic symbol for the unijunction transistor with polarity connections and base diagram. (Source: Delmar/Cengage Learning.)

current does not flow through either path until the voltage applied to the emitter is about 10 volts higher than the voltage applied to base #1. When the voltage applied to the emitter is about 10 volts higher than the voltage applied to base #1, the UJT turns on and current flows through the base #1–base #2 path and from the emitter through base #1. Current will continue to flow through the UJT until the voltage applied to the emitter drops to a point that is about 3 volts higher than the voltage applied to base #1. When the emitter voltage drops to this point, the UJT will turn off and will remain off until the voltage applied to the emitter again reaches a level about 10 volts higher than the voltage applied to base #1.

The unijunction transistor is generally connected to a circuit similar to the circuit shown in Figure 60–3. The variable resistor controls the capacitor's rate of charge time. When the capacitor has been charged to about 10 volts, the UJT turns on and discharges the capacitor through the emitter and base #1. When the capacitor has been discharged to about 3 volts, the UJT turns off and permits the capacitor to begin charging again. By varying the resistance connected in series with the capacitor, the amount of time needed for charging the capacitor can be changed, thereby controlling the pulse rate of the UJT (T = RC).

The unijunction transistor can furnish a large output pulse because the output pulse is produced by the discharging capacitor (Figure 60–4). This large output pulse is generally used for triggering the gate of a silicon-controlled rectifier.

The pulse rate is determined by the amount of resistance and capacitance connected to the emitter of the UJT. However, the amount of capacitance that can be connected to the UJT is limited. For instance, most UJTs should not be connected to capacitors larger than

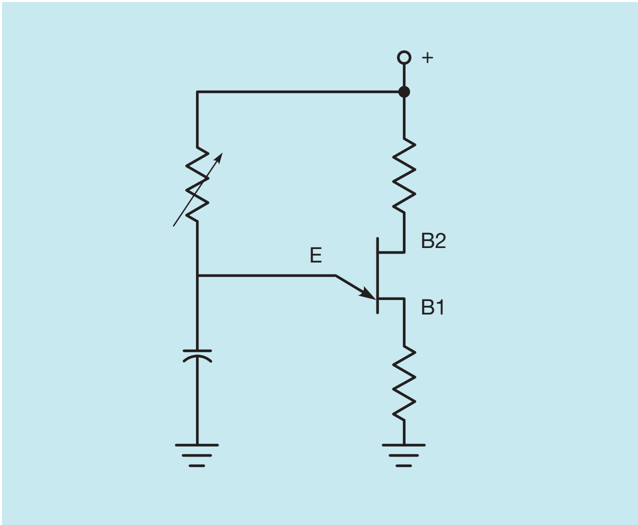


Figure 60–3 (Source: Delmar/Cengage Learning.)

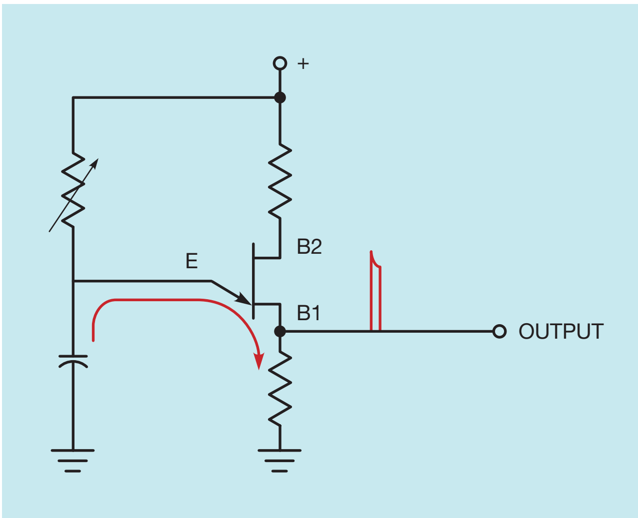


Figure 60–4 (Source: Delmar/Cengage Learning.)

10 microfarads because the UJT may not be able to handle the current spike produced by a larger capacitor, and the UJT could become damaged.

The unijunction transistor can be tested with an ohmmeter in a manner very similar to that used to test a common junction transistor. (For an explanation of how to test a unijunction transistor, see Procedure 3 in the Appendix.)

When testing the UJT with an ohmmeter, the UJT will appear as a circuit containing two resistors connected in series with a diode connected to the junction point of the two resistors as shown in Figure 60–5. If the positive lead of the ohmmeter is connected to the emitter of the UJT, a circuit should be seen between emitter and base 1 and emitter and base 2. If the negative lead of the ohmmeter is connected to the emitter, no circuit should be seen between the emitter and either base. If the ohmmeter leads are connected to the two bases, continuity will be seen between these two leads, provided that the output voltage of the ohmmeter is high enough.

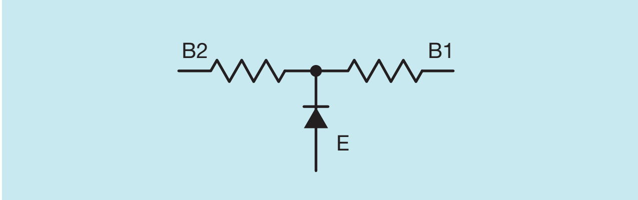


Figure 60–5 Testing a UJT. (Source: Delmar/Cengage Learning.)

Review Questions

1. What do the letters UJT stand for?
2. How many layers of semiconductor material are used to construct a UJT?
3. Briefly explain the operation of the UJT.
4. Draw the schematic symbol for the UJT.
5. Briefly explain how to test a UJT with an ohmmeter.

CHAPTER 61
THE SCR

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of an SCR in a DC circuit.
- Discuss the operation of an SCR in an AC circuit.
- Draw the schematic symbol for an SCR.
- Discuss phase shifting.
- Test an SCR with an ohmmeter.
- Connect an SCR in a circuit.

The silicon-controlled rectifier (SCR) is often referred to as a PNPN junction because it is made by joining four layers of semiconductor material (Figure 61–1). The schematic symbol for the SCR is shown in Figure 61–2. Notice that the symbol for the SCR is the same as the symbol for the diode except that a gate lead has been added. Case styles for SCRs are shown in Figure 61–3.

The SCR is a member of a family of devices known as thyristors. Thyristors are digital devices in that they have only two states, on and off. The SCR is used when it is necessary for an electronic device to control a large amount of power. For example, assume that an SCR has been connected in a circuit as shown in Figure 61–4. When the SCR is turned off, it will drop the full voltage of the circuit, and 200 volts will appear across the anode and cathode. Although the SCR has a voltage drop of 200 volts, there is no current flow in the circuit. The SCR does not have to dissipate any power in this condition (200 V × 0 A = 0 W). When the push button is pressed, the SCR turns on, producing a voltage drop

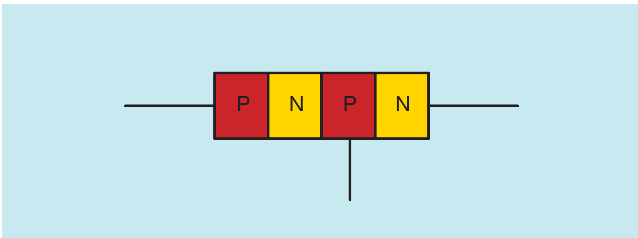


Figure 61–1 The PNPN junction. (Source: Delmar/Cengage Learning.)

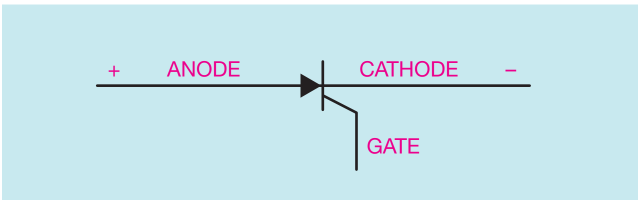


Figure 61–2 The schematic symbol for a silicon-controlled rectifier. (Source: Delmar/Cengage Learning.)

across its anode and cathode of about 1 volt. The load resistor limits the circuit current to 2 amperes:

$$\frac{200\text{ V}}{100\ \Omega} = 2\text{ A}$$

Since the SCR now has a voltage drop of 1 volt and 2 amperes of current flowing through it, it must dissipate 2 watts of heat (1 V × 2 A = 2 W). Notice that although the SCR is dissipating only 2 watts of power, it is controlling 400 watts of power.

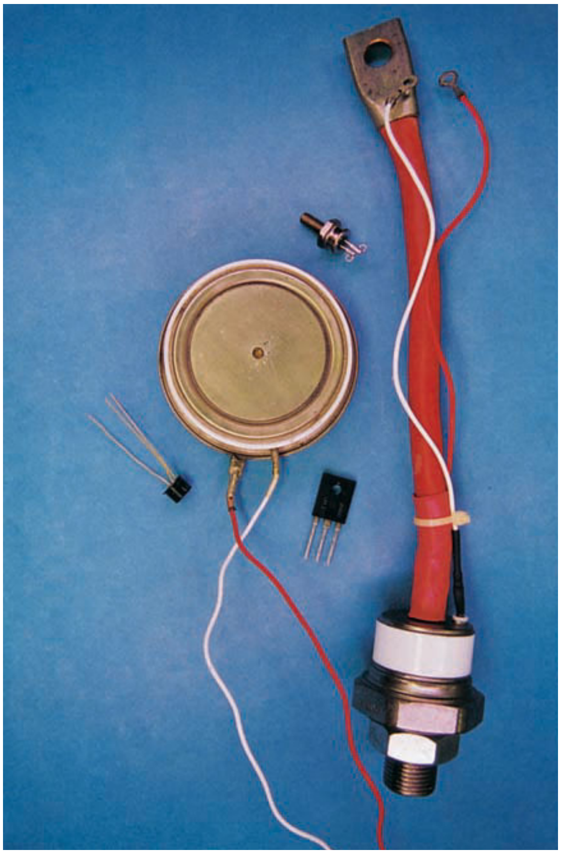


Figure 61–3 SCRs shown in different case styles. (Source: Delmar/Cengage Learning.)

The SCR in a DC Circuit

When an SCR is connected in a DC circuit as shown in Figure 61–4, the gate will turn the SCR on, but it will not turn the SCR off. To turn the anode-cathode section of the SCR on, the gate must be connected to the same polarity as the anode. Once the gate has turned the SCR on, the SCR will remain on until the current flowing through the anode-cathode section drops to a low enough level to permit the device to turn off. The amount of current required to keep the SCR turned on is called the *holding current.*

In Figure 61–5, assume that resistor R1 has been adjusted to its highest value and resistor R2 has been adjusted to its lowest or 0 value. When switch S1 is closed, no current will flow through the anode-cathode section of the SCR because resistor R1 prevents the amount of current needed to trigger the device from flowing through the gate-cathode section of the SCR. If the value of resistor R1 is slowly decreased, current flow through the gate-cathode section will slowly increase. When the gate reaches a certain level (assume 5 mA for this SCR) the SCR will fire, or turn on. When the SCR fires, current will flow through the anode-cathode section and the voltage drop across the device will be about 1 volt. Once the SCR is turned on, the gate has no control over the device. It could be disconnected from the anode without affecting the circuit. When the SCR fires, the anode-cathode section becomes a short circuit and current flow is limited by resistor R3.

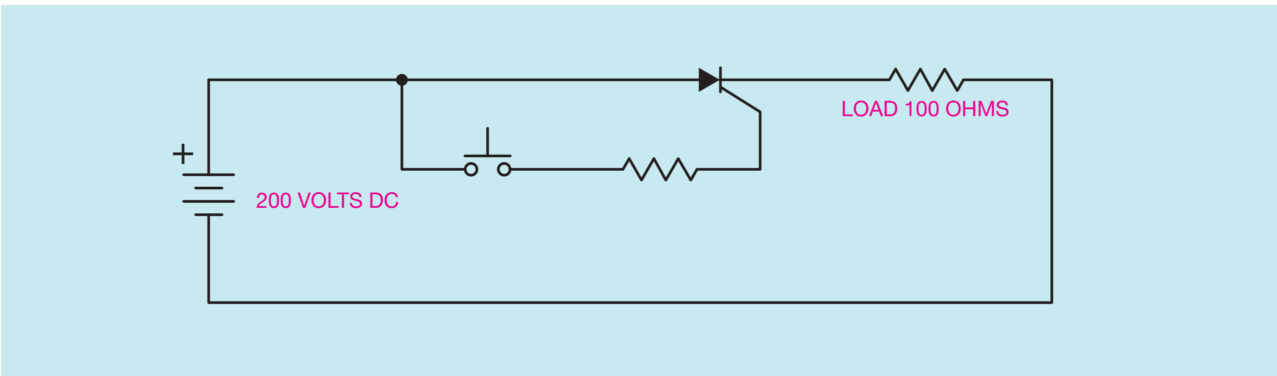


Figure 61–4 The SCR is turned on by the gate. (Source: Delmar/Cengage Learning.)

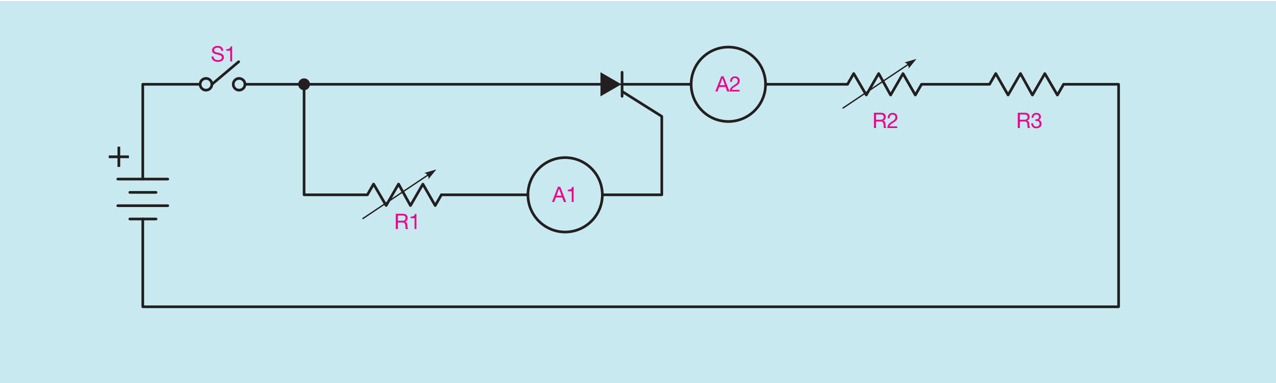


Figure 61–5 Operation of an SCR in a DC circuit. (Source: Delmar/Cengage Learning.)

Now assume that resistor R2 is slowly increased in value. When the resistance of R2 is slowly increased, the current flow through the anode-cathode section will slowly decrease. Assume that when the current flow through the anode-cathode section drops to 100 milliampere, the device suddenly turns off and the current flow drops to 0. This SCR requires 5 milliampere of gate current to turn it on, and has a holding current value of 100 milliampere.

The SCR in an AC Circuit

The SCR is a rectifier; when it is connected in an AC circuit, the output is direct current. The SCR operates in the same manner in an AC circuit as it does in a DC circuit. The difference in operation is caused by the AC waveform falling back to 0 at the end of each half cycle. When the AC waveform drops to 0 at the end of each half cycle, the SCR turns off. This means that the gate must retrigger the SCR for each cycle it is to conduct (Figure 61–6).

Assume that the variable resistor connected to the gate has been adjusted to permit 5 milliampere of current to flow when the voltage applied to the anode reaches its peak value. When the SCR turns on, current will begin flowing through the load resistor when the AC waveform is at its positive peak. Current will continue to flow through the load until the decreasing voltage of the sine wave causes the current to drop below the holding current level of 100 milliampere. When the current through the anode-cathode section drops below 100 milliampere, the SCR turns off and all current flow stops. The SCR will remain turned off when the AC waveform goes into its negative half cycle because during this half cycle the SCR is reverse biased and cannot be fired.

If the resistance connected in series with the gate is reduced, a current of 5 milliampere will be reached before the AC waveform reaches its peak value (Figure 61–7). This will cause the SCR to fire earlier in the

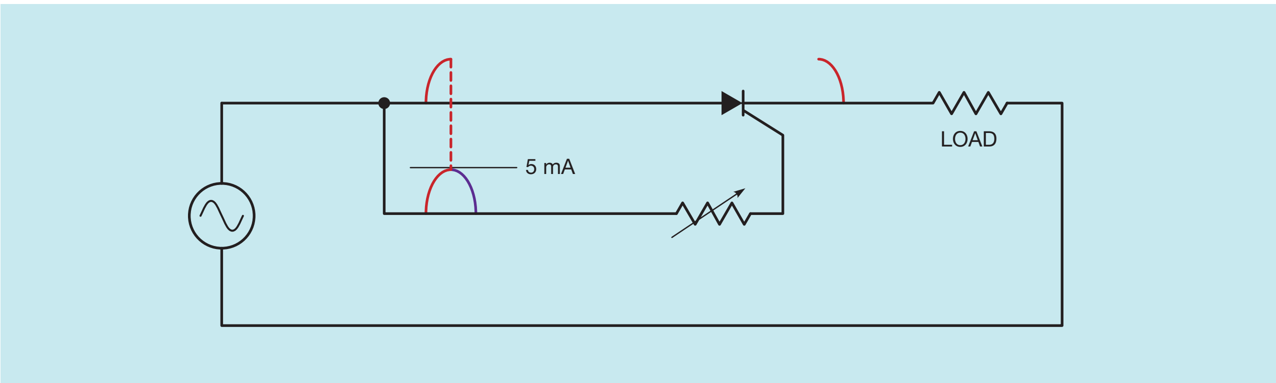


Figure 61–6 The SCR fires when the AC waveform reaches peak value. (Source: Delmar/Cengage Learning.)

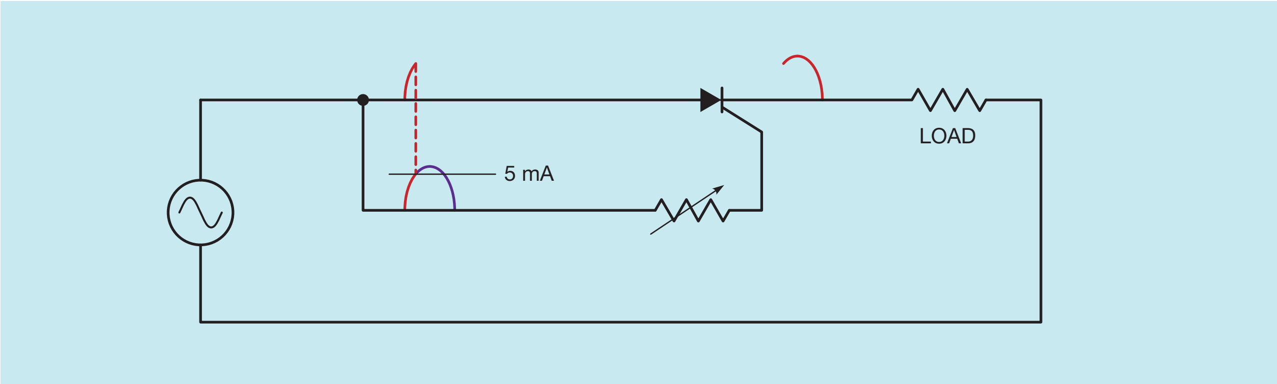


Figure 61–7 The SCR fires before the AC waveform reaches peak value. (Source: Delmar/Cengage Learning.)

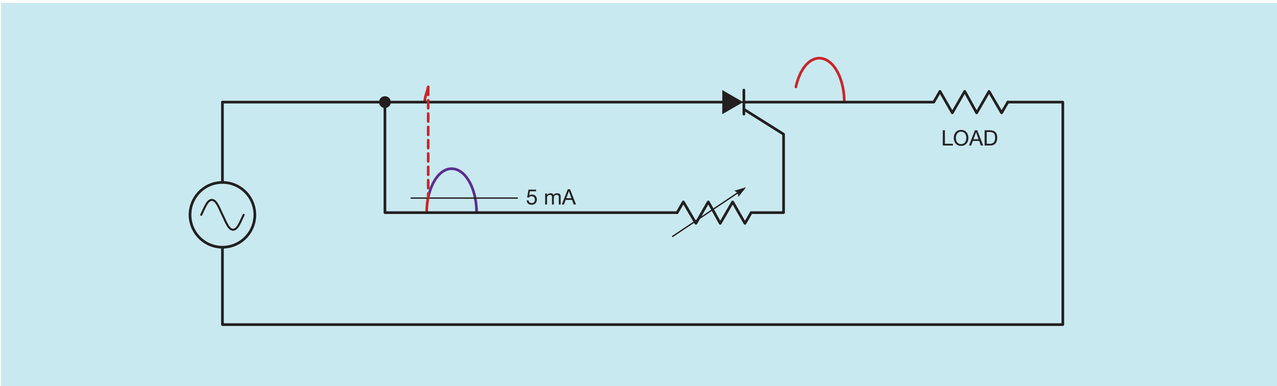


Figure 61–8 The SCR fires earlier than in Figure 61–7. (Source: Delmar/Cengage Learning.)

cycle. Since the SCR fires earlier in the cycle, current is permitted to flow through the load resistor for a longer period of time, which produces a higher average voltage drop across the load. If the resistance of the gate circuit is reduced again, as shown in Figure 61–8, the 5 milliampere of gate current needed to fire the SCR will be reached earlier than in Figure 61–7. Current will begin flowing through the load sooner than before, which will permit a higher average voltage to be dropped across the load.

Notice that this circuit enables the SCR to control only half of the positive waveform. The latest the SCR can be fired in the cycle is when the AC waveform is at 90° or peak. If a lamp were used as the load for this circuit, it would burn at half brightness when the SCR first turned on. This control would permit the lamp to be operated from half brightness to full brightness, but it could not be operated at a level less than half brightness.

Phase Shifting the SCR

The SCR can control all of the positive waveform through the use of *phase shifting*. As the term implies, phase shifting means to shift the phase of one thing in reference to another. In this instance, the voltage applied to the gate must be shifted out of phase with the voltage applied to the anode. Although there are several methods used for phase shifting an SCR, it is beyond the scope of this text to cover all of them. The basic principles are the same for all of the methods, however, so only one method is covered.

To phase shift an SCR, the gate circuit must be unlocked or separated from the anode circuit. The circuit shown in Figure 61–9 will accomplish this. A 24 volt, center-tapped transformer is used to isolate the gate circuit from the anode circuit. Diodes Dl and D2 are used to form a two-diode type of full-wave rectifier

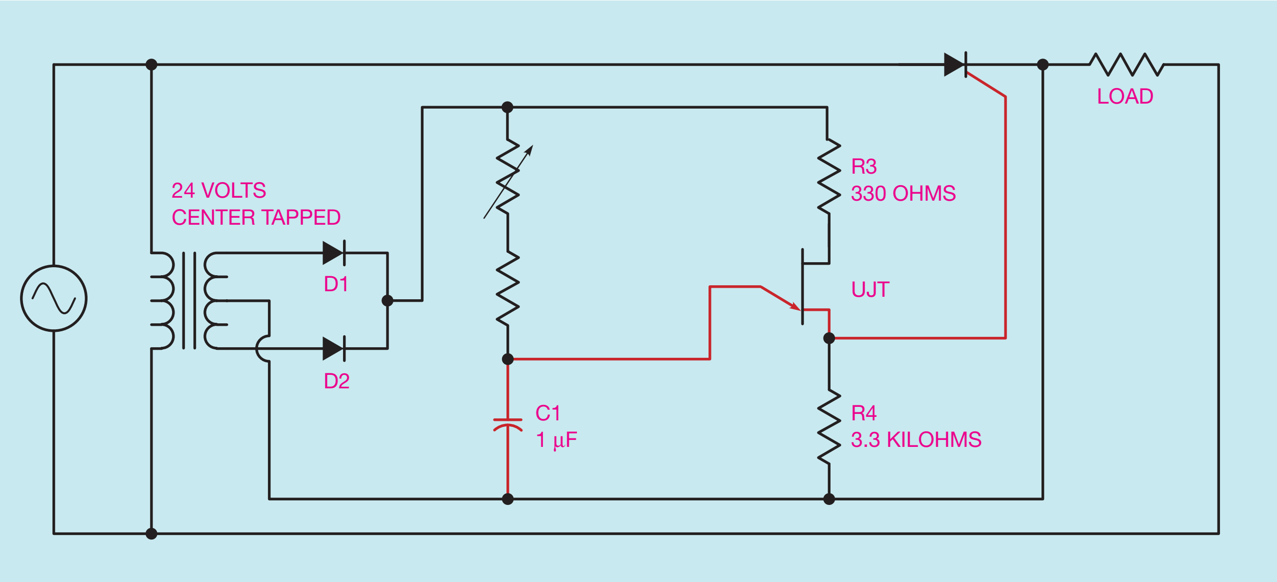


Figure 61–9 UJT phase shift for an SCR. SCR gate current is provided by the discharging capacitor when the UJT fires.

to operate the UJT circuit. Resistor R1 is used to determine the pulse rate of the UJT by controlling the charge time of capacitor C1. Resistor R2 is used to limit the current through the emitter of the UJT if resistor R1 is adjusted to 0 ohms. Resistor R3 limits current through the base 1–base 2 section when the UJT turns on. Resistor R4 permits a voltage spike or pulse to be produced across it when the UJT turns on and discharges capacitor C1. The pulse produced by the discharge of capacitor C1 is used to trigger the gate of the SCR.

Since the pulse of the UJT is used to provide a trigger for the gate of the SCR, the SCR can be fired at any time regardless of the voltage applied to the anode. This means that the SCR can now be fired as early or late during the positive half cycle as desired because the gate pulse is determined by the charge rate of capacitor C1. The voltage across the load can now be adjusted from 0 to the full applied voltage.

Testing the SCR

The SCR can be tested with an ohmmeter (see Procedure 4 in the Appendix). To test the SCR, connect the positive output lead of the ohmmeter to the anode and the negative lead to the cathode. The ohmmeter should indicate no continuity. Touch the gate of the SCR to the anode. The ohmmeter should indicate continuity through the SCR. When the gate lead is removed from the anode, conduction may stop or continue depending on whether the ohmmeter is supplying enough current to keep the device above its holding current level. If the ohmmeter indicates continuity through the SCR before the gate is touched to the anode, the SCR is shorted. If the ohmmeter will not indicate continuity through the SCR after the gate has been touched to the anode, the SCR is open.

Review Questions

1. What do the letters SCR stand for?
2. If an SCR is connected to an AC circuit, will the output voltage be AC or DC?
3. Briefly explain how an SCR operates when connected to a DC circuit.
4. How many layers of semiconductor material are used to construct an SCR?
5. SCRs are members of a family of devices known as thyristors. What is a thyristor?
6. Briefly explain why thyristors have the ability to control large amounts of power.
7. What is the average voltage drop of an SCR when it is turned on?
8. Explain why an SCR must be phase shifted.

CHAPTER 62
THE DIAC

OBJECTIVES

After studying this chapter, the student will be able to:

- Draw the schematic symbol for a diac.
- Discuss the operation of a diac.
- Connect a diac in a circuit.

The Diac

The *diac* is a special-purpose, bidirectional diode. The primary function of the diac is to phase shift a triac. The operation of the diac is very similar to that of a unijunction transistor, except that the diac is a two-directional device. The diac has the ability to operate in an AC circuit while the UJT can operate only in a DC circuit.

There are two schematic symbols for the diac (Figure 62–1). Both of these symbols are used in electronic schematics to illustrate the use of a diac. Therefore, you should make yourself familiar with both symbols.

The diac is a voltage sensitive switch that can operate on either polarity (Figure 62–2). Voltage applied to the diac must reach a predetermined level before the diac will activate. For this example, assume that the predetermined level is 15 volts. When the voltage reaches 15 volts, the diac will turn on, or fire. When the diac fires, it displays a negative resistance, which means that it will conduct at a lower voltage than the voltage needed to turn it on. In this example, assume that the voltage drops to 5 volts when the diac conducts. The diac will remain on until the applied voltage drops below its conduction level, which is 5 volts (Figure 62–3).

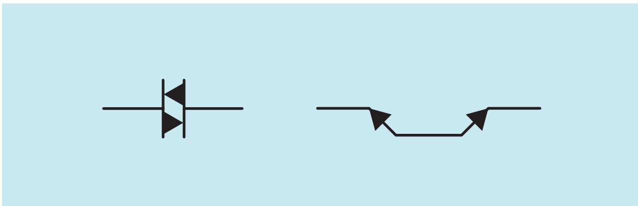


Figure 62–1 Schematic symbols for the diac. (Source: Delmar/Cengage Learning.)

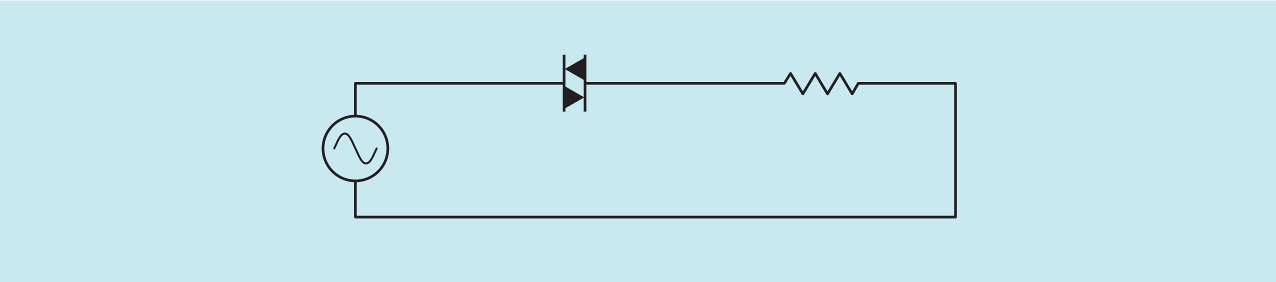


Figure 62–2 The diac can operate on either polarity. (Source: Delmar/Cengage Learning.)

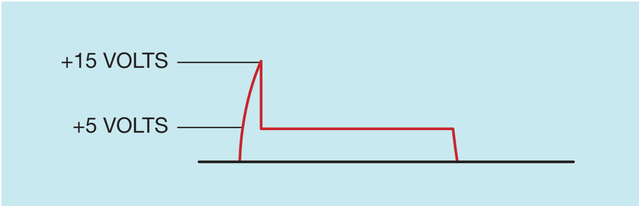


Figure 62–3 The diac operates until the applied voltage falls below its conduction level. (Source: Delmar/Cengage Learning.)

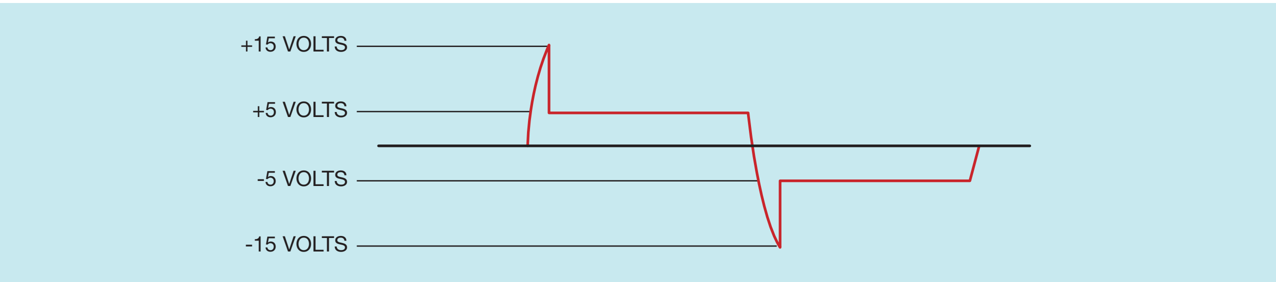


Figure 62–4 The diac will conduct on either half of the alternating current. (Source: Delmar/Cengage Learning.)

Since the diac is a bidirectional device, it will conduct on either half cycle of the alternating current applied to it (Figure 62–4). Note that the diac operates in the same manner on both halves of the AC cycle. The simplest way to summarize the operation of the diac is to say that it is a voltage sensitive AC switch.

Review Questions

1. Briefly explain how a diac operates.
2. Draw the two schematic symbols used to represent the diac.
3. What is the major use of the diac in industry?
4. When a diac first turns on, does the voltage drop, remain at the same level, or increase to a higher level?

CHAPTER 63
THE TRIAC

OBJECTIVES

After studying this chapter, the student will be able to:

- Draw the schematic symbol for a triac.
- Discuss the similarities and differences between SCRs and triacs.
- Discuss the operation of a triac in an AC circuit.
- Discuss phase shifting a triac.
- Connect a triac in a circuit.
- Test a triac with an ohmmeter.

The triac is a PNPN junction connected parallel to an NPNP junction. Figure 63–1 illustrates the semiconductor arrangement of a triac. The triac operates in a manner similar to that of two connected SCRs (Figure 63–2). The schematic symbol for the triac is shown in Figure 63–3.

When an SCR is connected in an AC circuit, the output voltage is direct current. When a triac is connected in an AC circuit, the output voltage is alternating current. Since the triac operates like two SCRs that are connected and facing in opposite directions, it will conduct both the positive and negative half cycles of AC current.

When a triac is connected in an AC circuit as shown in Figure 63–4, the gate must be connected to the same polarity as MT2. When the AC voltage applied to MT2 is positive, the SCR, which is forward biased, will conduct. When the voltage applied to MT2 is negative, the other SCR is forward biased and will conduct that half of the waveform. Since one of the SCRs is forward biased for each half cycle, the triac will conduct AC current as long as the gate lead is connected to MT2.

The triac, like the SCR, requires a certain amount of gate current to turn it on. Once the triac has been triggered by the gate, it will continue to conduct until the current flowing through MT2–MT1 drops below the holding current level.

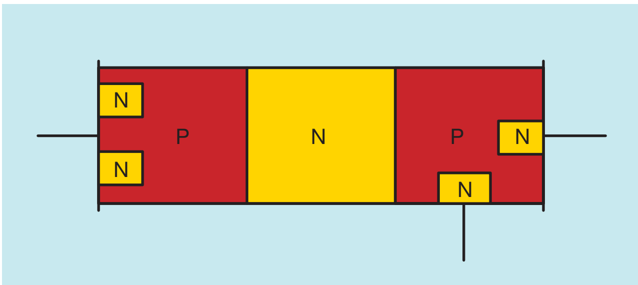


Figure 63–1 The semiconductor arrangement of a triac. (Source: Delmar/Cengage Learning.)

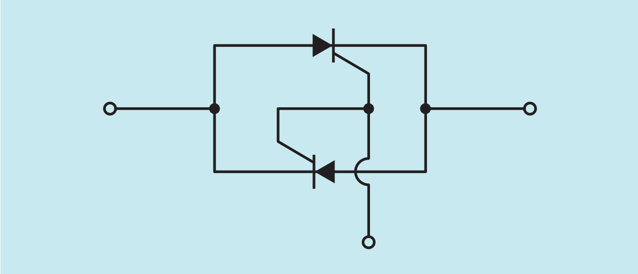


Figure 63–2 The triac operates in a manner similar to two SCRs with a common gate. (Source: Delmar/Cengage Learning.)

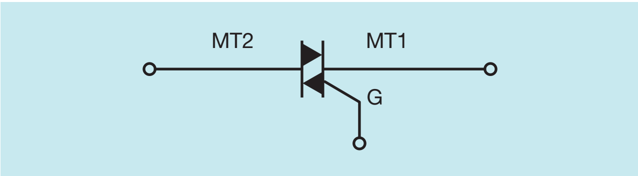


Figure 63–3 The schematic symbol for a triac. (Source: Delmar/Cengage Learning.)

The Triac Used as an AC Switch

The triac is a member of the thyristor family, which means that it has only two states of operation, on and off. When the triac is turned off, it drops the full applied voltage of the circuit at 0 amperes of current flow. When the triac is turned on, it has a voltage drop of about 1 volt, and circuit current must be limited by the load connected to the circuit.

The triac has become very popular in industrial circuits as an AC switch. Since it is a thyristor, it has the ability to control a large amount of voltage and current. There are no contacts to wear out, it is sealed against dirt and moisture, and it can operate thousands of times per second. The triac is used as the output device of many solid-state relays, which will be covered later. Two types of triacs are shown in Figures 63–5 and 63–6.

The Triac Used for AC Voltage Control

The triac can be used to control AC voltage (Figure 63–7). If a variable resistor is connected in series with the gate, the point at which the gate current is high enough to fire the triac can be adjusted. The resistance can be adjusted to permit the triac to fire when the AC waveform reaches its peak value. This will cause half of the AC voltage to be dropped across the triac and half to be dropped across the load.

If the gate resistance is reduced, the amount of gate current needed to fire the triac will be obtained before the AC waveform reaches its peak value. This means that less voltage will be dropped across the triac and more voltage will be dropped across the load. This circuit permits the triac to control only one half of the AC waveform applied to it. If a lamp is used as the load, it can be controlled from half brightness to full brightness. If an attempt is made to adjust the lamp to operate at less than half brightness, it will turn off.

Phase Shifting the Triac

To obtain complete voltage control, the triac, like the SCR, must be phase shifted. Several methods can be used to phase shift a triac, but only one will be covered

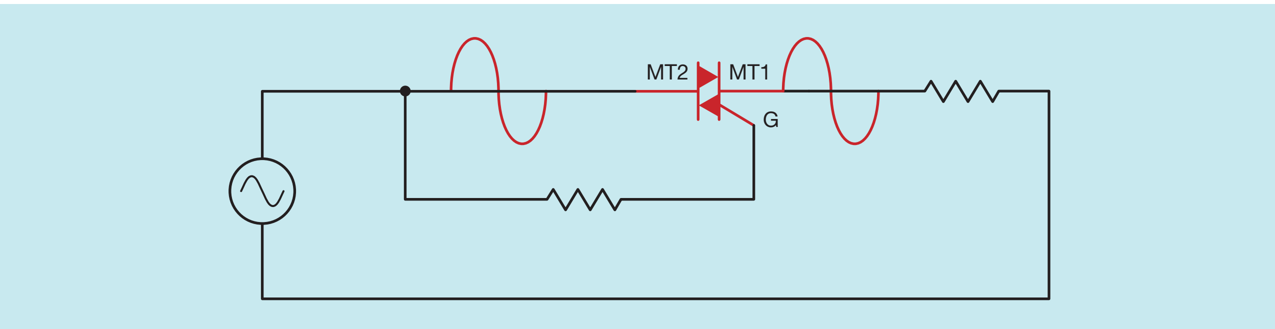


Figure 63–4 The triac conducts both halves of the ac waveform. (Source: Delmar/Cengage Learning.)

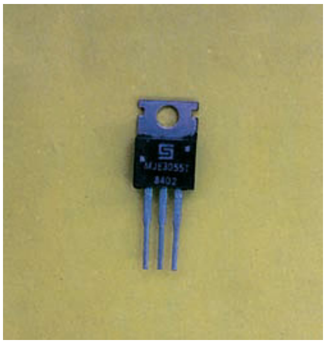


Figure 63–5 The triac used for low power applications. (Source: Delmar/Cengage Learning.)

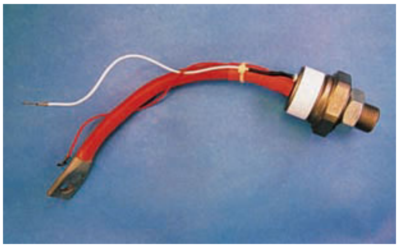


Figure 63–6 The triac shown in a stud mount case. (Source: Delmar/Cengage Learning.)

in this unit. In Figure 63–8, a diac is used to phase shift the triac. Resistors Rl and R2 are connected in series with capacitor C1. Resistor R1 is a variable resistor used to control the charge time of capacitor C1. Resistor R2 is used to limit current if resistor R1 is adjusted to 0 ohms. Assume that the diac connected in series with the gate of the triac will turn on when capacitor C1 has been charged to 15 volts. When the diac turns on, capacitor C1 will discharge through the gate of the triac. This permits the triac to fire, or turn on. Since the diac is a bidirectional device, it will permit a positive or negative pulse to trigger the gate of the triac.

When the triac fires, there is a voltage drop of about 1 volt across MT2 and MT1. The triac remains on until the AC voltage drops to a low enough value to permit the triac to turn off. Since the phase shift circuit is connected parallel to the triac, once the triac turns on, capacitor C1 cannot begin charging again until the triac turns off at the end of the AC cycle.

Notice that the pulse applied to the gate is controlled by the charging of capacitor C1, not the amplitude of voltage. If the correct values are chosen, the triac can be fired at any point in the AC cycle applied to it. The triac can now control the AC voltage from 0 to the full voltage of the circuit. A common example of this type of triac circuit is the light dimmer control used in many homes.

Testing the Triac

The triac can be tested with an ohmmeter (see Procedure 5 in the Appendix). To test the triac, connect the ohmmeter leads to MT2 and MT1. The ohmmeter should indicate no continuity. If the gate lead is touched to MT2, the triac should turn on and the ohmmeter should indicate continuity through the triac. When the gate lead is released from MT2, the triac may continue to conduct or it may turn off, depending on whether the ohmmeter supplies enough current to keep the device above its holding current level. This tests one half of the triac.

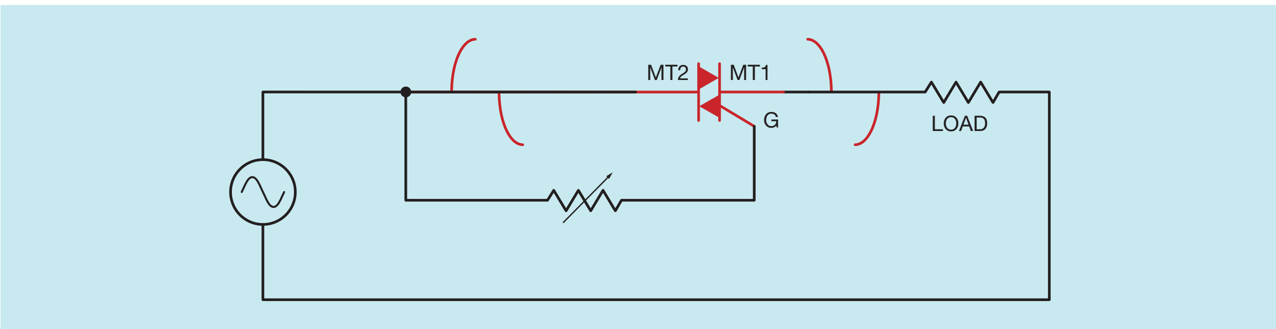


Figure 63–7 The triac controls half of the AC applied voltage. (Source: Delmar/Cengage Learning.)

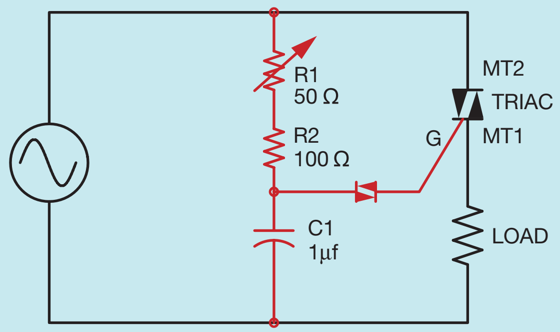


Figure 63–8 Phase shift circuit for a triac. When the diac turns on, gate current is supplied to the triac by the discharge of capacitor C1. (Source: Delmar/Cengage Learning.)

To test the other half of the triac, reverse the connection of the ohmmeter leads. The ohmmeter should indicate no continuity. If the gate is touched again to MT2, the ohmmeter should indicate continuity through the device. The other half of the triac has been tested.

Review Questions

1. Draw the schematic symbol for a triac.
2. When a triac is connected in an AC circuit, is the output AC or DC?
3. The triac is a member of what family of devices?
4. Briefly explain why a triac must be phase shifted.
5. What electronic component is frequently used to phase shift the triac?
6. When the triac is being tested with an ohmmeter, which other terminal should the gate be connected to if the ohmmeter is to indicate continuity?

CHAPTER 64

THE 555 TIMER

OBJECTIVES

After studying this chapter, the student will be able to:

- Describe the operation of the 555 timer.
- Discuss the uses of the 555 timer.
- Connect the timer as an oscillator.
- Connect the 555 timer as an on-delay timer.

The 555 timer is an eight-pin integrated circuit that has become one of the most popular electronic devices used in industrial electronic circuits. The reason for the 555's popularity is its tremendous versatility. The 555 timer is used in circuits that require a time delay function, and it is also used as an oscillator to provide the pulses needed to operate computer circuits.

The 555 timer is most often housed in an eight-pin, in-line integrated circuit (IC) (Figures 64–1 and 64–2). This package has a notch at one end, or a dot by one pin, which is used to identify pin #1. Once pin #1 has been identified, the other pins are numbered as shown in Figure 64–1. The 555 timer operates on voltages that range from about 3 to 16 volts. Following is an explanation of each pin and its function:

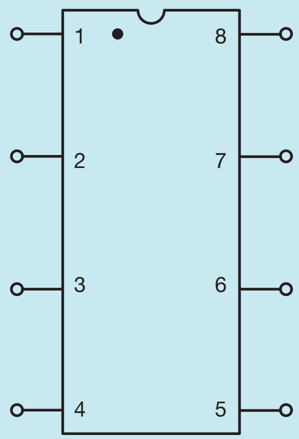


Figure 64–1 After pin #1 has been identified, the other pins are numbered as shown. (Source: Delmar/Cengage Learning.)

Pin #1 ***Ground***—This pin is connected to circuit ground.

Pin #2 ***Trigger***—Pin #2 must be connected to a voltage that is less than ⅓ Vcc (the applied voltage) to trigger the unit. This usually is done by

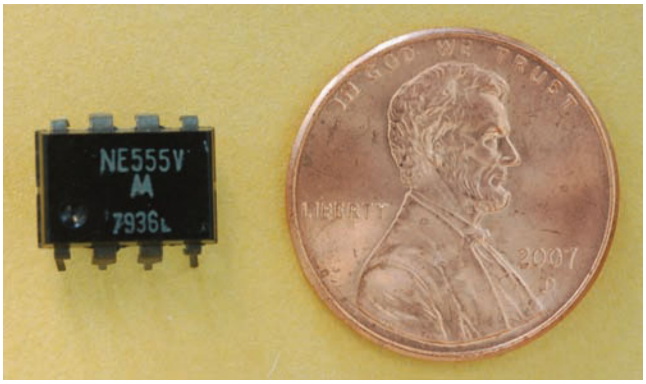


Figure 64–2 An eight-pin, in-line, integrated circuit. (Source: Delmar/Cengage Learning.)

connecting pin #2 to ground. The connection to ⅓ Vcc or ground must be momentary. If pin #2 is not removed from ground, the unit will not operate.

Pin #3 ***Output***—The output turns on when Pin #2 is triggered and turns off when the discharge is turned on.

Pin #4 ***Reset***—When this pin is connected to Vcc, it permits the unit to operate. When it is connected to ground, it activates the discharge and keeps the timer from operating.

Pin #5 ***Control Voltage***—If this pin is connected to Vcc through a variable resistor, the on time is longer, but the off time is not affected. If pin #5 is connected to ground through a variable resistor, the on time is shorter, and the off time is still not affected. If pin #5 is not to be used in the circuit, it is usually taken to ground through a small capacitor. This helps to keep circuit noise from "talking" to pin #5.

Pin #6 ***Threshold***—When the voltage across the capacitor connected to pin #6 reaches ⅔ the value of Vcc, the discharge turns on and the output turns off.

Pin #7 ***Discharge***—When pin #6 turns the discharge on, it discharges the capacitor connected to pin #6. The discharge remains turned on until pin #2 retriggers the timer. The discharge then turns off and the capacitor connected to pin #6 begins charging again.

Pin #8 ***Vcc***—Pin #8 is connected to Vcc.

(For the following explanation, assume that pin #2 is connected to pin #6. This permits the unit to be retriggered by the discharge each time it turns on and discharges the capacitor to ⅓ the value of Vcc.)

The 555 timer operates on a percentage of the applied voltage. This permits the time setting to remain constant even if the applied voltage changes. For example, when the capacitor connected to pin #6 reaches ⅔ of the applied voltage, the discharge turns on and discharges the capacitor until it reaches ⅓ of the applied voltage. If the applied voltage of the timer is connected to 12 volts DC, ⅔ of the applied voltage is 8 volts and ⅓ is 4 volts. This means that when the voltage across the capacitor connected to pin #6 reaches 8 volts, pin #7 will turn on until the capacitor is discharged to ⅓ the value of Vcc, or 4 volts, and will then turn off (Figure 64–3).

If the voltage is lowered to 6 volts at Vcc, ⅔ of the applied voltage is 4 volts and ⅓ of the applied voltage is 2 volts. Pin #7 will now turn on when the voltage across the capacitor connected to pin #6 reaches 4 volts and will turn off when the voltage across the capacitor drops to 2 volts.

The formula for a RC time constant is (Time = Resistance × Capacitance). Notice that there is no mention of voltage in the formula. This means that it will take the same amount of time to charge the capacitor regardless of whether the circuit is connected to 12 volts

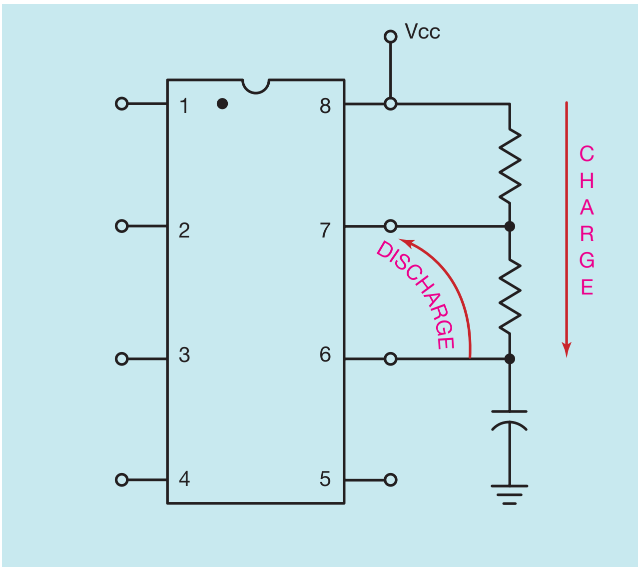


Figure 64–3 The charge and discharge is determined by a percentage of the applied voltage. (Source: Delmar/Cengage Learning.)

or to 6 volts. If the time it takes for the voltage of the capacitor connected to pin #6 to reach ⅔ of Vcc when the timer has an applied voltage of 12 volts is measured, it will be the same as the amount of time it takes when the applied voltage is only 6 volts. The timing of the circuit remains the same even if the voltage changes.

The circuit shown in Figure 64–4 is used to explain the operation of the 555 timer. In Figure 64–4, a normally closed switch, S1, is connected between the discharge, pin #7, and the ground, pin #1. A normally open switch, S2, is connected between the output, pin #3, and Vcc, pin #8.

The dotted line drawn between these two switches shows mechanical connection. This means that these switches operate together. If S1 opens, S2 closes at the same time. If S2 opens, S1 closes. Pin #2, the trigger, and pin #6, the threshold, are used to control these switches. The trigger can close switch S2, and the threshold can close S1.

To begin the analysis of this circuit, assume that switch S1 is closed and switch S2 is open as shown in Figure 64–4. When the trigger is connected to a voltage that is less than ⅓ of Vcc, it causes switch S2 to close and switch S1 to open. When switch S2 closes, voltage is supplied to the output at pin #3. When switch S1 opens, the discharge is no longer connected to ground, and capacitor C1 begins to charge through resistors R1 and R2. When the voltage across C1 reaches ⅔ of Vcc, the threshold, pin #6, causes switch S1 to close and switch S2 to open. When switch S2 opens, the output turns off. When switch S1 closes, the discharge, pin #7, is connected to ground. Capacitor C1 then discharges through resistor R2. The timer will remain in this position until the trigger is again connected to a voltage that is less than ⅓ of Vcc.

If the trigger is connected permanently to a voltage less than ⅓ of Vcc, switch S2 will be held closed and switch S1 will be held open. This, of course, will stop the operation of the timer. As stated previously, the trigger must be a momentary pulse, not a continuous connection, in order for the 555 timer to operate.

Circuit Applications

The Oscillator

The 555 timer can perform a variety of functions. It is commonly used as an oscillator. The 555 timer has become popular for this application because it is so easy to use.

The 555 timer shown in Figure 64–5 has pin #2 connected to pin #6. This permits the timer to retrigger itself at the end of each time cycle. When the applied voltage is turned on, capacitor C1 is discharged and has a voltage of 0 volts across it. Since pin #2 is connected to pin #6, and the voltage at that point is less than ⅓ of Vcc, the timer will trigger. When the timer is triggered, two things happen at the same time: the output turns on, and the discharge turns off. When the discharge at

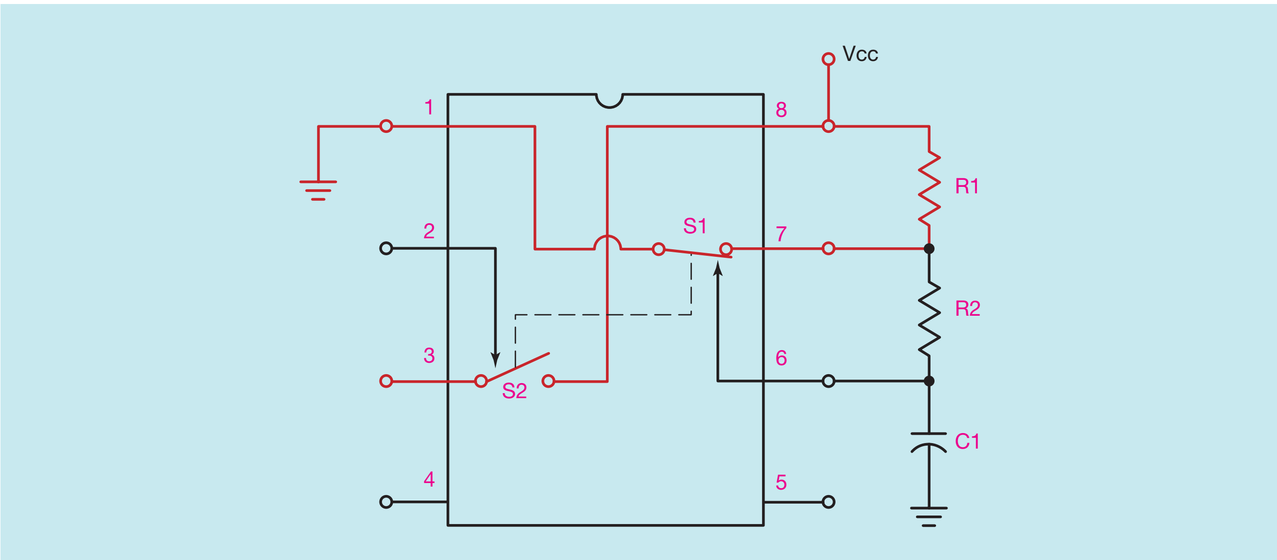


Figure 64–4 A simple circuit illustrates how the timer works. (Source: Delmar/Cengage Learning.)

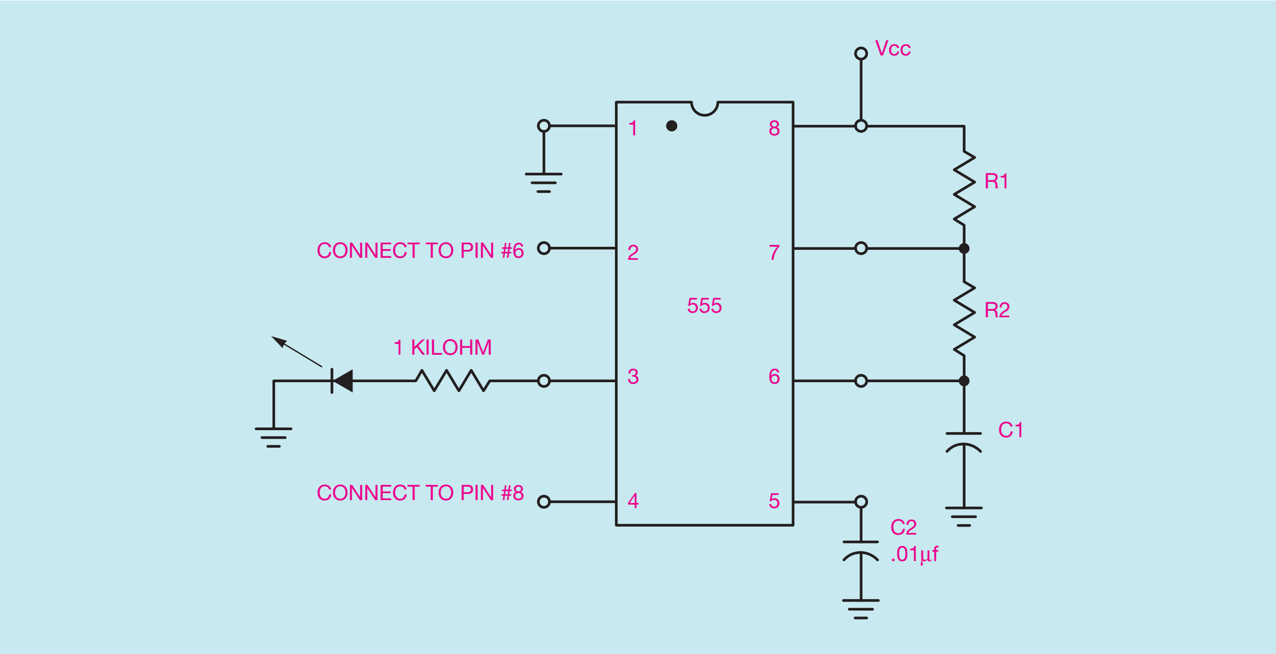


Figure 64–5 555 timer connected as a simple oscillator. (Source: Delmar/Cengage Learning.)

pin #7 turns off, capacitor C1 charges through resistors R1 and R2. The amount of time it takes for capacitor C1 to charge is determined by the capacitance of the capacitor and the combined resistance of R1 and R2.

When capacitor C1 is charged to a voltage that is ⅔ of Vcc, the output turns off, and the discharge at pin #7 turns on. When the discharge turns on, capacitor C1 discharges through resistor R2 to ground. The amount of time it takes C1 to discharge is determined by the capacitance of capacitor C1 and the resistance of R2. When capacitor C1 is discharged to a voltage that is ⅓ of Vcc, the timer is retriggered by pin #2, causing the output to turn on and the discharge to turn off. When the discharge turns off, capacitor C1 begins charging again.

The amount of time required to charge capacitor C1 is determined by the combined resistance of R1 and R2. The discharge time, however, is determined by the value of R2 (Figure 64–6).

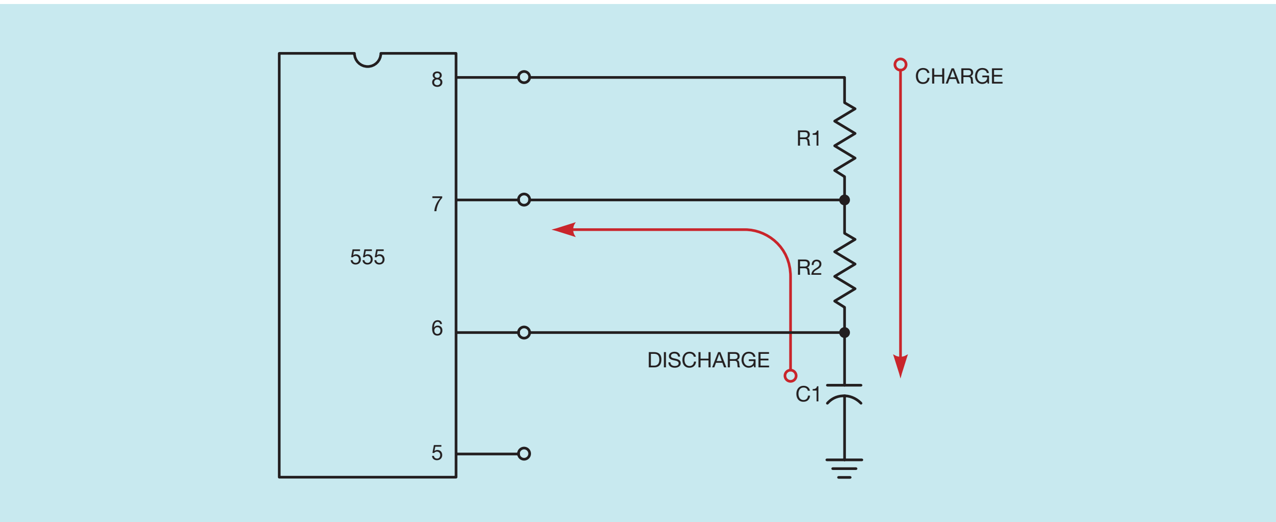


Figure 64–6 Charge time of C1 is determined by resistors R1 and R2. Discharge time of C1 is determined by resistor R2. (Source: Delmar/Cengage Learning.)

Since the timer's output is turned on while capacitor C1 is charging, and turned off while C1 is discharging, the on time of the output is longer than the off time. If the value of resistor R2 is much greater than the value of resistor R1, this condition is not too evident. For example, if resistor R1 has a value of 1 kilohm and R2 has a value of 100 kilohms, the resistance connected in series with the capacitor during charging is 101 kilohms. The resistance connected in series with the capacitor during discharge is 100 kilohms. In this circuit, the difference between the charge time and the discharge time of the capacitor is 1%. If an oscilloscope is connected to the output of the timer, a waveform similar to the waveform shown in Figure 64–7 will be seen.

Assume that the value of resistor R1 is changed to 100 kilohms and the value of resistor R2 remains at 100 kilohms. In this circuit, the resistance connected in series with the capacitor during charging is 200 kilohms. The resistance connected in series with the capacitor during discharge, however, is 100 kilohms. Therefore, the discharge time is 50% of the charge time. This means that the output of the timer will be turned on twice as long as it will be turned off. An oscilloscope connected to the output of the timer would display a waveform similar to the one shown in Figure 64–8.

Although this condition can exist, the 555 timer has a provision for solving the problem. Pin #5, the control voltage pin, can give complete control of the output voltage. If a variable resistor is connected between pin #5 and Vcc, the on time of the output can be lengthened to any value desired. If a variable resistor is connected between pin #5 and ground, the on time of the output can be shortened to any value desired. Since the on time of the timer is adjusted by connecting resistance to pin #5, the off time is set by the values of C1 and R2.

The output frequency of the unit is determined by the values of capacitor C1 and resistors R1 and R2. The 555 timer will operate at almost any frequency desired. It is used in many industrial electronic circuits that require the use of a square wave oscillator.

The On-Delay Timer

In this circuit, the 555 timer is used to construct an on-delay relay. The 555 produces accurate time delays that can range from seconds to hours depending on the values of resistance and capacitance used in the circuit. In Figure 64–9, transistor Q1 is used to switch relay coil K1 on or off. A transistor is used to control the relay because the 555 timer may not be able to supply the current needed to operate it.

Transistor Q2 is used as a stealer transistor to steal the base current from transistor Q1. As long as transistor Q2 is turned on by the output of the timer, transistor Q1 is turned off.

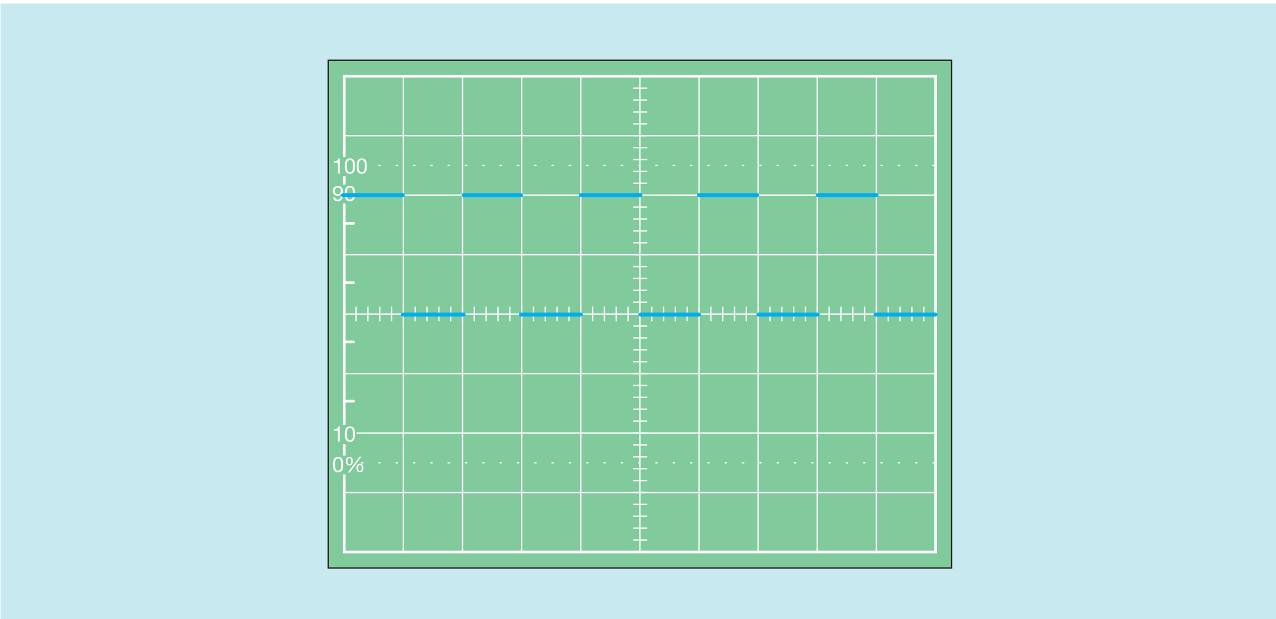


Figure 64–7 Waveform produced when an oscilloscope is connected to the output of the 555 timer. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

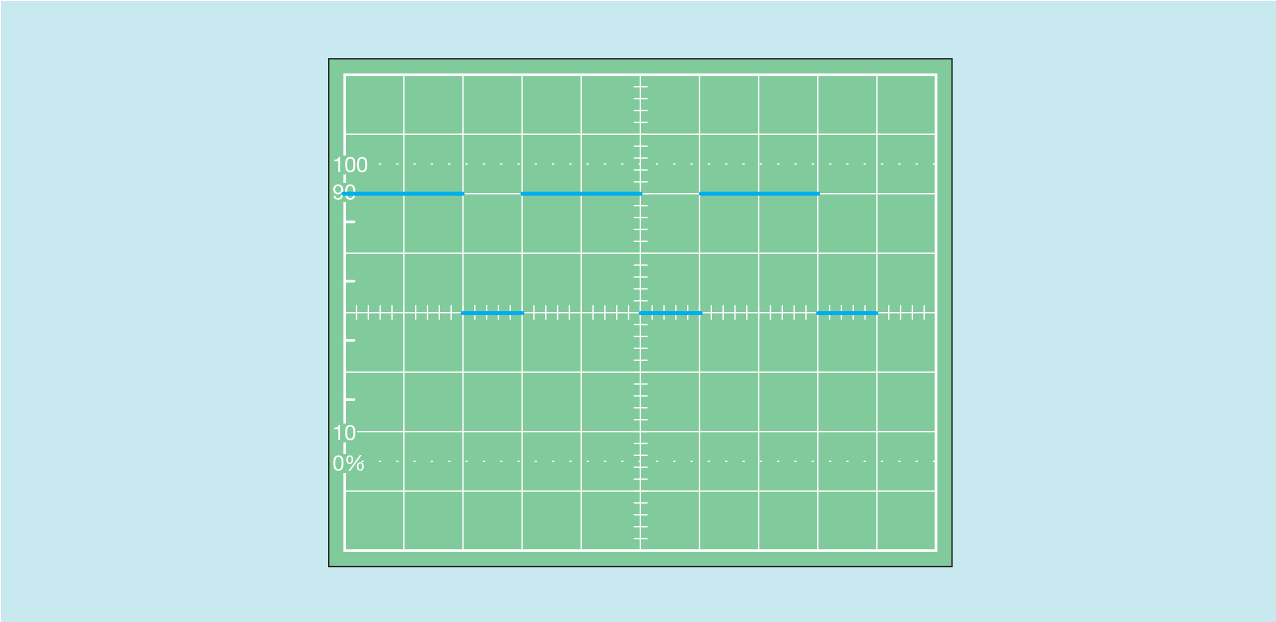


Figure 64–8 A different waveform is produced when the value of one of the resistors is changed. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

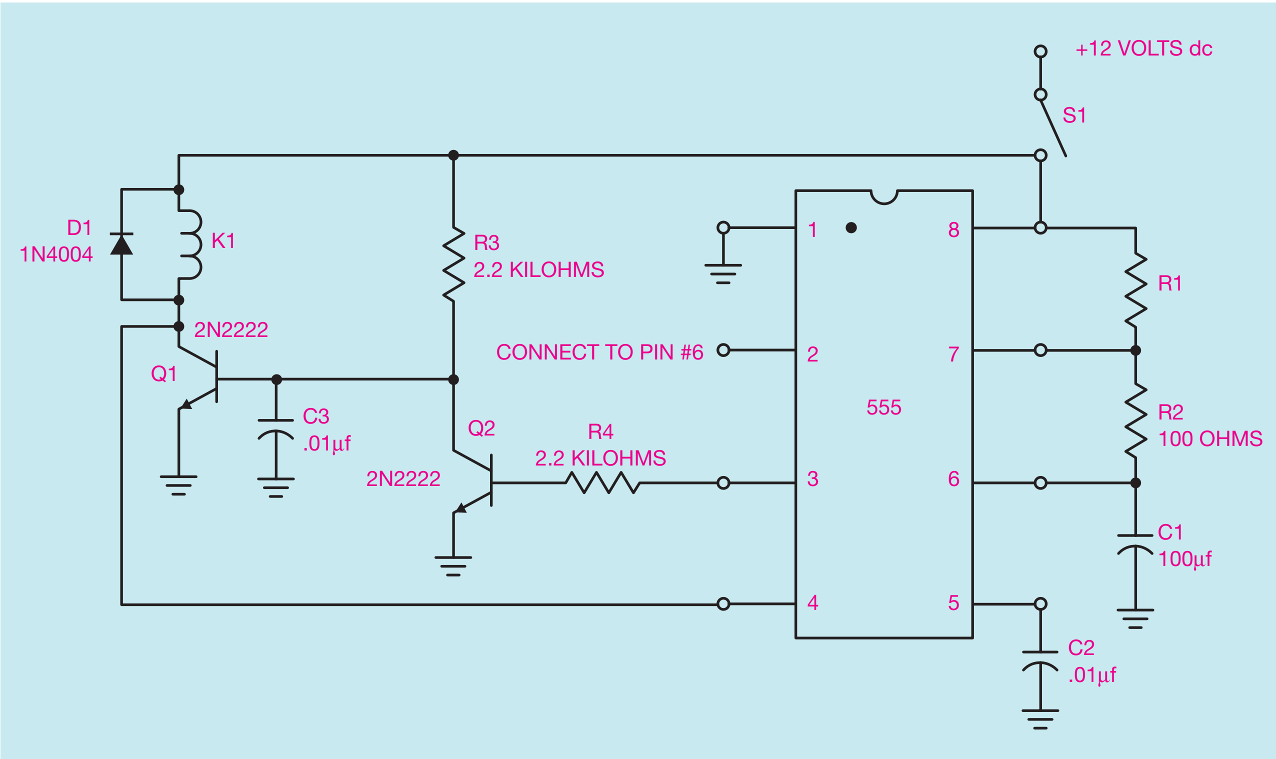


Figure 64–9 On-delay timer. (Source: Delmar/Cengage Learning.)

Capacitor C3 is connected from the base of transistor Q1 to ground. Capacitor C3 acts as a short time-delay circuit. When Vcc is turned on by switch S1, capacitor C3 is discharged. Before transistor Q1 can be turned on, capacitor C3 must be charged through resistor R3. This charging time is only a fraction of a second, but it ensures that transistor Q1 will not turn on before the output of the timer can turn transistor Q2 on. Once transistor Q2 has been turned on, it will hold transistor Q1 off by stealing its base current.

Diode Dl is used as a kickback, or freewheeling, diode to kill the spike voltage induced into the coil of relay K1 when switch S1 is opened. Resistor R3 limits the base current to transistor Q1 and resistor R4 limits the base current to transistor Q2.

Pin #4, the reset pin, is used as a latch in this circuit. When power is applied at Vcc, transistor Q1 is turned off. Since transistor Q1 is off, most of the applied voltage is dropped across the transistor, causing about 12 volts to appear at the collector of the transistor. Since pin #4 is connected to the collector of transistor Q1, 12 volts is applied to pin #4. For the timer to operate, pin #4 must be connected to a voltage that is greater than ⅔ of Vcc. When pin #4 is connected to a voltage that is less than ⅓ of Vcc, it turns on the discharge and keeps the timer from operating. When transistor Q1 turns on, the collector of the transistor drops to ground or 0 volts. Pin #4 is also connected to ground, which prevents the timer from further operation. Since the timer can no longer operate, the output remains turned off, which permits transistor Q1 to remain turned on.

Capacitor C1 and resistors R1 and R2 are used to set the amount of time delay. Resistor R2 should be kept at a value of about 100 ohms. The job of resistor R2 is to limit the current when capacitor C1 discharges. Resistor R2 has a relatively low value to enable capacitor C1 to discharge quickly. The time setting can be changed by changing the value of resistor R1.

To understand the operation of the circuit, assume that switch S1 is open and all capacitors are discharged. When switch S1 is closed, pin #2, which is connected to 0 volts, triggers the timer. When the timer is triggered, the output activates transistor Q2, which steals the base current from transistor Q1. Transistor Q1 remains off as long as transistor Q2 is on. When capacitor C1 has been charged to ⅔ of Vcc, the discharge turns on and the output of the timer turns off. When the output turns transistor Q2 off, transistor Q1 is supplied with base current through resistor R3 and turns on relay coil K1. When transistor Q1 is turned on, the voltage applied to the reset pin, #4, is changed from 12 volts to 0 volts. This causes the reset to lock the discharge on and the output off. Therefore, when transistor Q1 is turned on, switch S1 must be reopened to reset the circuit.

Review Questions

1. How is pin #1 of an in-line, integrated circuit identified?
2. A 555 timer is connected to produce a pulse at the output once each second. The timer is connected to 12 volts DC. If the voltage is reduced to 8 volts DC, the 555 will continue to operate at the same pulse rate. Explain why the timer will operate at the same pulse rate when the voltage is reduced.
3. What is the range of voltage the 555 timer will operate on?
4. Explain the function of the control voltage, pin #5, when the timer is being used as an oscillator.
5. Explain what happens to the output and discharge pins of the 555 timer when the trigger, pin #2, is connected to a voltage that is less than ⅓ of Vcc.
6. Explain what happens to the output and discharge pins when the threshold, pin #6, is connected to a voltage that is greater than ⅔ of Vcc.
7. Refer to figure 64–6. The values of what components determine the length of time the output will be turned on?
8. The values of what components determine the amount of time the output will remain turned off?
9. Explain the operation of pin #4 on the 555 timer.
10. What is a stealer transistor?

CHAPTER 65
THE OPERATIONAL AMPLIFIER

OBJECTIVES

After studying this chapter, the student will be able to:

- Discuss the operation of the operational amplifier (op amp).
- List the major types of connections for operational amplifiers.
- Connect a level detector circuit using an op amp.
- Connect an oscillator using an op amp.

The operational amplifier, like the 555 timer, has become a very common component in industrial electronic circuits. The operational amplifier, or op amp, is used in hundreds of applications. Different types of op amps are available for different types of circuits. Some op amps use bipolar transistors for input while others use field effect transistors. The advantage of field effect transistors is that they have an extremely high input impedance that can be several thousand megohms. As a result of this high input impedance, the amount of current needed to operate the amplifier is small. In fact, op amps that use field effect transistors for the inputs are generally considered to require no input current.

The ideal amplifier would have an input impedance of infinity. With an input impedance of infinity, the amplifier would not drain power from the signal source; therefore, the strength of the signal source would not be affected by the amplifier. The ideal amplifier would also have zero output impedance. With zero output impedance, the amplifier could be connected to any load resistance without causing a voltage drop inside the amplifier. If it had no internal voltage drop, the amplifier would utilize 100% of its gain. Finally, the ideal amplifier would have unlimited gain. This would enable it to amplify any input signal as much as desired.

Although the ideal amplifier does not exist, the op amp is close. In this chapter, the operation of an old op amp, the 741, is described as typical of all operational amplifiers. Other op amps may have different characteristics of input and output impedance, but the basic theory of operation is the same for all of them.

The 741 op amp uses bipolar transistors for the inputs. The input impedance is about 2 megohms, the output impedance is about 75 ohms, and the open loop, or maximum gain, is about 200,000. The 741 is impractical for use with such a high gain, so negative feedback (discussed later) is used to reduce the gain. For example, assume that the amplifier has an output voltage of 15 volts. If the input signal voltage is greater than 1/200,000 of the output voltage, or 75 microvolts,

$$\frac{15}{200{,}000} = .000075$$

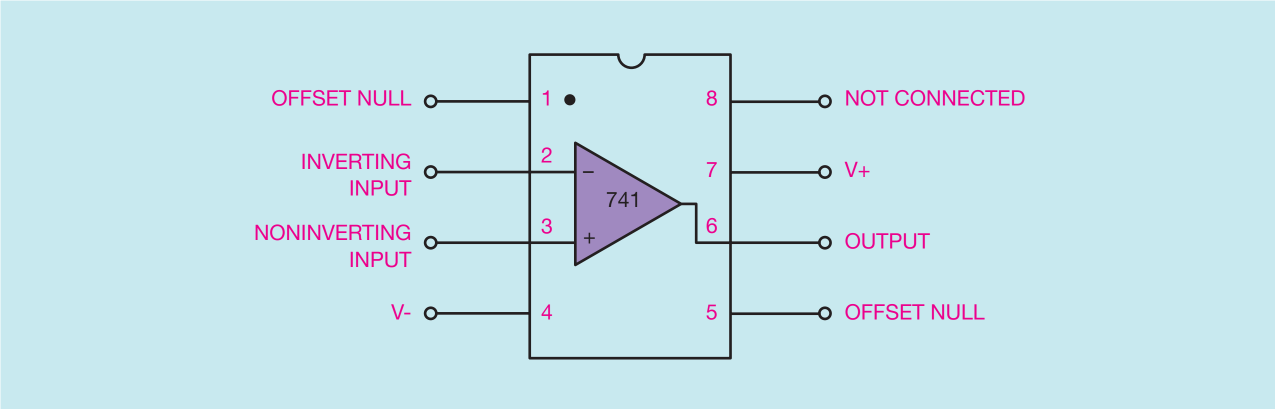


Figure 65–1 The 741 operational amplifier. (Source: Delmar/Cengage Learning.)

the amplifier will be driven into saturation, at which point it will not operate.

The 741 operational amplifier is usually housed in an eight-pin, in-line, integrated circuit package (Figure 65–1). The op amp has two inputs, the *inverting input* and the *noninverting input.* These inputs are connected to a differential amplifier that amplifies the difference between the two voltages. If both of these inputs are connected to the same voltage, say by grounding both inputs, the output should be 0 volts. In actual practice, however, unbalanced conditions within the op amp may cause a voltage to be produced at the output. Since the op amp has a very high gain, a slight imbalance of a few microvolts at the input can produce several millivolts at the output. To counteract any imbalance, pins #1 and #5 are connected to the offset null, which is used to produce 0 volts at the output. These pins are adjusted after the 741 is connected in a working circuit. To make the adjustments, a 10 kilohm potentiometer is connected across pins #1 and #5, and the wiper is connected to the negative voltage (Figure 65–2).

Pin #2 is the inverting input. When a signal voltage is applied to this input, the output is inverted. For example, if a positive AC voltage is applied to the inverting input, the output will be a negative voltage (Figure 65–3).

Pin #3 is the noninverting input. When a signal voltage is applied to the noninverting input, the output voltage is the same polarity. For example, if a positive AC voltage is applied to the noninverting input, the output voltage will be positive also (Figure 65–4).

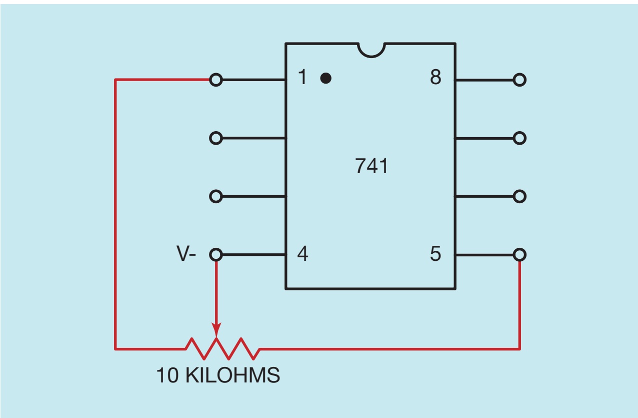


Figure 65–2 The offset null connection. (Source: Delmar/Cengage Learning.)

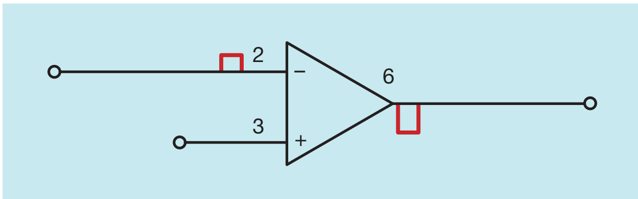


Figure 65–3 Inverting output. (Source: Delmar/Cengage Learning.)

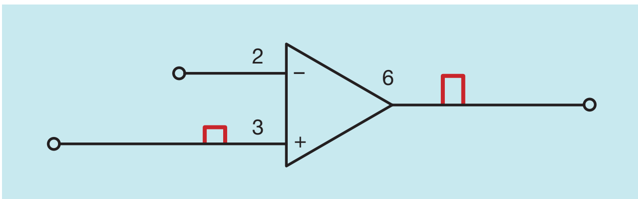


Figure 65–4 Noninverted output. (Source: Delmar/Cengage Learning.)

Operational amplifiers are usually connected to above and below ground power supplies. Although there are some circuit connections that do not require an above and below ground power supply, these are the exception instead of the rule. Pins #4 and #7 are the voltage input pins. Pin #4 is connected to the negative, or below ground, voltage and pin #7 is connected to the positive, or above ground, voltage.

The 741 operates on voltages that range from about 4 volts to 16 volts. Generally, the operating voltage for the 741 is 12 to 15 volts plus and minus. The 741 has a maximum power output rating of about 500 milliwatts.

Pin #6 is the output and pin #8 is not connected.

As stated previously, the open loop gain of the 741 operational amplifier is about 200,000. Since this amount of gain is not practical for most applications, something must be done to reduce the gain to a reasonable level. One of the great advantages of the op amp is the ease with which the gain can be controlled (Figure 65–5). The amount of gain is controlled by a negative feedback loop. This is accomplished by feeding a portion of the output voltage back to the inverting input. Since the output voltage is always opposite in polarity to the inverting input voltage, the amount of output voltage fed back to the input tends to reduce the input voltage. Negative feedback affects the operation of the amplifier in two ways: it reduces the gain, and it makes the amplifier more stable.

The gain of the amplifier is controlled by the ratio of resistor R2 to resistor R1. If a noninverting amplifier is used, the formula

$$\frac{R1 + R2}{R1}$$

is used to calculate the gain. If resistor R1 is 1 kilohm and resistor R2 is 10 kilohms, the gain of the amplifier is 11.

$$\frac{11{,}000}{1{,}000} = 11$$

If the op amp is connected as an inverting amplifier, the input signal will be out of phase with the feedback voltage of the output. This will cause a reduction in the input voltage applied to the amplifier and in the gain. The formula

$$\frac{R2}{R1}$$

is used to compute the gain of an inverting amplifier. If resistor R1 is 1 kilohm and resistor R2 is 10 kilohms, the gain of the inverting amplifier is 10.

$$\frac{10{,}000}{1{,}000} = 10$$

As a general rule, the 741 operational amplifier is not operated above a gain of about 100 because it tends to become unstable at high gains. If more gain is desired, it is obtained by using more than one amplifier (Figure 65–6). The output of one amplifier is fed into the input of another amplifier.

Another general rule for operating the 741 op amp is that the total feedback resistance (R1 + R2) is kept at more than 1,000 ohms and less than 100,000 ohms. These rules apply to the 741 operational amplifier but may not apply to other operational amplifiers.

Basic Circuits

Op amps are generally used in three basic circuits that are used to build other circuits. One of these basic circuits is the voltage follower. In this circuit, the output of the op amp is connected directly back to the inverting input (Figure 65–7). Since there is a direct

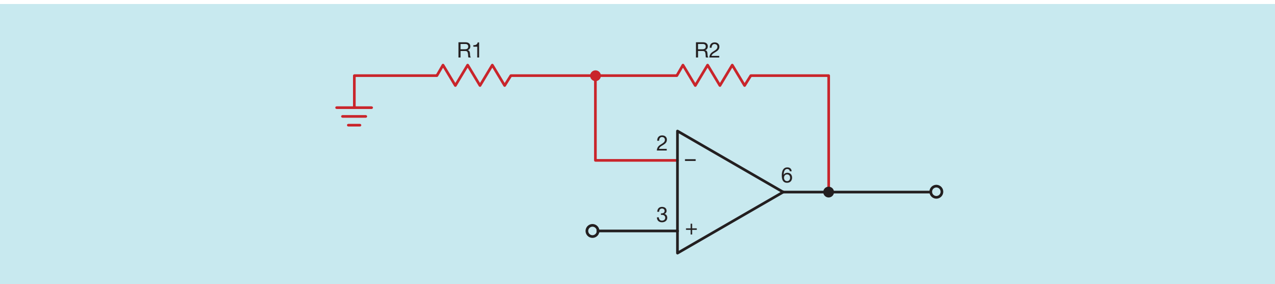


Figure 65–5 Negative feedback connection. (Source: Delmar/Cengage Learning.)

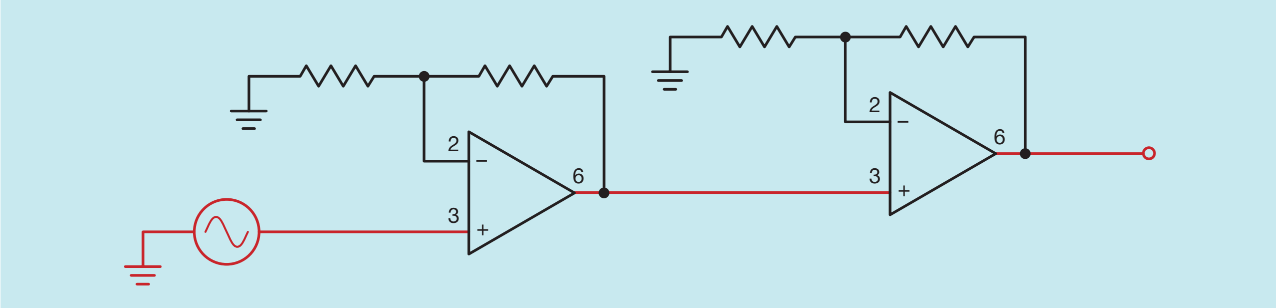


Figure 65–6 Two operational amplifiers are used to obtain a higher gain. (Source: Delmar/Cengage Learning.)

connection between the output of the amplifier and the inverting input, the gain of this circuit is 1. For example, if a signal voltage of 0.5 volts is connected to the noninverting input, the output voltage will be 0.5 volts also. You may wonder why anyone would want an amplifier that doesn't amplify. Actually, this circuit does amplify something. It amplifies the input impedance by the amount of the open loop gain. If the 741 has an open loop gain of 200,000 and an input impedance of 2 megohms, this circuit will give the amplifier an input impedance of 200 k × 2 meg, or 400,000 megohms. This circuit connection is generally used for impedance matching purposes.

The second basic circuit is the noninverting amplifier (Figure 65–8). In this circuit, the output voltage has the same polarity as the input voltage. If the input voltage is positive, the output voltage will be positive also. The formula

$$\frac{R1 + R2}{R1}$$

is used to calculate the amount of gain in the negative feedback loop.

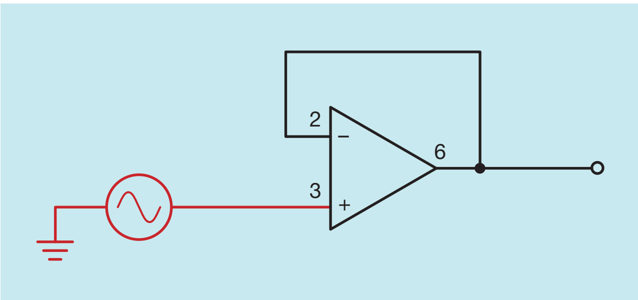


Figure 65–7 Voltage follower connection. (Source: Delmar/Cengage Learning.)

The third basic circuit is the inverting amplifier (Figure 65–9). In this circuit, the output voltage is opposite in polarity to the input voltage. If the input signal is positive, the output voltage will be negative at the same instant in time. The formula

$$\frac{R2}{R1}$$

is used to calculate the amount of gain in this circuit.

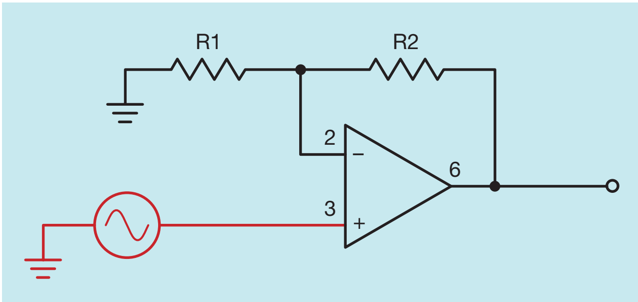


Figure 65–8 Noninverting amplifier connection. (Source: Delmar/Cengage Learning.)

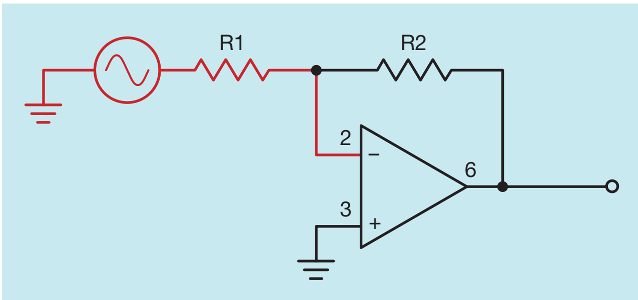


Figure 65–9 Inverting amplifier connection. (Source: Delmar/Cengage Learning.)

Circuit Applications

The Level Detector

The operational amplifier is often used as a level detector or comparator. In this type of circuit, the 741 op amp is used as an inverted amplifier to detect when one voltage becomes greater than another (Figure 65–10). This circuit does not use above and below ground power supplies. Instead, it is connected to a power supply that has a single positive and negative output.

During normal operation, the noninverting input of the amplifier is connected to a zener diode that produces a constant positive voltage at the noninverting input of the amplifier. This constant positive voltage is used as a reference. As long as the noninverting input is more positive than the inverting input, the output of the amplifier is high.

A light-emitting diode (LED), D1, is used to detect a change in the polarity of the output. As long as the output of the op amp is high, the LED is turned off. When the output of the amplifier is high, the LED has equal voltage applied to its anode and cathode. Since both the anode and cathode are connected to +12 volts, there is no potential difference and, therefore, no current flow through the LED.

If the voltage at the inverting input becomes more positive than the reference voltage applied to pin #3, the output voltage will fall to about +2.5 volts. The output voltage of the op amp will not fall to 0 or ground in this circuit because the op amp is not connected to a voltage that is below ground. To enable the output voltage to fall to 0 volts, pin #4 must be connected to a voltage below ground. When the output drops, a potential of about 9.5 volts (12 – 2.5 = 9.5) is produced across R1 and D1. The lowering of potential causes the LED to turn on, which indicates that the op amp's output has changed from high to low.

In this type of circuit, the op amp appears to be a digital device in that the output seems to have only two states, high and low. But, the op amp is not a digital device. This circuit only makes it appear to be digital. In Figure 65–10, there is no negative feedback loop connected between the output and the inverting input. Therefore, the amplifier uses its open loop gain, which is about 200,000 for the 741, to amplify the voltage difference between the inverting input and the noninverting input. If the voltage applied to the inverting input becomes 1 millivolt more positive than the reference voltage applied to the noninverting input, the amplifier will try to produce an output that is 200 volts more negative than its high state voltage ($0.001 \times 200{,}000 = 200$). The output voltage of the amplifier cannot be driven 200 volts more negative, though, because only 12 volts are applied to the circuit. Therefore, the output voltage reaches the lowest voltage it can and goes into saturation. This causes the op amp to act like a digital device.

If the zener diode is replaced with a voltage divider as shown in Figure 65–11, the reference voltage can be set to any value by adjusting the variable resistor. For example, if the voltage at the noninverting input is set for 3 volts, the output of the op amp will go low when the voltage applied to the inverting input becomes greater than +3 volts. If the voltage at the

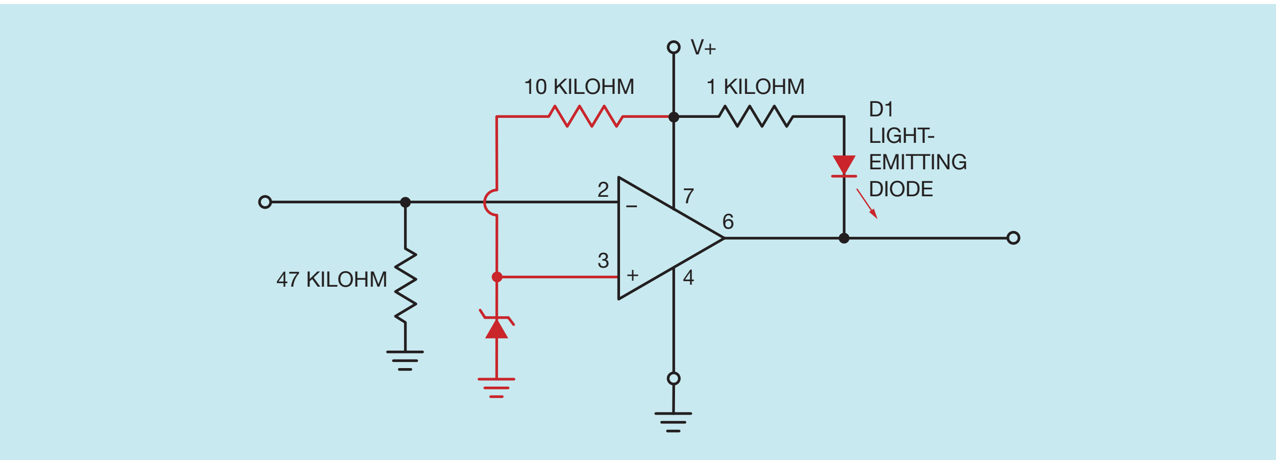


Figure 65–10 Inverting level detector. (Source: Delmar/Cengage Learning.)

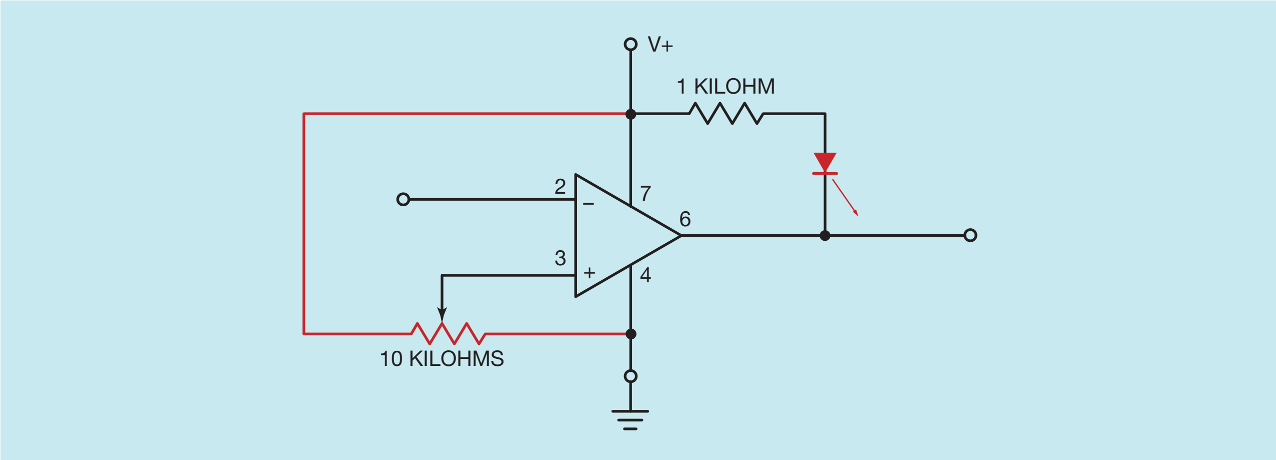


Figure 65–11 Adjustable inverting level detector. (Source: Delmar/Cengage Learning.)

noninverting input is set for 8 volts, the output voltage will go low when the voltage applied to the inverting input becomes greater than +8 volts. In this circuit, the output of the op amp can be manipulated through the adjustment of the noninverting input.

In the two circuits just described, the op amp's output shifted from a high level to a low level. There may be occasions, however, when the output must be changed from a low level to a high level. This can be accomplished by connecting the inverting input to the reference voltage, and the noninverting input to the voltage being sensed (Figure 65–12). In this circuit, the zener diode is used to supply a positive reference voltage to the inverting input. As long as the voltage at the inverting input is more positive than the voltage at the noninverting input, the output voltage of the op amp will be low. If the voltage applied to the noninverting input becomes more positive than the reference voltage, the output of the op amp will become high.

Depending on the application, this circuit could cause a small problem. As stated previously, since this circuit does not use an above and below ground power supply, the low output voltage of the op amp is about +2.5 volts. This positive output voltage could cause any other devices connected to the op amp's output to be on when they should be off. For instance, if the LED shown in Figure 65–12 is used, it will glow dimly even when the output is in the low state.

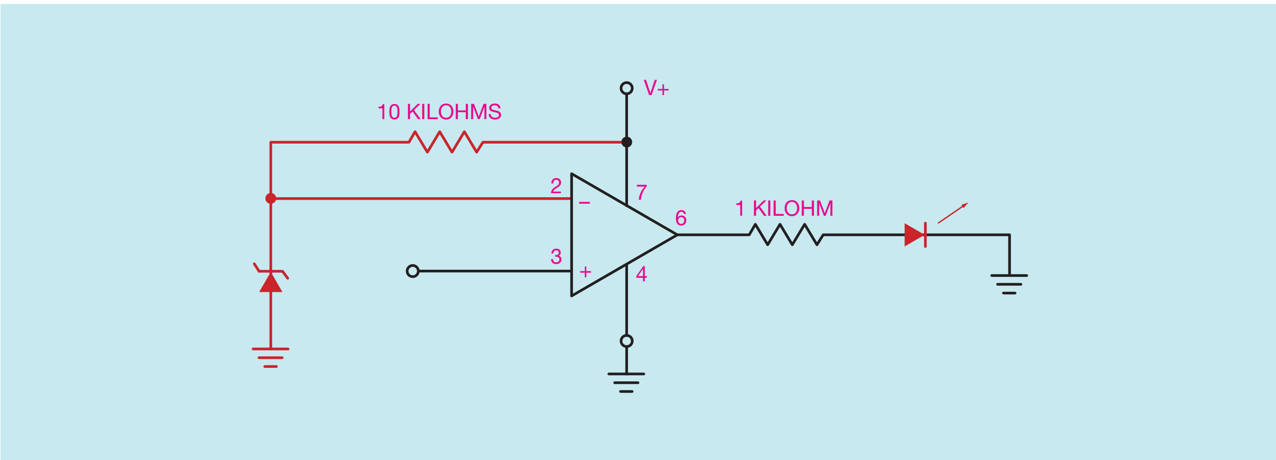


Figure 65–12 Noninverting level detector. (Source: Delmar/Cengage Learning.)

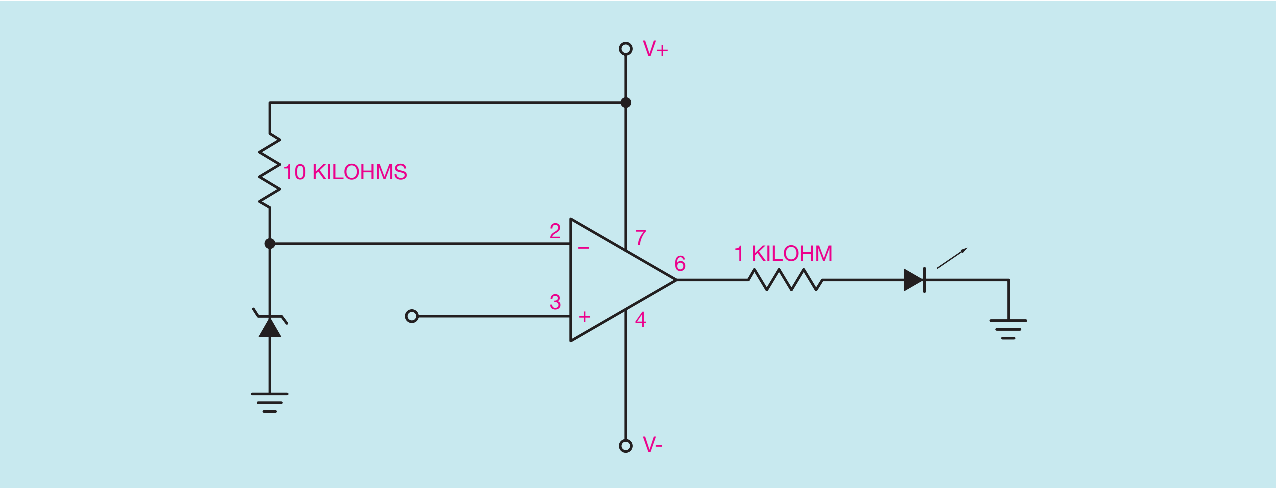


Figure 65–13 Below ground power connection permits the output voltage to become negative. (Source: Delmar/Cengage Learning.)

One way to correct this problem is to connect the op amp to an above and below ground power supply as shown in Figure 65–13. In this circuit, the output voltage of the op amp is negative or below ground as long as the voltage applied to the inverting input is more positive than the voltage applied to the noninverting input. When the output voltage of the op amp is negative with respect to ground, the LED is reverse biased and cannot operate. If the voltage applied to the noninverting input becomes more positive than the voltage applied to the inverting input, the output of the op amp will become positive and the LED will turn on.

Another method of correcting the output voltage problem is shown in Figure 65–14. In this circuit, the op amp is connected again to a power supply that has a single positive and negative output. A zener diode, D2, is connected in series with the output of the op amp and the LED. The voltage value of diode D2 is greater than the output voltage of the op amp in its low state, but less than the output voltage of the op amp in its high state. For instance, assume that the value of zener diode D2 is 5.1 volts. If the output voltage of the op amp in its low state is 2.5 volts, diode D2 will not conduct. If the output voltage becomes +12 volts when the op amp

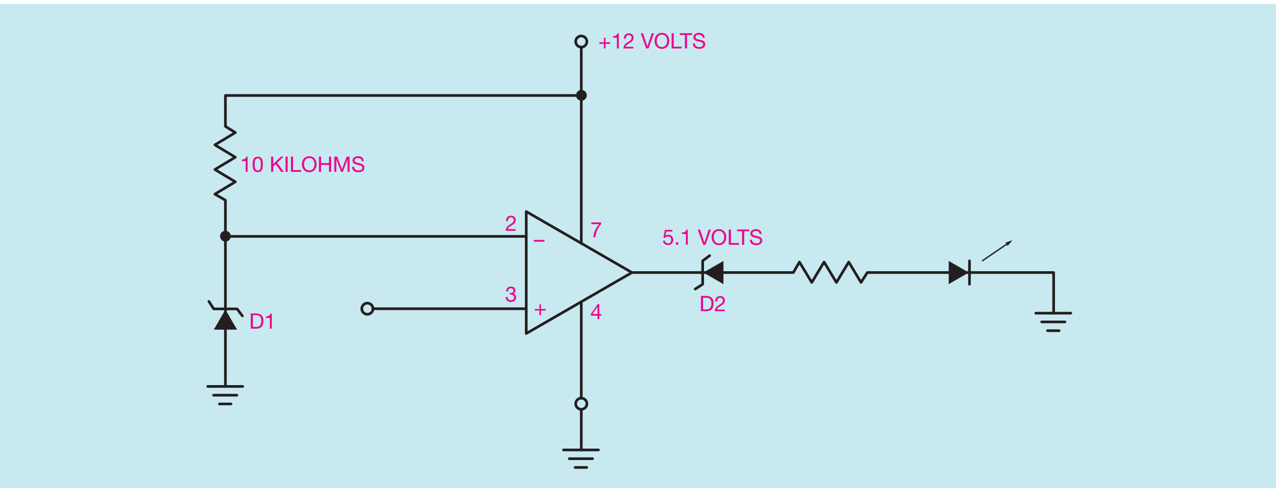


Figure 65–14 A zener diode is used to keep the output turned off. (Source: Delmar/Cengage Learning.)

switches to its high state, diode D2 will turn on and conduct current to the LED. The zener diode, D2, keeps the LED completely off until the op amp switches to its high state, providing enough voltage to overcome the reverse voltage drop of the zener diode.

In the preceding circuits, an LED was used to indicate the output state of the amplifier. Keep in mind that the LED is used only as a detector, while the output of the op amp can be used to control almost anything. For example, the output of the op amp can be connected to the base of a transistor as shown in Figure 65–15. The transistor can then control the coil of a relay which could, in turn, control almost anything.

The Oscillator

The operational amplifier can be used as an oscillator. The simple circuit shown in Figure 65–16 produces a square wave output. However, this circuit is impractical because it depends on a slight imbalance in the op amp, or random circuit noise, to start the oscillator. A voltage difference of a few millivolts between the two inputs is all that is needed to raise or lower the output of the amplifier. For example, if the inverting input becomes slightly more positive than the noninverting input, the output will go low or become negative. When the output is negative, capacitor CT

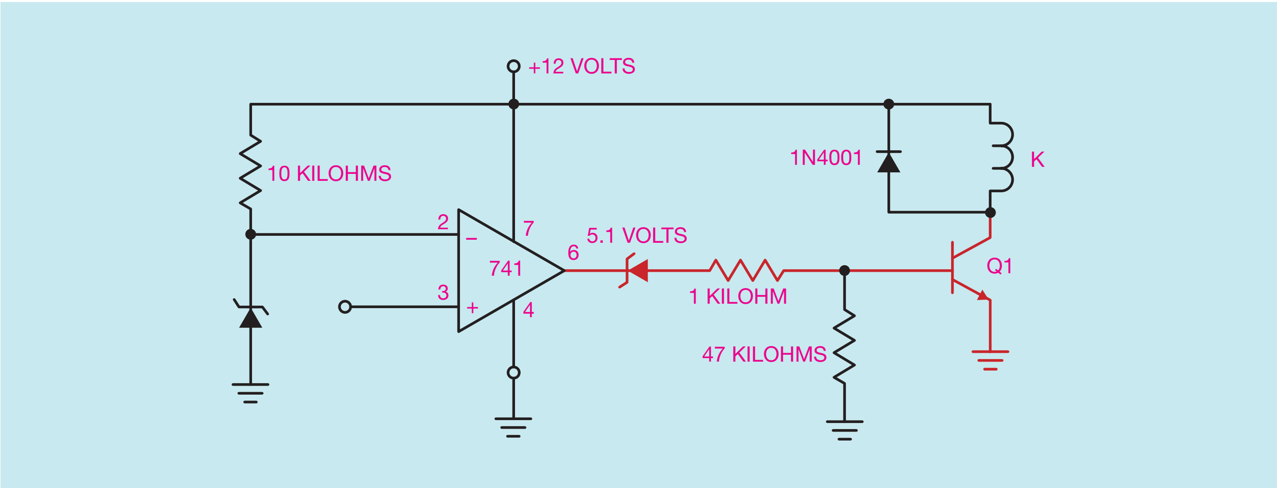


Figure 65–15 The operational amplifier supplies the base current for a switching transistor. (Source: Delmar/Cengage Learning.)

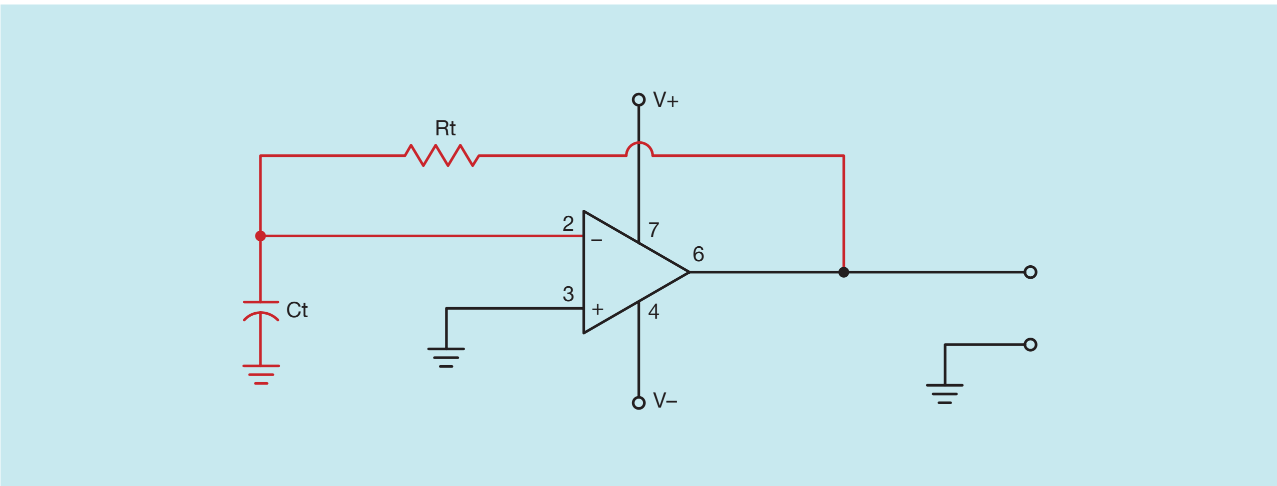


Figure 65–16 A simple square wave oscillator. (Source: Delmar/Cengage Learning.)

charges through resistor RT to the negative value of the output voltage. When the voltage applied to the inverting input becomes slightly more negative than the voltage applied to the noninverting input, the output changes to a high, or positive, value of voltage. When the output is positive, capacitor CT charges through resistor RT toward the positive output voltage.

This circuit would work well if there were no imbalance in the op amp and if the op amp were shielded from all electrical noise. In practical application, however, there is generally enough imbalance in the amplifier or enough electrical noise to send the op amp into saturation, which stops the operation of the circuit.

The problem with this circuit is that a millivolt difference between the two inputs is enough to drive the amplifier's output from one state to the other. This problem can be corrected by the addition of a hysteresis loop connected to the noninverting input as shown in Figure 65–17. Resistors R1 and R2 form a voltage divider for the noninverting input. These resistors generally have equal value. To understand the circuit operation, assume that the inverting input is slightly more positive than the noninverting input. This causes the output voltage to be negative. Also assume that the output voltage is −12 volts as compared to ground. If resistors R1 and R2 have equal value, the noninverting input is driven to −6 volts by the voltage divider. Capacitor CT begins to charge through resistor RT to the value of the output voltage. When capacitor CT has been charged to a value slightly more negative than the −6 volts applied to the noninverting input, the op amp's output rises to +12 volts above ground. When the output of the op amp changes from −12 volts to +12 volts, the voltage applied to the noninverting input changes from −6 volts to +6 volts. Capacitor CT now begins to charge through resistor RT to the positive voltage of the output. When the voltage applied to the inverting input becomes more positive than the voltage applied to the noninverting input, the output changes to −12 volts. The voltage applied to the noninverting input is driven from +6 volts to −6 volts, and capacitor CT again begins to charge toward the negative output voltage of the op amp.

The addition of the hysteresis loop has greatly changed the operation of the circuit. The voltage differential between the two inputs is now volts instead of millivolts. The output frequency of the oscillator is determined by the values of CT and RT. The period of one cycle can be computed by using the formula T = 2RC.

The Pulse Generator

The operational amplifier can be used as a pulse generator. The difference between an oscillator and a pulse generator is the period of time the output is on compared to the period of time it is low or off. For instance, an oscillator is generally considered to produce a waveform that has positive and negative pulses of equal voltage and time (Figure 65–18). The positive value of voltage is the same as the negative value, and the positive and negative cycles are turned on for the same amount of time. This waveform is produced when an oscilloscope is connected to the output of a square wave oscillator.

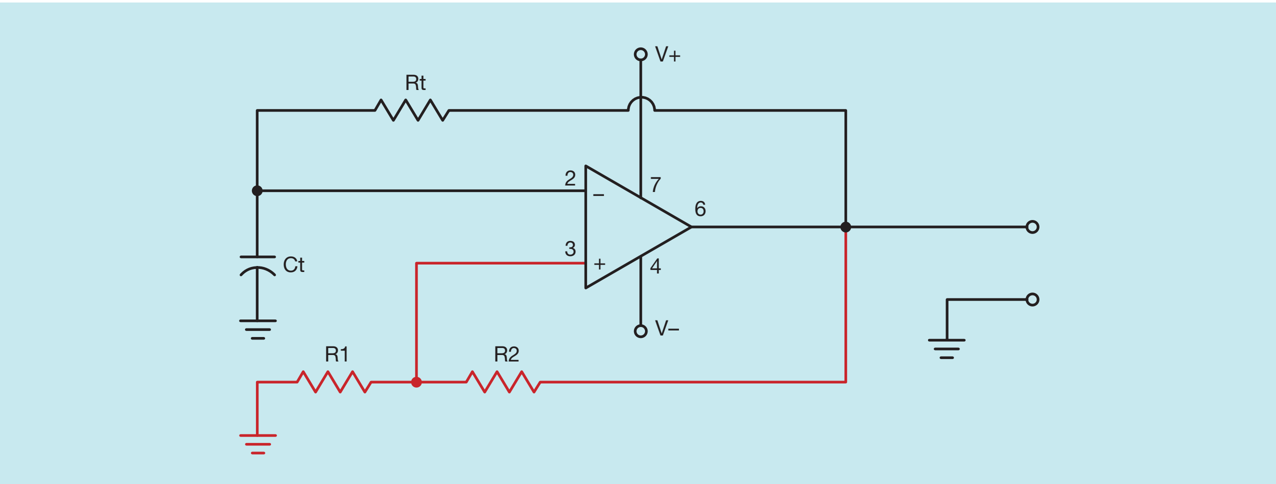


Figure 65–17 A square wave oscillator using a hysteresis loop. (Source: Delmar/Cengage Learning.)

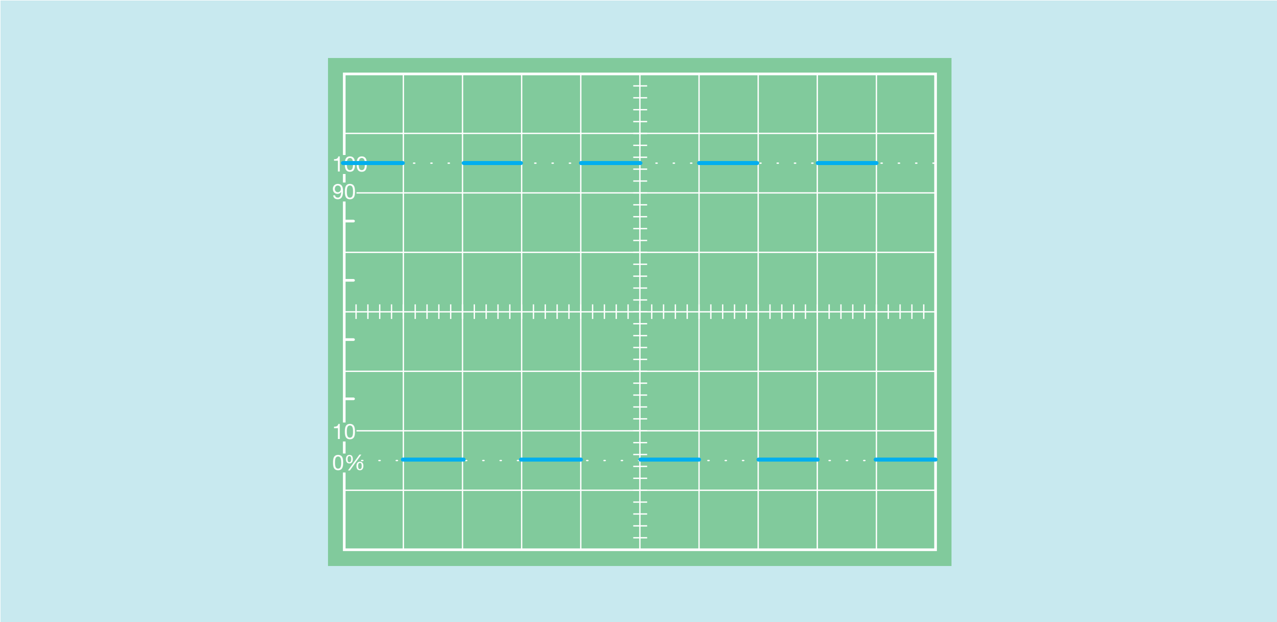


Figure 65–18 Output of an oscillator. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

If the oscilloscope is connected to a pulse generator, however, a waveform similar to the one shown in Figure 65–19 will be produced. The positive value of voltage is the same as the negative value, just as it was in Figure 65–18, but the positive pulse is of a much shorter duration than the negative pulse.

The 741 operational amplifier can easily be changed from a square wave oscillator to a pulse generator (Figure 65–20). The pulse generator circuit is the same basic circuit as the square wave oscillator with the addition of resistors R3 and R4, and diodes D1 and D2. This circuit permits capacitor CT to charge at a

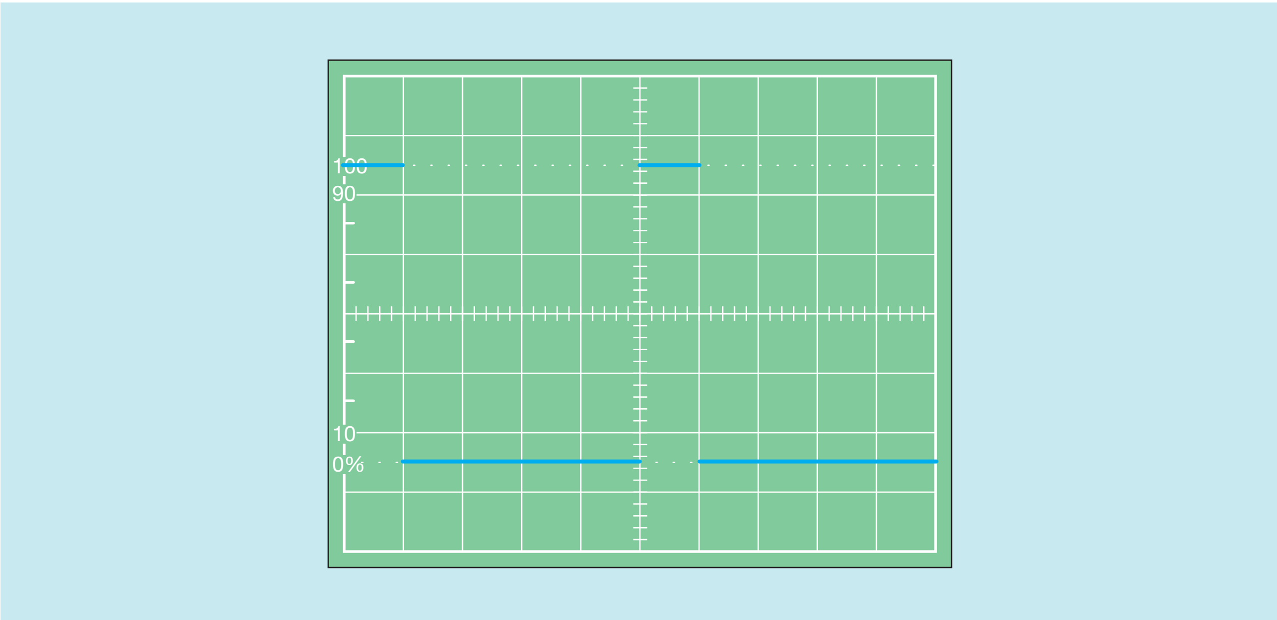


Figure 65–19 Output of a pulse generator. (Reproduced by permission of Tektronix, Inc., copyright © 1983.)

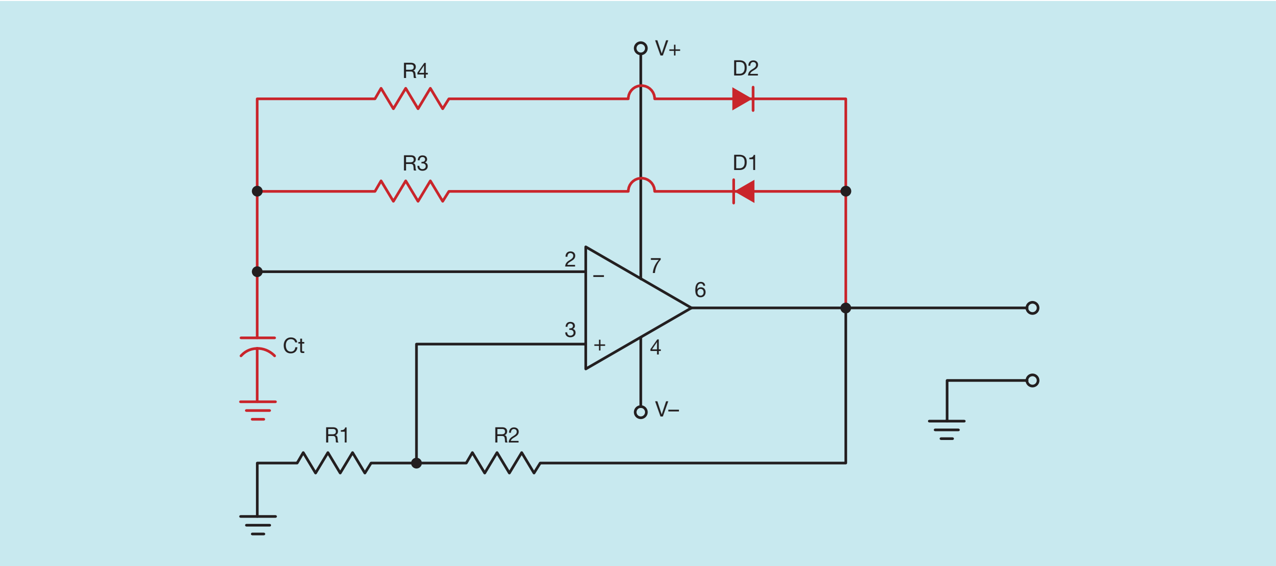


Figure 65–20 Pulse generator circuit. (Source: Delmar/Cengage Learning.)

different rate when the output is high, or positive, than when the output is low, or negative. For instance, assume that the voltage of the op amp's output is −12 volts. When the output voltage is negative, diode D1 is reverse biased and no current can flow through resistor R3. Therefore, capacitor CT must charge through resistor R4 and diode D2, which is forward biased. When the voltage applied to the inverting input becomes more negative than the voltage applied to the noninverting input, the output voltage of the op amp rises to +12 volts. When the output voltage is +12 volts, diode D2 is reverse biased and diode D1 is forward biased. Therefore, capacitor CT begins charging toward the +12 volts through resistor R3 and diode D1. The amount of time the output of the op amp is low is determined by the value of CT and R4, and the amount of time the output remains high is determined by the value of CT and R3. The ratio of the amount of time the output voltage is high to the amount of time it is low can be determined by the ratio of resistor R3 to resistor R4. A typical 741 operational amplifier is shown in Figure 65–21.

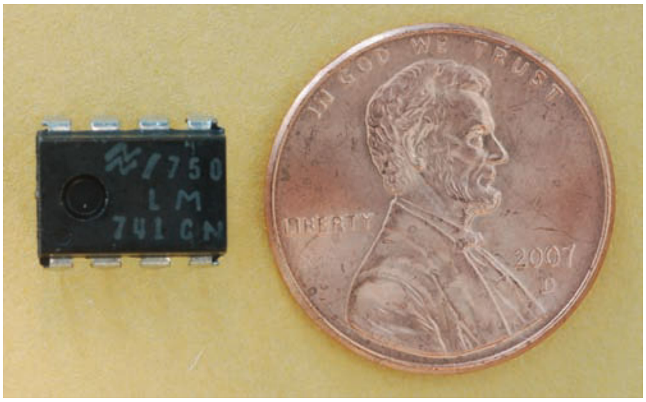


Figure 65–21 Typical 741 Operational Amplifier (Source: Delmar/Cengage Learning.)

Review Questions

1. When the voltage connected to the inverting input is more positive than the voltage connected to the noninverting input, will the output be positive or negative?
2. What is the input impedance of a 741 operational amplifier?
3. What is the average open loop gain of the 741 operational amplifier?
4. What is the average output impedance of the 741 operational amplifier?
5. Operational amplifiers are commonly used in what three connections?

6. When the operational amplifier is connected as a voltage follower, it has a gain of 1 (one). If the input voltage is not amplified, what is?
7. Name two effects of negative feedback.
8. Refer to Figure 65–8. If resistor R1 is 200 ohms and resistor R2 is 10 kilohms, what is the gain of the amplifier?
9. Refer to Figure 65–9. If resistor R1 is 470 ohms and resistor R2 is 47 kilohms, what is the gain of the amplifier?
10. What is the purpose of the hysteresis loop when the op amp is used as an oscillator?

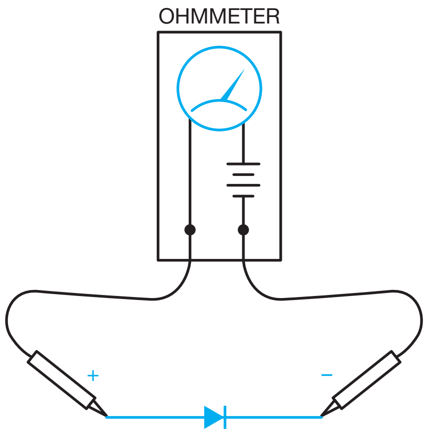
This page intentionally left blank

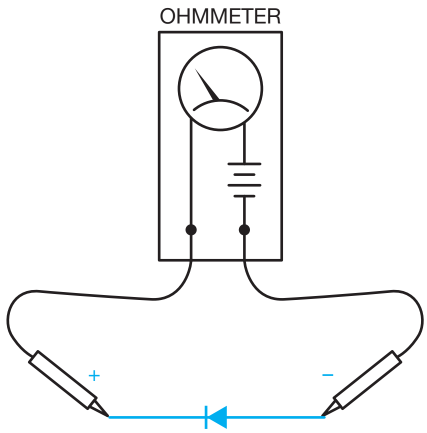
APPENDIX

Testing Solid-State Components

1. Testing a Diode

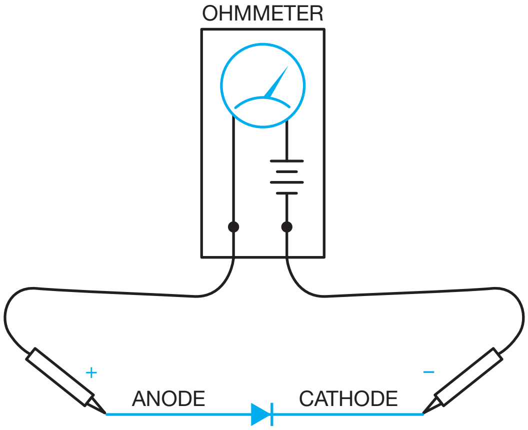
1. Connect the ohmmeter leads to the diode. Notice if the meter indicates continuity through the diode or not.
2. Reverse the diode connection to the ohmmeter. Notice if the meter indicates continuity through the diode or not. The ohmmeter should indicate continuity through the diode in only one direction. NOTE: If continuity is not indicated in either direction, the diode is open. If continuity is indicated in both directions, the diode is shorted.



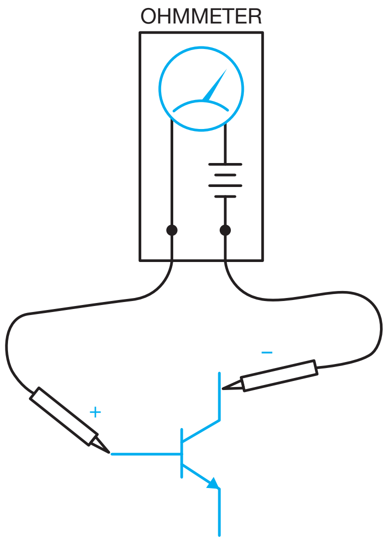


2. Testing a Transistor

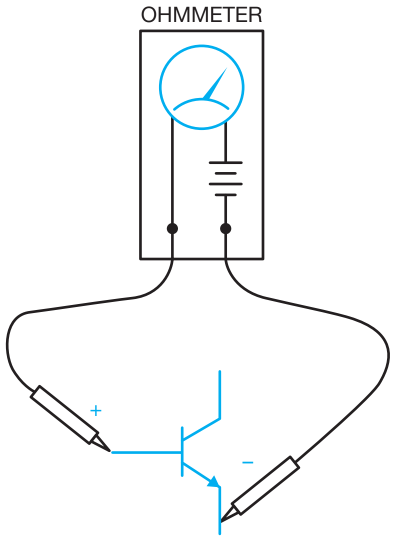
1. Using a diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity through the diode only when the positive lead is connected to the anode and the negative lead is connected to the cathode.



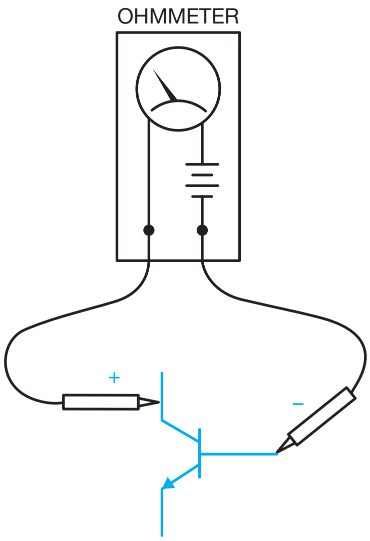
2. If the transistor is an NPN, connect the positive ohmmeter lead to the base and the negative lead to the collector. The ohmmeter should indicate continuity. The reading should be about the same as the reading obtained when the diode was tested.



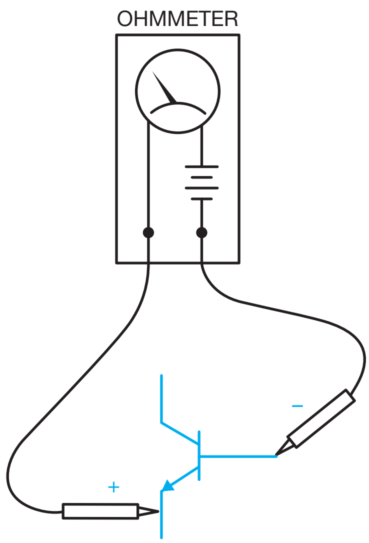
3. With the positive ohmmeter lead still connected to the base of the transistor, connect the negative lead to the emitter. The ohmmeter should again indicate a forward diode junction. NOTE: If the ohmmeter does not indicate continuity between the base-collector or the base-emitter, the transistor is open.



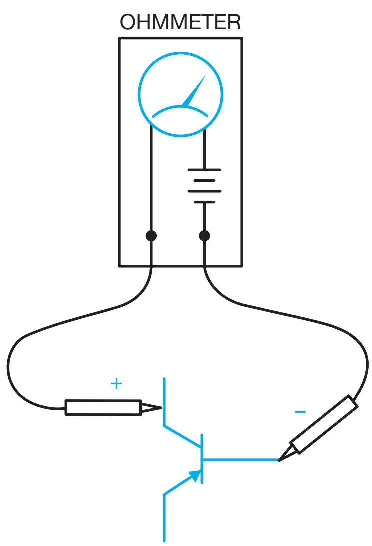
4. Connect the negative ohmmeter lead to the base and the positive lead to the collector. The ohmmeter should indicate infinity or no continuity.



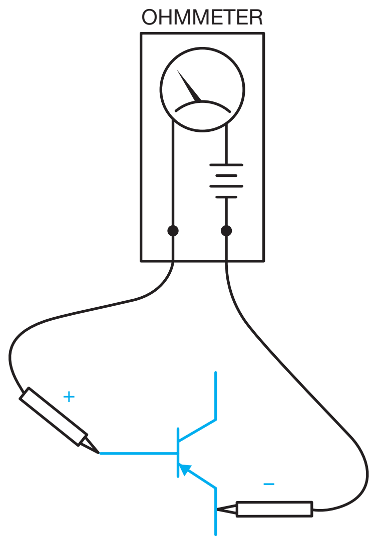
5. With the negative ohmmeter lead connected to the base, reconnect the positive lead to the emitter. There should, again, be no indication of continuity. NOTE: If a very high resistance is indicated by the ohmmeter, the transistor is "leaky" but it may still operate in the circuit. If a very low resistance is seen, the transistor is shorted.



6. To test a PNP transistor, reverse the polarity of the ohmmeter leads and repeat the test. When the negative ohmmeter lead is connected to the base, a forward diode junction should be indicated when the positive lead is connected to the collector or emitter.

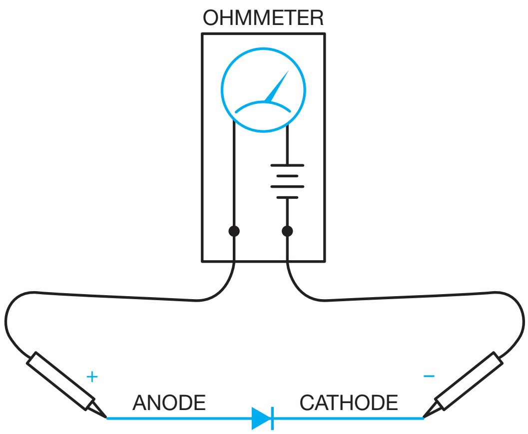


7. If the positive ohmmeter lead is connected to the base of a PNP transistor, no continuity should be indicated when the negative lead is connected to the collector or the emitter.

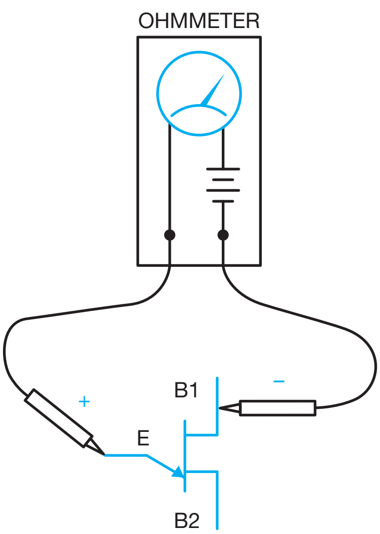


3. Testing a Unijunction Transistor

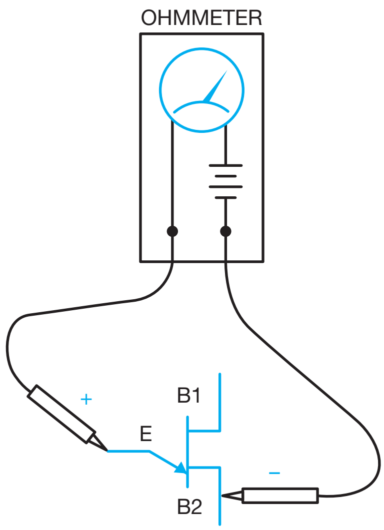
1. Using a junction diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity when the positive lead is connected to the anode and the negative lead is connected to the cathode.



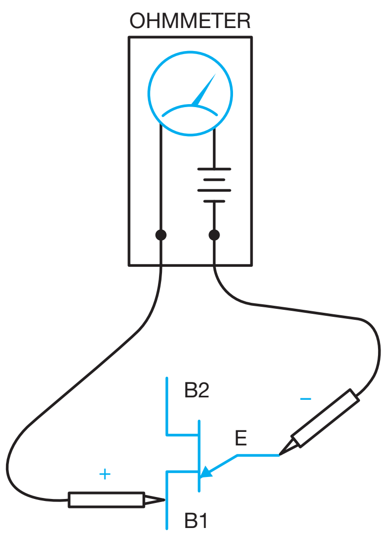
2. Connect the positive ohmmeter lead to the emitter lead and the negative lead to base #1. The ohmmeter should indicate a forward diode junction.



3. With the positive ohmmeter lead connected to the emitter, reconnect the negative lead to base #2. The ohmmeter should again indicate a forward diode junction.

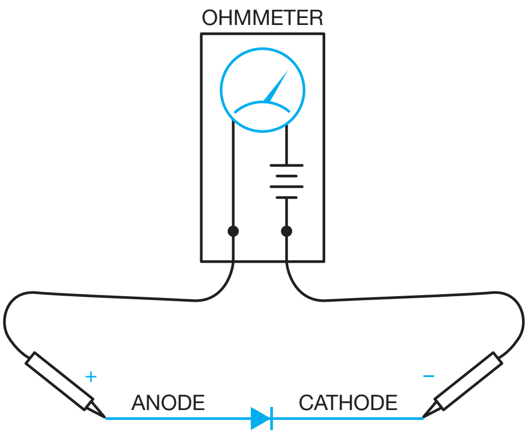


4. If the negative ohmmeter lead is connected to the emitter, no continuity should be indicated when the positive lead is connected to base #1 or base #2.

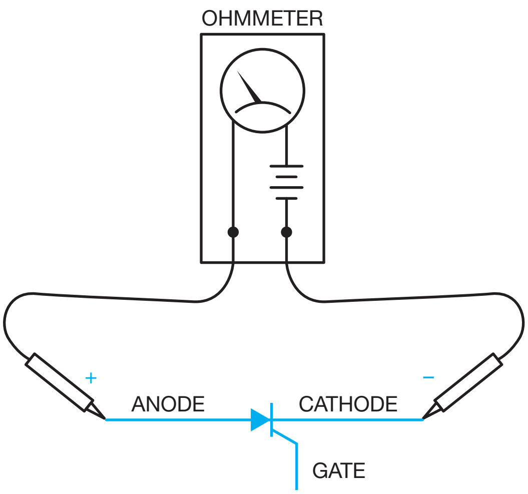


4. Testing an SCR

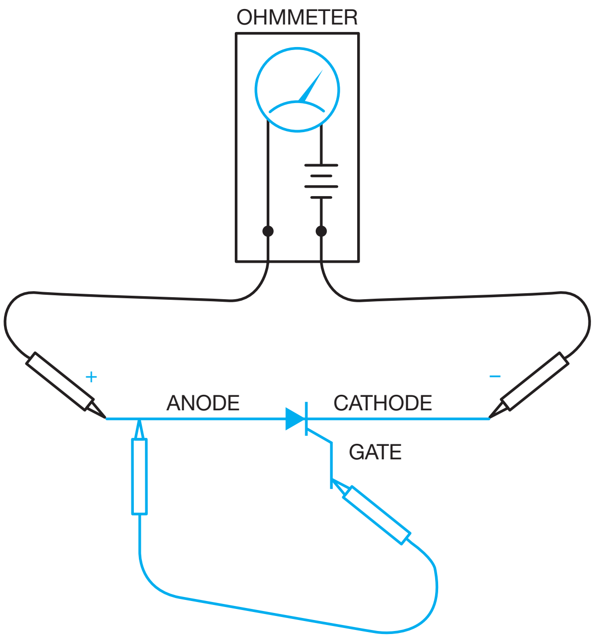
1. Using a junction diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity only when the positive lead is connected to the anode of the diode and the negative lead is connected to the cathode.



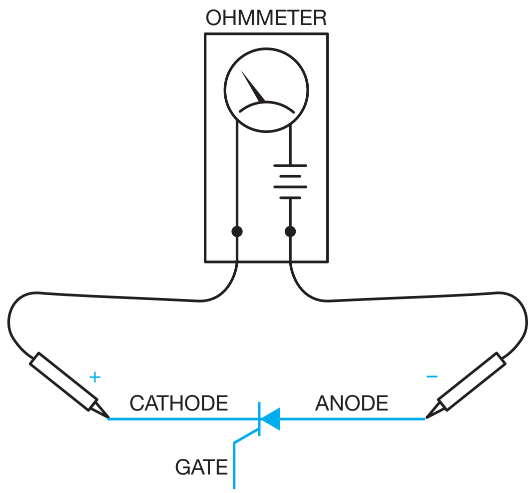
2. Connect the positive ohmmeter lead to the anode of the SCR and the negative lead to the cathode. The ohmmeter should indicate no continuity.



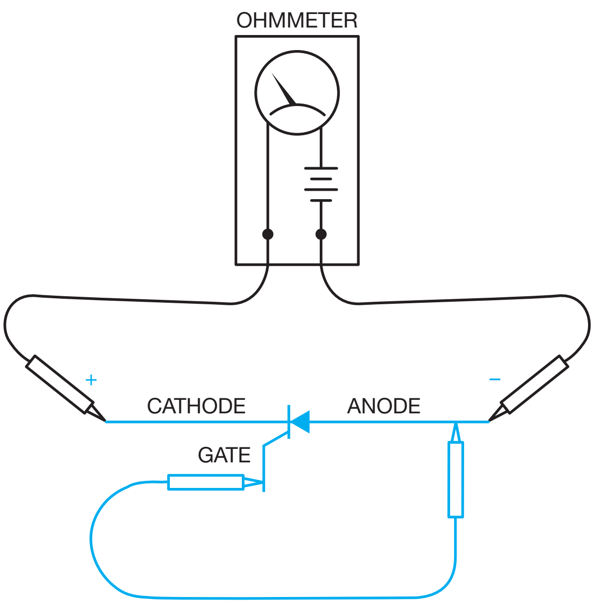
3. Using a jumper lead, connect the gate of the SCR to the anode. The ohmmeter should indicate a forward diode junction when the connection is made. NOTE: If the jumper is removed, the SCR may continue to conduct or it may turn off. This will be determined by whether or not the ohmmeter can supply enough current to keep the SCR above its holding current level.



4. Reconnect the SCR so that the cathode is connected to the positive ohmmeter lead and the anode is connected to the negative lead. The ohmmeter should indicate no continuity.

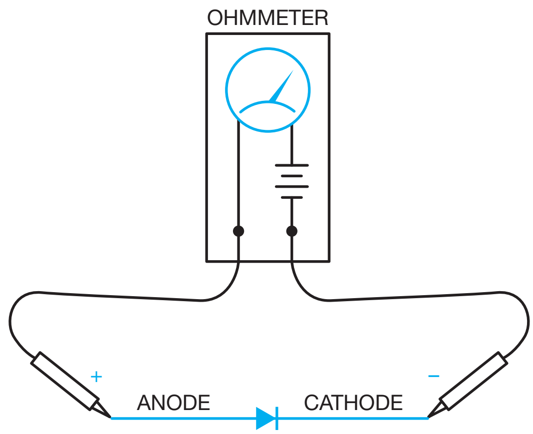


5. If a jumper lead is used to connect the gate to the anode, the ohmmeter should indicate no continuity. NOTE: SCRs designed to switch large currents (50 amperes or more) may indicate some leakage current with this test. This is normal for some devices.

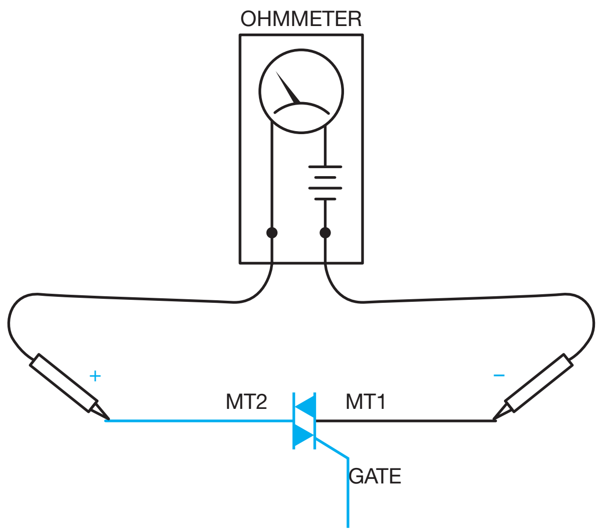


5. Testing a Triac

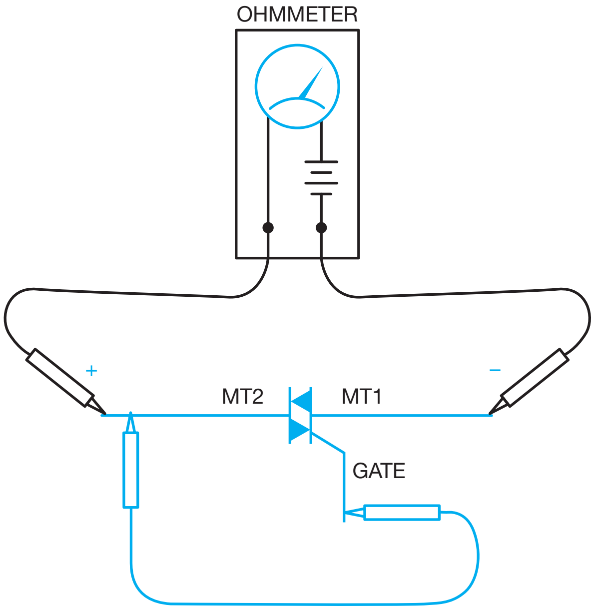
1. Using a junction diode, determine which ohmmeter lead is positive and which is negative. The ohmmeter will indicate continuity only when the positive lead is connected to the anode and the negative lead is connected to the cathode.



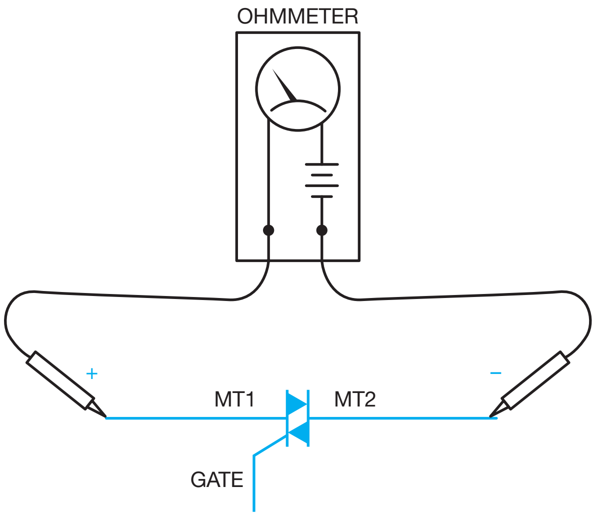
2. Connect the positive ohmmeter lead to MT2 and the negative lead to MT1. The ohmmeter should indicate no continuity through the triac.



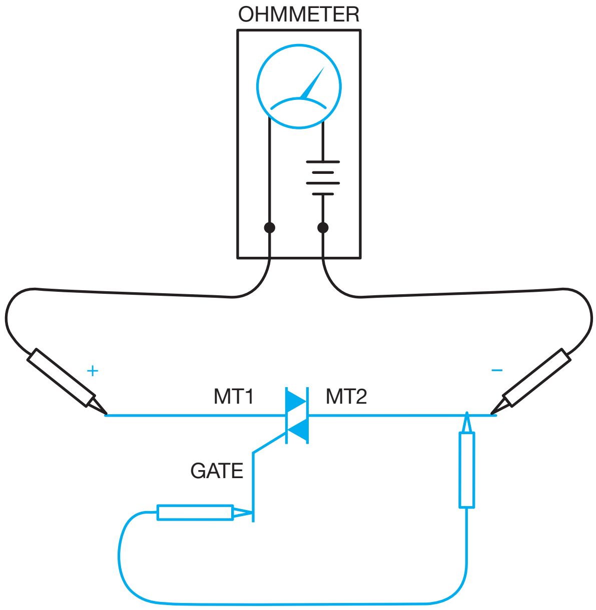
3. Using a jumper lead, connect the gate of the triac to MT2. The ohmmeter should indicate a forward diode junction.



4. Reconnect the triac so that MTl is connected to the positive ohmmeter lead and MT2 is connected to the negative lead. The ohmmeter should indicate no continuity through the triac.



5. Using a jumper lead, again connect the gate to MT2. The ohmmeter should indicate a forward diode junction.



Identifying the Leads of a Three-Phase, Wye-Connected, Dual-Voltage Motor

The terminal markings of a three-phase motor are standardized and used to connect the motor for operation on 240 or 480 volts. Figure A–1 shows these terminal markings and their relationship to the other motor windings. If the motor is to be connected to a 240 volt line, the motor windings are connected parallel to each other as shown in Figure A–2. If the motor is to be operated on a 480 volt line, the motor windings are connected in series as shown in Figure A–3.

As long as these motor windings remain marked with the proper numbers, connecting the motor for operation on a 240 or 480 volt power line is relatively simple. If these numbers are removed or damaged, however, the leads must be reidentified before the motor can be connected. The following procedure can be used to identify the proper relationship of the motor windings:

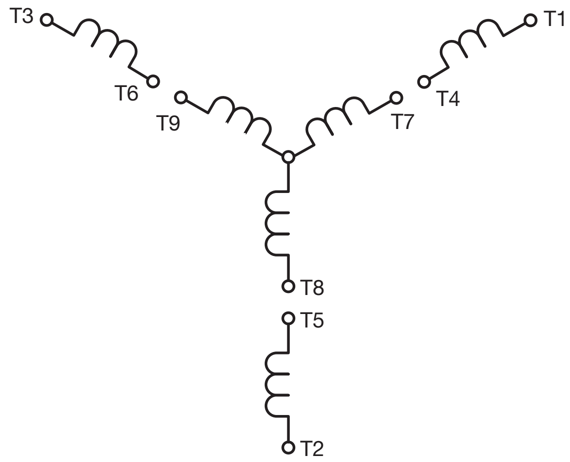


Figure A–1 Standard terminal markings for a three-phase motor. (Source: Delmar/Cengage Learning.)

1. Using an ohmmeter, divide the motor windings into four separate circuits. One circuit will have continuity to three leads, and the other three circuits will have continuity between only two leads (Figure #1). *Caution: the circuits that exhibit continuity between*

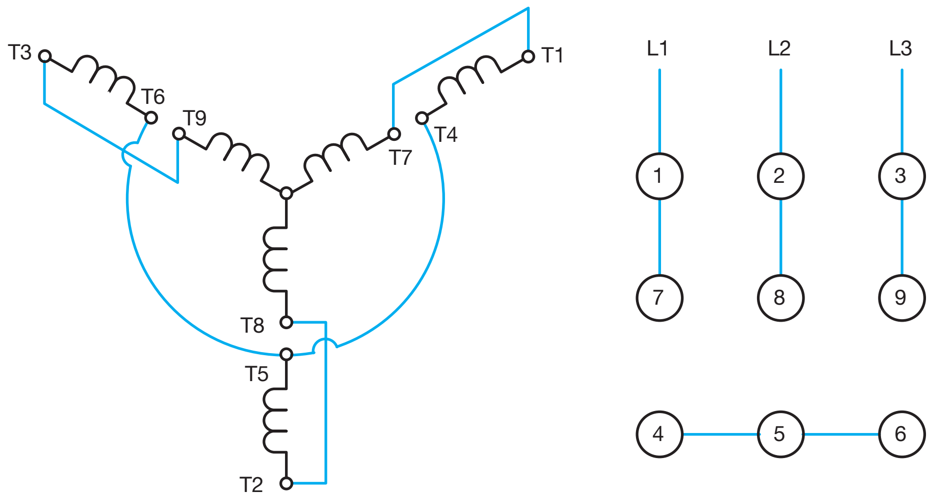


Figure A–2 Low voltage connection. (Source: Delmar/Cengage Learning.)

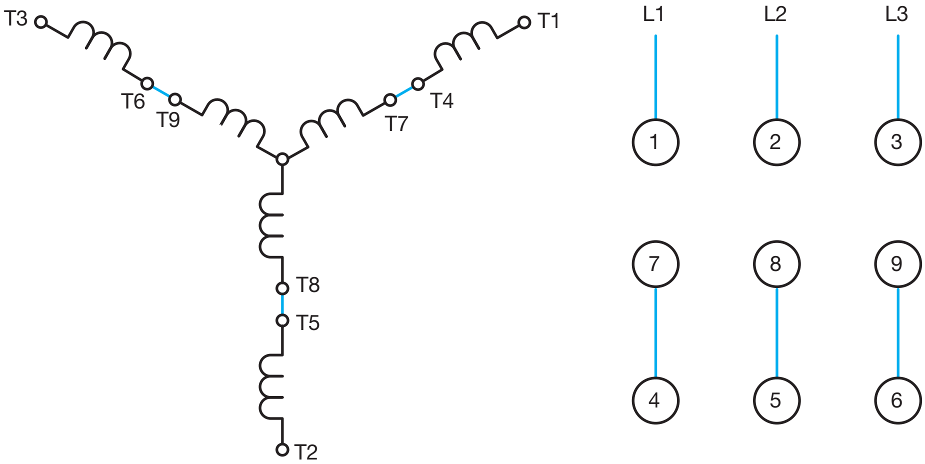


Figure A–3 High voltage connection. (Source: Delmar/Cengage Learning.)

two leads must be identified as pairs, but do not let the ends of the leads touch anything.

2. Mark the three leads that have continuity with each other as T7, T8, and T9. Connect these three leads to a 240 volt, three-phase power source (Figure A–4). (Note: Since these windings are rated at 240 volts each, the motor can be safely operated on one set of windings as long as it is not connected to a load.)

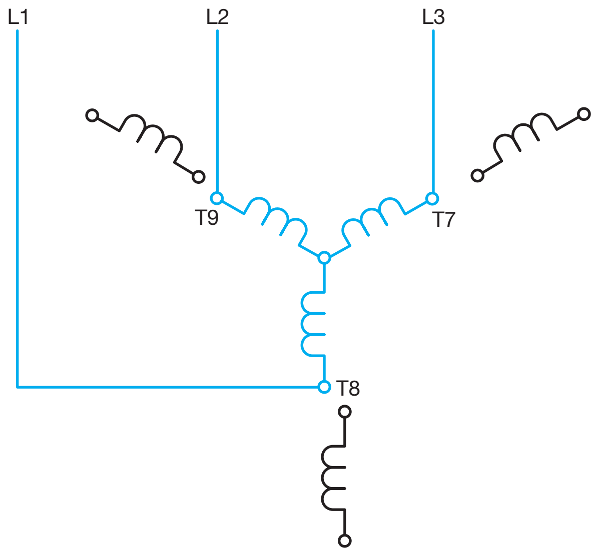


Figure A–4 T7, T8, and T9 connected to a three-phase, 240 volt line. (Source: Delmar/Cengage Learning.)

3. With the power turned off, connect one end of one of the paired leads to the terminal marked T7. Turn the power on, and using an AC voltmeter set for a range not less than 480 volts, measure the voltage from the unconnected end of the paired lead to terminals T8 and T9 (Figure A–5). If the measured voltages are unequal, the wrong paired lead is connected to terminal T7. Turn the power off, and connect another paired lead to T7. When the correct set of paired leads is connected to T7, the voltage readings to T8 and T9 will be equal.
4. After finding the correct pair of leads, a decision must be made as to which lead should be labeled T4 and which should be labeled T1. Since an induction motor is basically a transformer, the phase windings act very similar to a multiwinding autotransformer. If terminal T1 is connected to terminal T7, it will operate similar to a transformer with its windings connected to form subtractive polarity. If an AC voltmeter is connected to T4, a voltage of about 140 volts should be seen between T4 and T8 or T4 and T9 (Figure A–6).

   If terminal T4 is connected to T7, the winding will operate similar to a transformer with its windings connected for additive polarity. If an AC voltmeter is connected to T1, a voltage of about 360 volts will be indicated when the other lead of the voltmeter is connected to T8 or T9 (Figure A–7).

   Label leads T1 and T4 using the preceding procedure to determine which lead is correct. Then disconnect and separate T1 and T4.
5. To identify the other leads, follow the same basic procedure. Connect one end of one of the remaining pairs to T8. Measure the voltage between the unconnected lead and T7 and T9 to determine if it is the correct lead pair for terminal T8. When the correct lead pair is connected to T8, the voltage between the unconnected terminal and T7 or T9 will be equal. Then determine which is T5 or T2 by measuring for a high or low voltage. When T5 is connected to T8, about 360 volts can be measured between T2 and T7 or T2 and T9.
6. The remaining pair can be identified as T3 or T6. When T6 is connected to T9, a voltage of about 360 volts can be measured between T3 and T7 or T3 and T8.

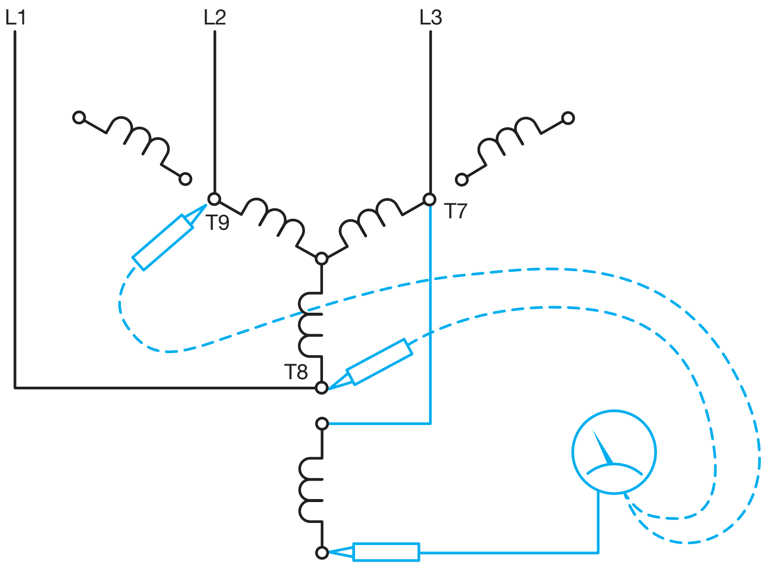


Figure A–5 Measure voltage from unconnected paired lead to T8 and T9. (Source: Delmar/Cengage Learning.)

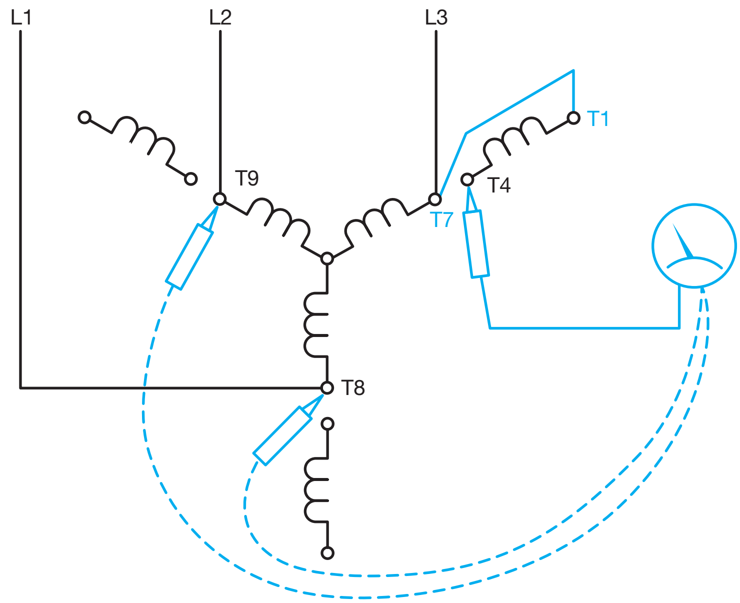


Figure A–6 T1 connected to T7. (Source: Delmar/Cengage Learning.)

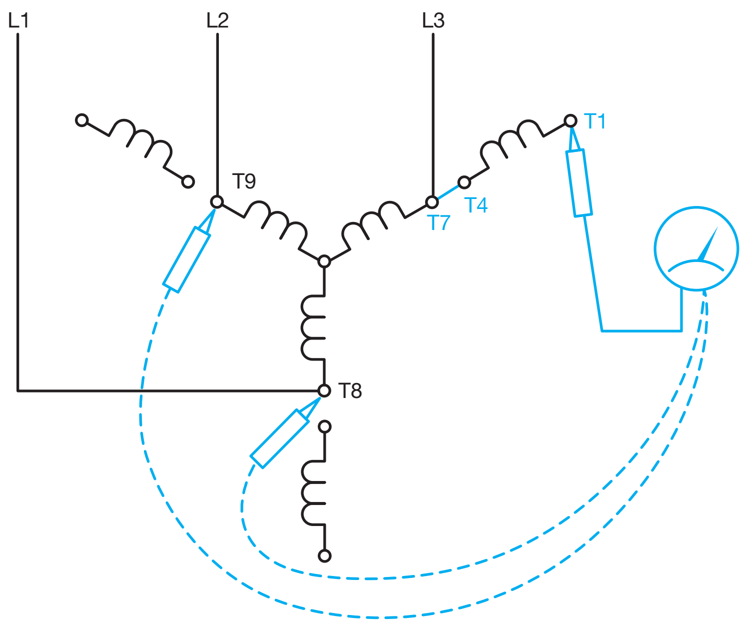
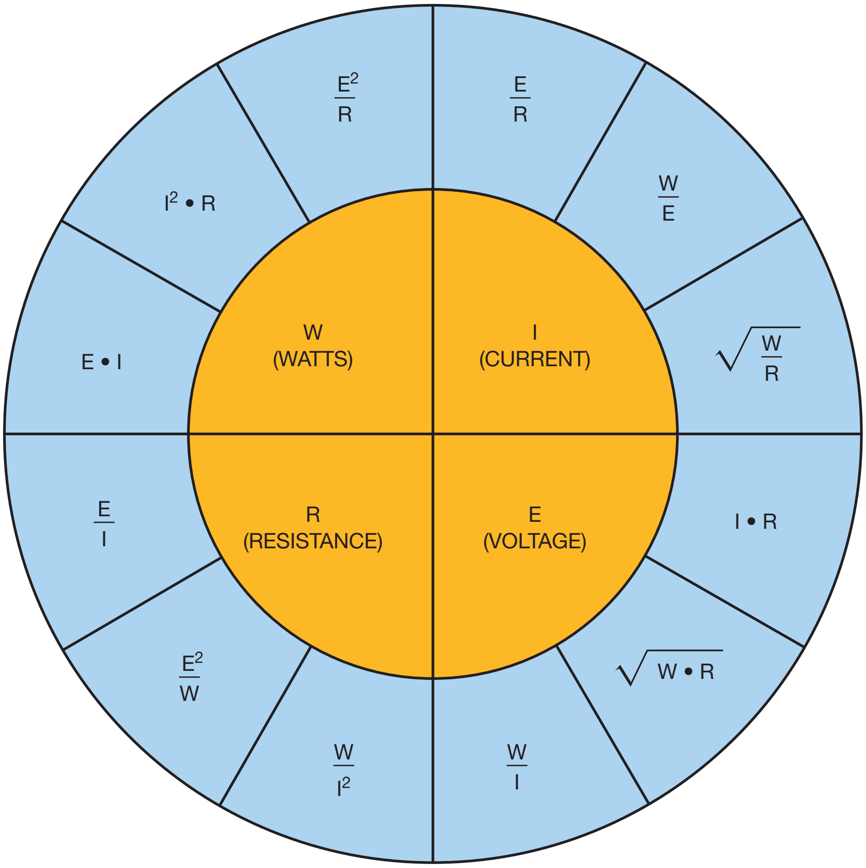
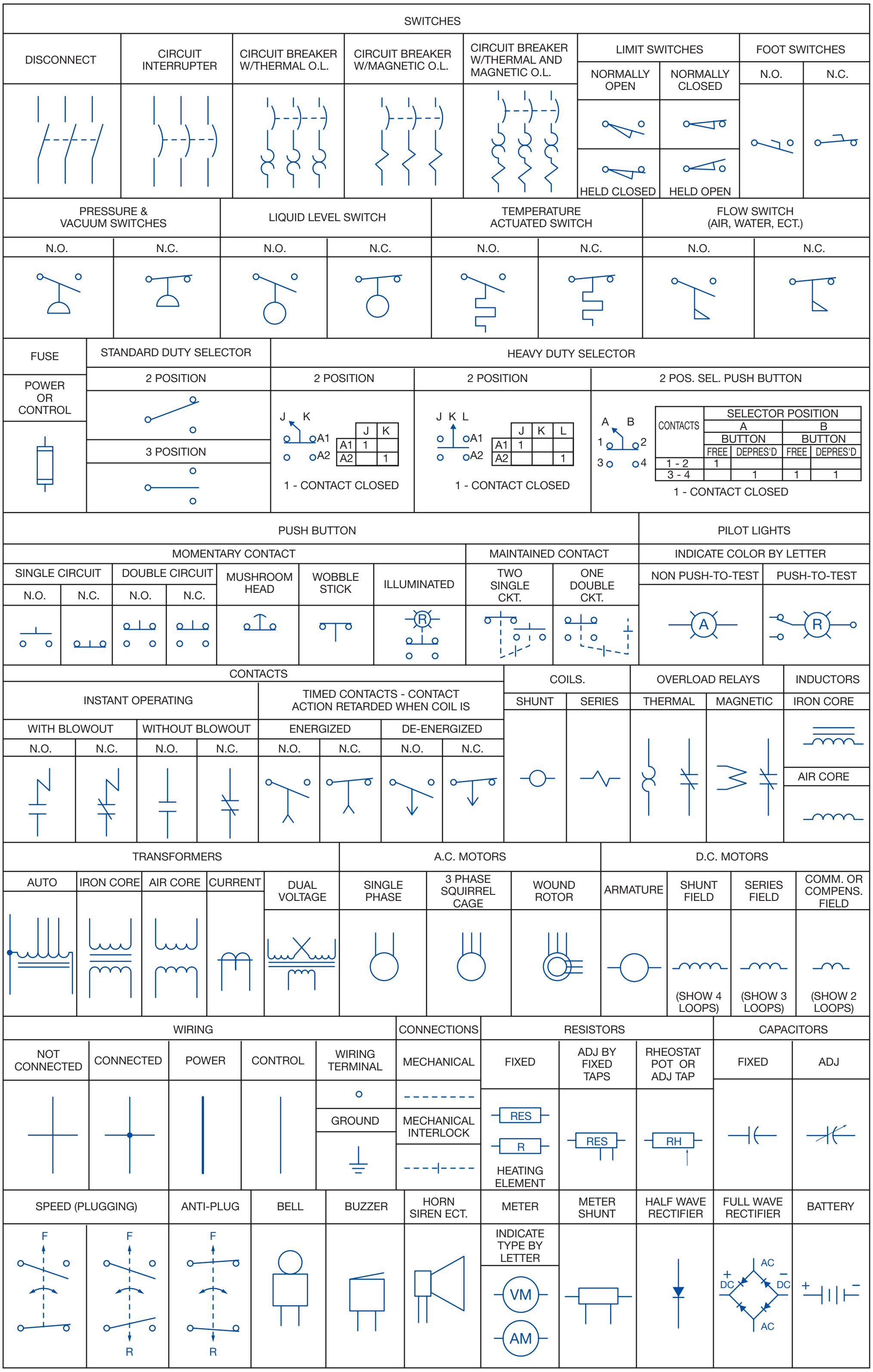


Figure A–7 T4 connected to T7. (Source: Delmar/Cengage Learning.)

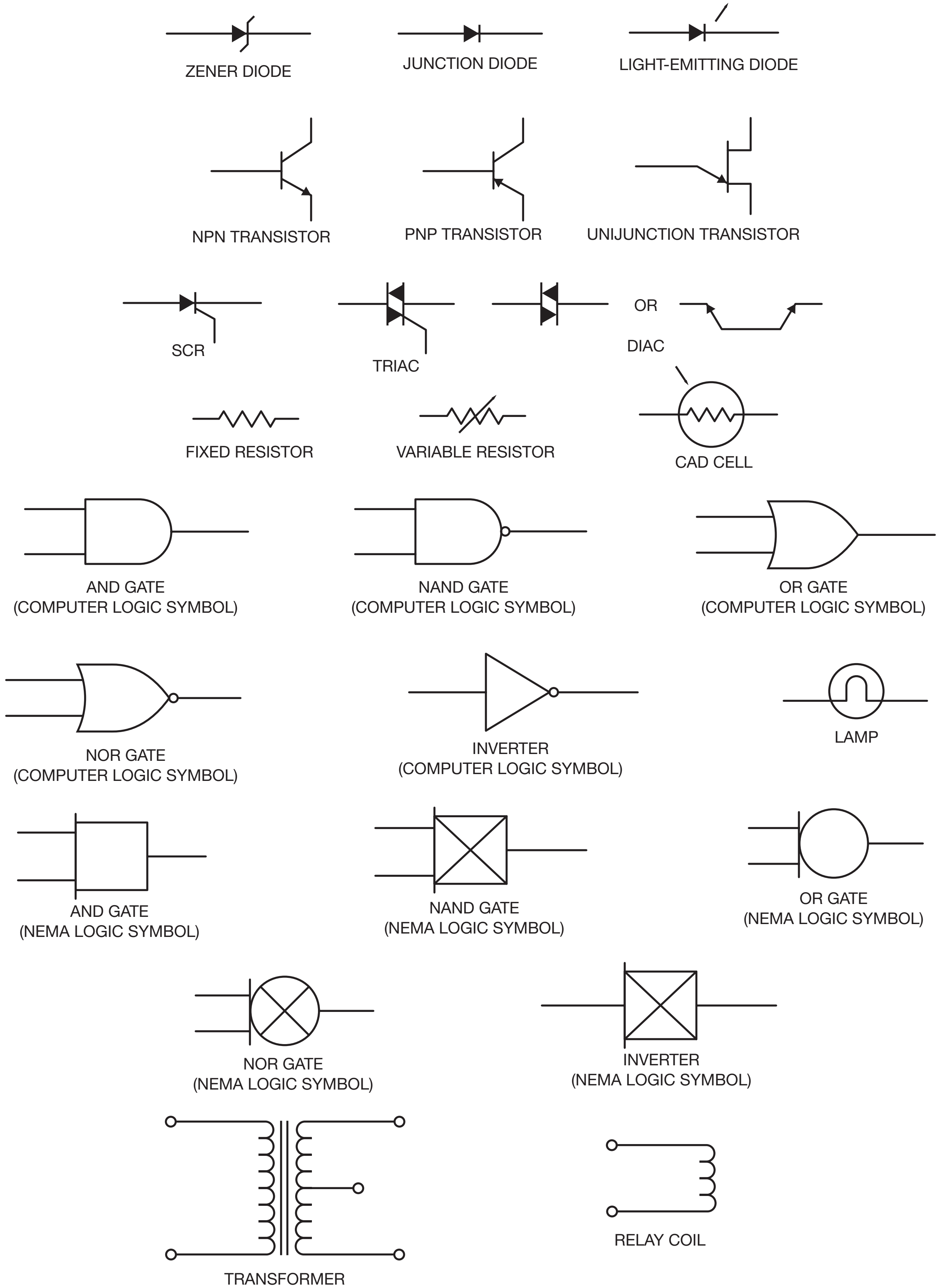
Ohm's Law Formulas



Standard Wiring Diagram Symbols



Electronic Symbols



GLOSSARY

Accelerating Relay Any type of relay used to aid in starting a motor or to accelerate a motor from one speed to another. Accelerating relays may function by: motor armature current (current limit acceleration); armature voltage (counter EMF acceleration); or definite time (definite time acceleration).

Accessory (control use) A device that controls the operation of magnetic motor control. (Also see Master Switch, Pilot Device, and Push Button.)

Across-the-line Method of motor starting that connects the motor directly to the supply line on starting or running. (Also called Full Voltage Control.)

Alternating Current (AC) Current changing both in magnitude and direction; most commonly used current.

Alternator A machine used to generate alternating current by rotating conductors through a magnetic field.

Ambient Temperature The temperature surrounding a device.

Ampacity The maximum current rating of a wire or cable.

Ampere Unit of electrical current.

Amplifier A device used to increase a signal.

Amplitude The highest value reached by a signal, voltage, or current.

AND Gate A digital logic gate that must have all of its inputs high to produce an output.

Anode The positive terminal of an electronic device.

Applied Voltage The amount of voltage connected to a circuit or device.

ASA American Standards Association.

Astable Mode The state in which an oscillator can continually turn itself on and off, or continually change from positive to negative output.

Atom The smallest part of an element that contains all the properties of that element.

Attenuator A device that decreases the amount of signal, voltage, or current.

Automatic Self-acting, operating by its own mechanism when actuated by some triggering signal such as a change in current strength, pressure, temperature, or mechanical configuration.

Automatic Starter A self-acting starter that is completely controlled by master or pilot switches or other sensing devices; designed to control automatically the acceleration of a motor during the acceleration period.

Auxiliary Contacts Contacts of a switching device in addition to the main circuit contacts; auxiliary contacts operate with the movement of the main contacts.

Barrier Charge The potential developed across a semiconductor junction.

Base The semiconductor region between the collector and emitter of a transistor. The base controls the current flow through the collector-emitter circuit.

Base Current The amount of current that flows through the base-emitter section of a transistor.

Bias A DC voltage applied to the base of a transistor to preset its operating point.

Bimetal Strip A strip made by bonding two unlike metals together that, when heated, expand at different rates. This causes a bending or warping action.

Blowout Coil Electromagnetic coil used in contactors and starters to deflect an arc when a circuit is interrupted.

Bounceless Switch A circuit used to eliminate contact bounce in mechanical contacts.

Branch Circuit That portion of a wiring system that extends beyond the final overcurrent device protecting the circuit.

Brake An electromechanical friction device to stop and hold a load. Generally electric release spring applied—coupled to motor shaft.

Breakdown Torque (of a motor) The maximum torque that will develop with the rated voltage applied at the rated frequency, without an abrupt drop in speed. (ASA)

Bridge Circuit A circuit that consists of four sections connected in series to form a closed loop.

Bridge Rectifier A device constructed with four diodes, which converts both positive and negative cycles of AC voltage into DC voltage.

Busway A system of enclosed power transmission that is current and voltage rated.

Cad Cell A device that changes its resistance with a change of light intensity.

Capacitance The electrical size of a capacitor.

Capacitive Any circuit or device having characteristics similar to those of a capacitor.

Capacitor A device made with two conductive plates separated by an insulator or dielectric.

Capacitor Start Motor A single-phase induction motor with a main winding arranged for direct connection to the power source and an auxiliary winding connected in series with a capacitor. The auxiliary winding is in the circuit only during starting. (NEMA)

Cathode The negative terminal of a device.

Cathode-Ray Tube (CRT) An electron beam tube in which the beam of electrons can be focused to any point on the face of the tube. The electron beam causes the face of the tube to produce light when it is struck by the beam.

Center-Tapped A transformer that has a wire connected to the electrical midpoint of its winding. Generally the secondary is tapped.

Charge Time The amount of time necessary to charge a capacitor.

Choke An inductor designed to present an impedance to AC current, or to be used as the current filter of a DC power supply.

Circuit Breaker Automatic device that opens under abnormal current in carrying circuit; circuit breaker is not damaged on current interruption; device is ampere, volt, and horsepower rated.

Clock Timer A time-delay device that uses an electric clock to measure the delay period.

Collapse (of a magnetic field) When a magnetic field suddenly changes from its maximum value to a zero value.

Collector The semiconductor region of a transistor, which must be connected to the same polarity as the base.

Comparator A device or circuit that compares two like quantities such as voltage levels.

Conduction Level The point at which an amount of voltage or current will cause a device to conduct.

Conductor A device or material that permits current to flow through it easily.

Contact A conducting part of a relay that acts with another conducting part to complete or to interrupt a circuit.

Contactor A device that repeatedly establishes or interrupts an electric power circuit.

Continuity A complete path for current flow.

Controller A device or group of devices that governs, in a predetermined manner, the delivery of electric power to apparatus connected to it.

Controller Function Regulate, accelerate, decelerate, start, stop, reverse, or protect devices connected to an electric controller.

Controller Service Specific application of controller. General Purpose: standard or usual service. Definite Purpose: service condition for specific application other than usual.

Current The rate of flow of electrons. Measured in amperes.

Current Flow The flow of electrons.

Current Rating The amount of current flow a device is designed to withstand.

Current Relay A relay that functions at a predetermined value of current. A current relay may be either an overcurrent relay or an undercurrent relay.

Dashpot Consists of a piston moving inside a cylinder filled with air, oil, mercury, silicon, or other fluid. Time delay is caused by allowing the air or fluid to escape through a small orifice in the piston. Moving contacts actuated by the piston close the electrical circuit.

Definite Time (or Time Limit) Definite time is a qualifying term indicating that a delay in action is purposely introduced. This delay remains substantially constant regardless of the magnitude of the quantity that causes the action.

Definite-Purpose Motor Any motor designed, listed, and offered in standard ratings with standard operating characteristics or mechanical construction for use under service conditions other than usual or for use on a particular type of application. (NEMA)

Delta Connection A circuit formed by connecting three electrical devices in series to form a closed loop. Most often used in three-phase connections.

Device A unit of an electrical system that is intended to carry but not utilize electrical energy.

Diac A bidirectional diode.

Dielectric An electrical insulator.

Digital Device A device that has only two states of operation.

Digital Logic Circuit elements connected in such a manner as to solve problems using components that have only two states of operation.

Digital Voltmeter A voltmeter that uses a direct-reading, numerical display as opposed to a meter movement.

Diode A two-element device that permits current to flow through it in only one direction.

Direct Current (DC) Current that does not reverse its direction of flow. A continuous nonvarying current in one direction.

Disconnecting Means (Disconnect) A device, or group of devices, or other means whereby the conductors of a circuit can be disconnected from their source of supply.

Drum Controller Electrical contacts made on the surface of a rotating cylinder or section; contacts made also by operation of a rotating cam.

Drum Switch A switch having electrical connecting parts in the form of fingers held by spring pressure against contact segments or surfaces on the periphery of a rotating cylinder or sector.

Duty Specific controller functions. Continuous (time) Duty: constant load, indefinite long time period. Short Time Duty: constant load, short or specified time period. Intermittent Duty: varying load, alternate intervals, specified time periods. Periodic Duty: intermittent duty with recurring load conditions. Varying duty: varying loads, varying time intervals, wide variations.

Dynamic Braking Using a DC motor as a generator, taking it off the line and applying an energy dissipating resistor to the armature. Dynamic braking for an AC motor is accomplished by disconnecting the motor from the line and connecting DC power to the stator windings.

Eddy Currents Circular induced currents contrary to the main currents; a loss of energy that shows up in the form of heat.

Electrical Interlocking Accomplished by control circuits in which the contacts in one circuit control another circuit.

Electric Controller A device, or group of devices, which governs, in some predetermined manner, the electric power delivered to the apparatus to which it is connected.

Electron One of the three major subatomic parts of an atom. The electron carries a negative charge.

Electronic Control Control system using gas and/or vacuum tubes, or solid-state devices.

Emitter The semiconductor region of a transistor, which must be connected to a polarity different than the base.

Enclosure Mechanical, electrical, and environmental protection for control devices.

Eutectic Alloy Metal with low and sharp melting point; used in thermal overload relays; converts from a solid to a liquid state at a specific temperature; commonly called solder pot.

EXCLUSIVE OR Gate A digital logic gate that will produce an output when its inputs have opposite states of logic level.

Feeder The circuit conductor between the service equipment, or the generator switchboard of an isolated plant, and the branch circuit overcurrent device.

Feeler Gauge A precision instrument with blades in thicknesses of thousandths of an inch for measuring clearances.

Filter A device used to remove the ripple produced by a rectifier.

Frequency Number of complete variations made by an alternating current per second; expressed in hertz. (See Hertz)

Full Load Torque (of a motor) The torque necessary to produce the rated horsepower of a motor at full load speed.

Full Voltage Control (*Across-the-line*) Connects equipment directly to the line supply on starting.

Fuse An overcurrent protective device with a fusible member, which is heated directly and destroyed by the current passing through it to open a circuit.

Gain The increase in signal power produced by an amplifier.

Gate A device that has multiple inputs and a single output; or one terminal of some solid-state devices such as SCRs or triacs.

General-Purpose Motor Any open motor that has a continuous 40C rating and is designed, listed, and offered in standard ratings with standard operating characteristics and mechanical construction for use under usual service conditions without restrictions to a particular application or type of application. (NEMA)

Heat Sink A metallic device designed to increase the surface area of an electronic component to remove heat at a faster rate.

Hertz International unit of frequency, equal to one cycle per second of alternating current.

High Voltage Control Formerly, all control above 600 volts. Now, all control above 5,000 volts. See Medium Voltage Control for 600 to 5,000 volt equipment.

Holding Contacts Contacts used for the purpose of maintaining current flow to the coil of a relay.

Holding Current The amount of current needed to keep an SCR or a triac turned on.

Horsepower Measure of the time rate of doing work (working rate).

Hysteresis Loop A graphic curve that shows the value of magnetizing force for a particular type of material.

Impedance The total opposition to current flow in an electrical circuit.

Induced Current produced in a conductor by the cutting action of a magnetic field.

Inductor A coil used to introduce inductance into an electrical circuit.

Input Power delivered to an electrical device.

Input Voltage The amount of voltage connected to a device or circuit.

Instantaneous A qualifying term indicating that no delay is purposely introduced in the action of a device.

Insulator A material used to electrically isolate two conductive surfaces.

Integral Whole or complete; not fractional.

Interlock To interrelate with other controllers; an auxiliary contact. A device is connected in such a way that the motion of one part is held back by another part.

Internal Relay Digital logic circuits in a programmable controller that can be programmed to operate in the same manner as control relays.

Inverse Time A qualifying term indicating that a delayed action is introduced purposely. This delay decreases as the operating force increases.

Inverter (Gate) A digital logic gate that has an output opposite its input.

Isolation Transformer A transformer whose secondary winding is electrically isolated from its primary winding.

Jogging (Inching) Momentary operations; the quickly repeated closure of the circuit to start a motor from rest for the purpose of accomplishing small movements of the driven machine.

Jumper A short length of conductor used to make a connection between terminals or around a break in a circuit.

Junction Diode A diode that is made by joining two pieces of semiconductor material.

Kickback Diode A diode used to eliminate the voltage spike induced in a coil by the collapse of a magnetic field.

Lattice Structure An orderly arrangement of atoms in a crystalline material.

LED (Light-Emitting Diode) A diode that will produce light when current flows through it.

Limit Switch A mechanically operated device that stops a motor from revolving or reverses it when certain limits have been reached.

Load Center Service entrance; controls distribution; provides protection of power; generally of the circuit breaker type.

Local Control Control function, initiation, or change accomplished at the same location as the electric controller.

Locked Rotor Current (of a motor) The steady-state current taken from the line with the rotor locked (stopped) and with the rated voltage and frequency applied to the motor.

Locked Rotor Torque (of a motor) The minimum torque that a motor will develop at rest for all angular positions of the rotor with the rated voltage applied at a rated frequency. (ASA)

Lockout A mechanical device that may be set to prevent the operation of a push button.

Logic A means of solving complex problems through the repeated use of simple functions that define basic concepts. Three basic logic functions are: and, or, and not.

Low Voltage Protection (LVP) Magnetic control only; nonautomatic restarting; three-wire control; power failure disconnects service; power restored by manual restart.

Low Voltage Release (LVR) Manual and magnetic control; automatic restarting; two-wire control; power failure disconnects service; when power is restored, the controller automatically restarts the motor.

Magnet Brake Friction brake controlled by electromagnetic means.

Magnetic Contactor A contactor that is operated electromechanically.

Magnetic Controller An electric controller; device functions operated by electromagnets.

Magnetic Field The space in which a magnetic force exists.

Maintaining Contact A small control contact used to keep a coil energized; usually actuated by the same coil. Holding contact; Pallet switch.

Manual Controller An electric controller; device functions operated by mechanical means or manually.

Master Switch A main switch to operate contactors, relays, or other remotely-controlled electrical devices.

Medium Voltage Control Formerly known as High Voltage; includes 600 to 5000 volt apparatus; air break or oil-immersed main contactors; high interrupting capacity fuses; 150,000 kilovolt-amperes at 2,300 volts; 250,000 kilovolt-amperes at 4,000–5,000 volts.

Microprocessor A small computer. The central processing unit is generally made from a single integrated circuit.

Mode A state or condition.

Monostable (Mode) The state in which an oscillator or timer will operate through only one sequence of events.

Motor Device for converting electrical energy to mechanical work through rotary motion; rated in horsepower.

Motor Circuit Switch Motor branch circuit switch rated in horsepower; capable of interrupting overload motor current.

Motor Controller A device used to control the operation of a motor.

Motor-Driven Timer A device in which a small pilot motor causes contacts to close after a predetermined time.

Multispeed Motor A motor that can be operated at more than one speed.

Multispeed Starter An electric controller with two or more speeds; reversing or nonreversing; full or reduced voltage starting.

NAND Gate A digital logic gate that will produce a high output only when all of its inputs are in a low state.

Negative One polarity of voltage, current, or a charge.

Negative Resistance The property of a device in which an increase of current flow causes an increase of conductance. The increase of conductance causes a decrease in the voltage drop across the device.

NEMA National Electrical Manufacturers Association.

NEMA Size Electric controller device rating; specific standards for horsepower, voltage, current, and interrupting characteristics.

Neutron One of the principal parts of an atom. The neutron has no charge and is part of the nucleus.

Nonautomatic Controller Requires direct operation to perform function; not necessarily a manual controller.

Noninductive Load An electrical load that does not have induced voltages caused by a coil. Noninductive loads are generally resistive, but can be capacitive.

Nonreversing Operation in one direction only.

NOR Gate A digital logic gate that will produce a high output when any of its inputs are low.

Normally Open and Normally Closed When applied to a magnetically-operated switching device, such as a contactor or relay, or to the contacts of these devices, these terms signify the position taken when the operating magnet is de-energized. The terms apply only to nonlatching types of devices.

Off-Delay Timer A timer in which the contacts change position immediately when the coil or circuit is energized, but delay returning to their normal positions when the coil or circuit is de-energized.

Ohmmeter A meter used to measure resistance.

On-Delay Timer A timer in which the contacts delay changing position when the coil or circuit is energized, but change back immediately to their normal positions when the coil or circuit is de-energized.

Operational Amplifier (Op amp) An integrated circuit used as an amplifier.

Optoisolator A device used to connect sections of a circuit by means of a light beam.

Oscillator A device or circuit used to change DC voltage into AC voltage.

Oscilloscope An instrument that measures the amplitude of voltage with respect to time.

Out-of-phase Voltage A voltage that is not in phase when compared to some other voltage or current.

Output Devices Elements such as solenoids, motor starters, and contactors that receive input.

Output Pulse A short duration voltage or current, which can be negative or positive, produced at the output of a device or circuit.

Overload Protection Overload protection is the result of a device that operates on excessive current, but not necessarily on short circuit, to cause and maintain the interruption of current flow to the device governed. NOTE: Operating overload means a current that is not in excess of six times the rated current for alternating-current motors, and not in excess of four times the rated current for direct-current motors.

Overload Relay Running overcurrent protection; operates on excessive current; not necessarily protection for short circuit; causes and maintains interruption of device from power supply. Overload Relay Heater Coil: Coil used in thermal overload relays; provides heat to melt eutectic alloy.

Overload Relay Reset Push button used to reset thermal overload relay after relay has operated.

Panelboard Panel, group of panels, or units; an assembly that mounts in a single panel; includes buses, with or without switches and/or automatic overcurrent protective devices; provides control of light, heat, power circuits; placed in or against wall or partition; accessible from front only.

Parallel Circuit A circuit that has more than one path for current flow.

Peak Inverse/Peak Reverse Voltage The rating of a semiconductor device, which indicates the maximum amount of voltage that can be applied to the device in the reverse direction.

Peak-To-Peak Voltage The amplitude of voltage measured from the negative peak of an AC waveform to the positive peak.

Peak Voltage The amount of voltage of a waveform measured from the zero voltage point to the positive or negative peak.

Permanent-split Capacitor Motor A single-phase induction motor similar to the capacitor start motor except that it uses the same capacitance, which remains in the circuit for both starting and running. (NEMA)

Permeability The ease with which a material will conduct magnetic lines of force.

Phase Relation of current to voltage at a particular time in an AC circuit. Single Phase: A single voltage and current in the supply. Three Phase: Three electrically-related (120-degree electrical separation) single-phase supplies.

Phase-Failure Protection Phase-failure protection is provided by a device that operates when the power fails in one wire of a polyphase circuit to cause and maintain the interruption of power in all the wires of the circuit.

Phase-Reversal Protection Phase-reversal protection is provided by a device that operates when the phase rotation in a polyphase circuit reverses to cause and maintain the interruption of power in all the wires of the circuit.

Phase Rotation Relay A relay that functions in accordance with the direction of phase rotation.

Phase Shift A change in the phase relationship between two quantities of voltage or current.

Photodetector A device that responds to change in light intensity.

Photodiode A diode that conducts in the presence of light, but not in darkness.

Pilot Device Directs operation of another device. Float Switch: A pilot device that responds to liquid levels. Foot Switch: A pilot device operated by the foot of an operator. Limit Switch: A pilot device operated by the motion of a power-driven machine; alters the electrical circuit with the machine or equipment.

Plugging Braking by reversing the line voltage or phase sequence; motor develops retarding force.

Pneumatic Timer A device that uses the displacement of air in a bellows or diaphragm to produce a time delay.

Polarity The characteristic of a device that exhibits opposite quantities, such as positive and negative, within itself.

Pole The north or south magnetic end of a magnet; a terminal of a switch; one set of contacts for one circuit of main power.

Potentiometer A variable resistor with a sliding contact, which is used as a voltage divider.

Power Factor A comparison of the true power (WATTS) to the apparent power (VOLT AMPS) in an AC circuit.

Power Rating The rating of a device that indicates the amount of current flow and voltage drop that can be permitted.

Pressure Switch A device that senses the presence or absence of pressure and causes a set of contacts to open or close.

Printed Circuit A board on which a predetermined pattern of printed connections has been formed.

Proton One of the three major parts of an atom. The proton carries a positive charge.

Pull-up Torque (of alternating-current motor) The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown occurs. (ASA)

Push Button A master switch; manually-operable plunger or button for an actuating device; assembled into push-button stations.

RC Time Constant The time constant of a resistor and capacitor connected in series. The time in seconds is equal to the resistance in ohms multiplied by the capacitance in farads.

Reactance The opposition to current flow in an AC circuit offered by pure inductance or pure capacitance.

Rectifier A device that converts alternating current into direct current.

Regulator A device that maintains a quantity at a predetermined level.

Relay Operated by a change in one electrical circuit to control a device in the same circuit or another circuit; rated in amperes; used in control circuits.

Remote Control Controls the function initiation or change of an electrical device from some remote point or location.

Remote Control Circuit Any electrical circuit that controls any other circuit through a relay or an equivalent device.

Residual Magnetism The retained or small amount of remaining magnetism in the magnetic material of an electromagnet after the current flow has stopped.

Resistance The opposition offered by a substance or body to the passage through it of an electric current; resistance converts electrical energy into heat; resistance is the reciprocal of conductance.

Resistance Start Induction Run Motor One type of split-phase motor that uses the resistance of the start winding to produce a phase shift between the current in the start winding and the current in the run winding.

Resistor A device used primarily because it possesses the property of electrical resistance. A resistor is used in electrical circuits for purposes of operation, protection, or control; commonly consists of an aggregation of units.

- *Starting Resistors* Used to accelerate a motor from rest to its normal running speed without damage to the motor and connected load from excessive currents and torques, or without drawing undesirable in-rush current from the power system.
- *Armature Regulating Resistors* Used to regulate the speed of torque of a loaded motor by resistance in the armature or power circuit.
- *Dynamic Braking Resistors* Used to control the current and dissipate the energy when a motor is decelerated by making it act as a generator to convert its mechanical energy to electrical energy and then to heat in the resistor.
- *Field Discharge Resistors* Used to limit the value of voltage that appears at the terminals of a motor field (or any highly inductive circuit) when the circuit is opened.
- *Plugging Resistors* Used to control the current and torque of a motor when deceleration is forced by electrically reversing the motor while it is still running in the forward direction.

Rheostat A resistor that can be adjusted to vary its resistance without opening the circuit in which it may be connected.

Ripple An AC component in the output of a DC power supply; caused by improper filtering.

RMS Value The value of AC voltage that will produce as much power when connected across a resistor as a like amount of DC voltage.

Safety Switch Enclosed manually-operated disconnecting switch; horsepower and current rated; disconnects all power lines.

Saturation The maximum amount of magnetic flux a material can hold.

Schematic An electrical diagram that shows components in their electrical sequence without regard for physical location.

Selector Switch A master switch that is manually operated; rotating motion for actuating device; assembled into push-button master stations.

Semiautomatic Starter Part of the operation of this type of starter is nonautomatic while selected portions are automatically controlled.

Semiconductor A material that contains four valence electrons and is used in the production of solid-state devices. The most common types are silicon and germanium.

Semimagnetic Control An electric controller in which functions are partly controlled by electromagnets.

Sensing Device A pilot device that measures, compares, or recognizes a change or variation in the system that it is monitoring; provides a controlled signal to operate or control other devices.

Series-Aiding Two or more voltage producing devices connected in series in such a manner that their voltages add to produce a higher total voltage.

Series Circuit An electric circuit formed by the connection of one or more components in such a manner that there is only one path for current flow.

Service The conductors and equipment necessary to deliver energy from the electrical supply system to the premises served.

Service Equipment Necessary equipment, circuit breakers, or switches and fuses with accessories mounted near the entry of the electrical supply; constitutes the main control or cutoff for supply.

Service Factor (of a general-purpose motor) An allowable overload; the amount of allowable overload is indicated by a multiplier which, when applied to a normal horsepower rating, indicates the permissible loading.

Shaded-Pole Motor A single-phase induction motor provided with an auxiliary short-circuited winding or windings displaced in magnetic position from the main winding. (NEMA)

Shading Loop A large copper wire or band connected around part of a magnetic pole piece to oppose a change of magnetic flux.

Short Circuit An electrical circuit that contains no resistance to limit the flow of current.

Signal The event, phenomenon, or electrical quantity that conveys information from one point to another.

Signal Generator A text instrument used to produce a low-value, ac voltage for the purpose of testing or calibrating electronic equipment.

Silicon Controlled Rectifier (SCR) A four-layer semiconductor device that is a rectifier and must be triggered by a pulse applied to the gate before it will conduct.

Sine-Wave Voltage A voltage waveform; its value at any point is proportional to the trigonometric sine of the angle of the generator producing it.

Slip Difference between the rotor rpm and the rotating magnetic field of an AC motor.

Snap Action The quick opening and closing action of a spring-loaded contact.

Solder Pot See Eutectic Alloy.

Solenoid A magnetic device used to convert electrical energy into linear motion. A tubular, current-carrying coil that provides magnetic action to perform various work functions.

Solenoid-and-Plunger A solenoid-and-plunger is a solenoid provided with a bar of soft iron or steel called a plunger.

Solenoid Valve A valve operated by an electric solenoid.

Solid-State Devices Electronic components that control electron flow through solid materials such as crystals; e.g., transistors, diodes, integrated circuits.

Special-Purpose Motor A motor with special operating characteristics or special mechanical construction, or both, designed for a particular application and not falling within the definition of a general-purpose or definite-purpose motor. (NEMA)

Split-Phase A single-phase induction motor with auxiliary winding, displaced in magnetic position from, and connected parallel to, the main winding. (NEMA)

Starter A starter is a controller designed for accelerating a motor to normal speed in one direction of rotation. NOTE: A device designed for starting a motor in either direction of rotation includes the additional function of reversing and should be designated as a controller.

Startup The time between equipment installation and the full operation of the system.

Static Control Control system in which solid-state devices perform the functions. Refers to no moving parts or without motion.

Stealer Transistor A transistor used in such a manner as to force some other component to remain in the off state by shunting its current to electrical ground.

Step-Down Transformer A transformer that produces a lower voltage at its secondary winding than is applied to its primary winding.

Step-Up Transformer A transformer that produces a higher voltage at its secondary winding than is applied to its primary winding.

Surge A transient variation in the current and/or potential at a point in the circuit; unwanted, temporary.

Switch A device for making, breaking, or changing the connections in an electric circuit.

Switchboard A large, single panel with a frame or assembly of panels; devices may be mounted on the face of the panels, on the back, or both; contains switches, overcurrent, or protective devices; instruments accessible from the rear and front; not installed in wall-type cabinets. (See Panelboard)

Synchronous Speed The speed of the rotating magnetic field of an AC induction motor.

Tachometer Generator Used for counting revolutions per minute. Electrical magnitude or impulses are calibrated with a dial-gauge reading in rpm.

Temperature Relay A relay that functions at a predetermined temperature in the apparatus protected. This relay is intended to protect some other apparatus such as a motor or controller and does not necessarily protect itself.

Terminal A fitting attached to a circuit or device for convenience in making electrical connections.

Thermal Compound A grease-like substance used to thermally bond two surfaces together for the purpose of increasing the rate of heat transfer from one object to another.

Thermal Protector (as applied to motors) An inherent overheating protective device that is responsive to motor current and temperature. When properly applied to a motor, this device protects the motor against dangerous overheating due to overload or failure to start.

Thermistor A resistor that changes its resistance with a change of temperature.

Thyristor An electronic component that has only two states of operation, on and off.

Time Limit See Definite Time.

Timer A pilot device that is also considered a timing relay; provides adjustable time period to perform function; motor driven; solenoid-actuated; electronic.

Torque The torque of a motor is the twisting or turning force that tends to produce rotation.

Transducer A device that transforms power from one system to power of a second system: for example, heat to electrical.

Transformer An electromagnetic device that converts voltages for use in power transmission and operation of control devices.

Transient See Surge.

Transistor A solid-state device made by combining three layers of semiconductor material. A small amount of current flow through the base-emitter can control a larger amount of current flow through the collector-emitter.

Triac A bidirectional, thyristor device used to control AC voltage.

Trigger Pulses A voltage or current of short duration used to activate the gate, base, or input of some electronic device.

Trip Free Refers to a circuit breaker that cannot be held in the on position by the handle on a sustained overload.

Troubleshoot To locate and eliminate the source of trouble in any flow of work.

Truth Table A chart used to show the output condition of a logic gate or circuit as compared to different conditions of input.

Undervoltage Protection The result when a device operates on the reduction or failure of voltage to cause and maintain the interruption of power to the main circuit.

Undervoltage Release Occurs when a device operates on the reduction or failure of voltage to cause the interruption of power to the main circuit, but does not prevent the reestablishment of the main circuit on the return of voltage.

Unijunction Transistor (UJT) A special transistor that is a member of the thyristor family of devices and operates like a voltage-controlled switch.

Valence Electron The electron in the outermost shell or orbit of an atom.

Variable Resistor A resistor in which the resistance value can be adjusted between the limits of its minimum and maximum value.

Varistor A resistor that changes its resistance value with a change of voltage.

Volt/Voltage An electrical measure of potential difference, electromotive force, or electrical pressure.

Voltage Divider A series connection of resistors used to produce different values of voltage drop across them.

Voltage Drop The amount of voltage required to cause an amount of current to flow through a certain value of resistance or reactance.

Voltage Rating A rating that indicates the amount of voltage that can safely be connected to a device.

Voltage Regulator A device or circuit that maintains a constant value of voltage.

Voltage Relay A relay that functions at a predetermined value of voltage. A voltage relay may be either an overvoltage or an undervoltage relay.

Voltmeter An instrument used to measure a level of voltage.

Volt-Ohm-Milliammeter (VOM) A test instrument so designed that it can be used to measure voltage, resistance, or milliamperes.

Watt A measure of true power.

Waveform The shape of a wave as obtained by plotting a graph with respect to voltage and time.

Wye Connection A connection of three components made in such a manner that one end of each component is connected. This connection generally connects devices to a three-phase power system.

Zener Diode A special diode that exhibits a constant voltage drop when connected in such a manner that current flows through it in the reverse direction.

Zener Region The region current enters into when it flows through a diode in the reverse direction.

Zero Switching A feature of some solid-state relays that causes current to continue flowing through the device until the AC waveform returns to zero.

This page intentionally left blank

INDEX

This page intentionally left blank

License Agreement for Delmar Cengage Learning

IMPORTANT! READ CAREFULLY: This End User License Agreement ("Agreement") sets forth the conditions by which Cengage Learning will make electronic access to the Cengage Learning-owned licensed content and associated media, software, documentation, printed materials, and electronic documentation contained in this package and/or made available to you via this product (the "Licensed Content"), available to you (the "End User"). BY CLICKING THE "I ACCEPT" BUTTON AND/OR OPENING THIS PACKAGE, YOU ACKNOWLEDGE THAT YOU HAVE READ ALL OF THE TERMS AND CONDITIONS, AND THAT YOU AGREE TO BE BOUND BY ITS TERMS, CONDITIONS, AND ALL APPLICABLE LAWS AND REGULATIONS GOVERNING THE USE OF THE LICENSED CONTENT.

1.0 SCOPE OF LICENSE

1.1 Licensed Content. The Licensed Content may contain portions of modifiable content ("Modifiable Content") and content which may not be modified or otherwise altered by the End User ("Non-Modifiable Content"). For purposes of this Agreement, Modifiable Content and Non-Modifiable Content may be collectively referred to herein as the "Licensed Content." All Licensed Content shall be considered Non-Modifiable Content, unless such Licensed Content is presented to the End User in a modifiable format and it is clearly indicated that modification of the Licensed Content is permitted.

1.2 Subject to the End User's compliance with the terms and conditions of this Agreement, Cengage Learning hereby grants the End User, a nontransferable, nonexclusive, limited right to access and view a single copy of the Licensed Content on a single personal computer system for noncommercial, internal, personal use only. The End User shall not (i) reproduce, copy, modify (except in the case of Modifiable Content), distribute, display, transfer, sublicense, prepare derivative work(s) based on, sell, exchange, barter or transfer, rent, lease, loan, resell, or in any other manner exploit the Licensed Content; (ii) remove, obscure, or alter any notice of Cengage Learning's intellectual property rights present on or in the Licensed Content, including, but not limited to, copyright, trademark, and/or patent notices; or (iii) disassemble, decompile, translate, reverse engineer, or otherwise reduce the Licensed Content.

2.0 TERMINATION

2.1 Cengage Learning may at any time (without prejudice to its other rights or remedies) immediately terminate this Agreement and/or suspend access to some or all of the Licensed Content, in the event that the End User does not comply with any of the terms and conditions of this Agreement. In the event of such termination by Cengage Learning, the End User shall immediately return any and all copies of the Licensed Content to Cengage Learning.

3.0 PROPRIETARY RIGHTS

3.1 The End User acknowledges that Cengage Learning owns all rights, title and interest, including, but not limited to all copyright rights therein, in and to the Licensed Content, and that the End User shall not take any action inconsistent with such ownership. The Licensed Content is protected by U.S., Canadian and other applicable copyright laws and by international treaties, including the Berne Convention and the Universal Copyright Convention. Nothing contained in this Agreement shall be construed as granting the End User any ownership rights in or to the Licensed Content.

3.2 Cengage Learning reserves the right at any time to withdraw from the Licensed Content any item or part of an item for which it no longer retains the right to publish, or which it has reasonable grounds to believe infringes copyright or is defamatory, unlawful, or otherwise objectionable.

4.0 PROTECTION AND SECURITY

4.1 The End User shall use its best efforts and take all reasonable steps to safeguard its copy of the Licensed Content to ensure that no unauthorized reproduction, publication, disclosure, modification, or distribution of the Licensed Content, in whole or in part, is made. To the extent that the End User becomes aware of any such unauthorized use of the Licensed Content, the End User shall immediately notify Cengage Learning. Notification of such violations may be made by sending an e-mail to infringement@cengage.com.

5.0 MISUSE OF THE LICENSED PRODUCT

5.1 In the event that the End User uses the Licensed Content in violation of this Agreement, Cengage Learning shall have the option of electing liquidated damages, which shall include all profits generated by the End User's use of the Licensed Content plus interest computed at the maximum rate permitted by law and all legal fees and other expenses incurred by Cengage Learning in enforcing its rights, plus penalties.

6.0 FEDERAL GOVERNMENT CLIENTS

6.1 Except as expressly authorized by Cengage Learning, Federal Government clients obtain only the rights specified in this Agreement and no other rights. The Government acknowledges that (i) all software and related documentation incorporated in the Licensed Content is existing commercial computer software within the meaning of FAR 27.405(b)(2); and (2) all other data delivered in whatever form, is limited rights data within the meaning of FAR 27.401. The restrictions in this section are acceptable as consistent with the Government's need for software and other data under this Agreement.

7.0 DISCLAIMER OF WARRANTIES AND LIABILITIES

7.1 Although Cengage Learning believes the Licensed Content to be reliable, Cengage Learning does not guarantee or warrant (i) any information or materials contained in or produced by the Licensed Content, (ii) the accuracy, completeness or reliability of the Licensed Content, or (iii) that the Licensed Content is free from errors or other material defects. THE LICENSED PRODUCT IS PROVIDED "AS IS," WITHOUT ANY WARRANTY OF ANY KIND AND CENGAGE LEARNING DISCLAIMS ANY AND ALL WARRANTIES, EXPRESSED OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. IN NO EVENT SHALL CENGAGE LEARNING BE LIABLE FOR: INDIRECT, SPECIAL, PUNITIVE OR CONSEQUENTIAL DAMAGES INCLUDING FOR LOST PROFITS, LOST DATA, OR OTHERWISE. IN NO EVENT SHALL CENGAGE LEARNING'S AGGREGATE LIABILITY HEREUNDER, WHETHER ARISING IN CONTRACT, TORT, STRICT LIABILITY OR OTHERWISE, EXCEED THE AMOUNT OF FEES PAID BY THE END USER HEREUNDER FOR THE LICENSE OF THE LICENSED CONTENT.

8.0 GENERAL

8.1 Entire Agreement. This Agreement shall constitute the entire Agreement between the Parties and supercedes all prior Agreements and understandings oral or written relating to the subject matter hereof.

8.2 Enhancements/Modifications of Licensed Content. From time to time, and in Cengage Learning's sole discretion, Cengage Learning may advise the End User of updates, upgrades, enhancements and/or improvements to the Licensed Content, and may permit the End User to access and use, subject to the terms and conditions of this Agreement, such modifications, upon payment of prices as may be established by Cengage Learning.

8.3 No Export. The End User shall use the Licensed Content solely in the United States and shall not transfer or export, directly or indirectly, the Licensed Content outside the United States.

8.4 Severability. If any provision of this Agreement is invalid, illegal, or unenforceable under any applicable statute or rule of law, the provision shall be deemed omitted to the extent that it is invalid, illegal, or unenforceable. In such a case, the remainder of the Agreement shall be construed in a manner as to give greatest effect to the original intention of the parties hereto.

8.5 Waiver. The waiver of any right or failure of either party to exercise in any respect any right provided in this Agreement in any instance shall not be deemed to be a waiver of such right in the future or a waiver of any other right under this Agreement.

8.6 Choice of Law/Venue. This Agreement shall be interpreted, construed, and governed by and in accordance with the laws of the State of New York, applicable to contracts executed and to be wholly preformed therein, without regard to its principles governing conflicts of law. Each party agrees that any proceeding arising out of or relating to this Agreement or the breach or threatened breach of this Agreement may be commenced and prosecuted in a court in the State and County of New York. Each party consents and submits to the nonexclusive personal jurisdiction of any court in the State and County of New York in respect of any such proceeding.

8.7 Acknowledgment. By opening this package and/or by accessing the Licensed Content on this Web site, THE END USER ACKNOWLEDGES THAT IT HAS READ THIS AGREEMENT, UNDERSTANDS IT, AND AGREES TO BE BOUND BY ITS TERMS AND CONDITIONS. IF YOU DO NOT ACCEPT THESE TERMS AND CONDITIONS, YOU MUST NOT ACCESS THE LICENSED CONTENT AND RETURN THE LICENSED PRODUCT TO CENGAGE LEARNING (WITHIN 30 CALENDAR DAYS OF THE END USER'S PURCHASE) WITH PROOF OF PAYMENT ACCEPTABLE TO CENGAGE LEARNING, FOR A CREDIT OR A REFUND. Should the End User have any questions/comments regarding this Agreement, please contact Cengage Learning at Delmar.help@cengage.com.