Electric Motors *and* Control Systems

Second Edition

Mc Graw Hill Education

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ELECTRIC MOTORS AND CONTROL SYSTEMS, SECOND EDITION

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Preface

This book has been written for a course of study that will introduce the reader to a broad range of motor types and control systems. It provides an overview of electric motor operation, selection, installation, control, and maintenance. Every effort has been made to present the most up-to-date information, reflecting the current needs of the industry.

The broad-based approach taken makes this text viable for a variety of motor and control system courses. Content is suitable for colleges, technical institutions, and vocational/technical schools as well as apprenticeship and journeymen training. Electrical apprentices and journeymen will find this book to be invaluable because of National Electrical Code references as well as information on maintenance and troubleshooting techniques. Personnel involved in motor maintenance and repair will find the book to be a useful reference text.

The text is comprehensive! It includes coverage of how motors operate in conjunction with their associated control circuitry. Both older and newer motor technologies are examined. Topics covered range from motor types and controls to installing and maintaining conventional controllers, electronic motor drives, and programmable logic controllers.

Features you will find unique to this motors and controls text include:

Self-Contained Chapters. Each chapter constitutes a complete and independent unit of study. All chapters are divided into parts designed to serve as individual lessons. Instructors can easily pick and choose chapters or parts of chapters that meet their particular curriculum needs.

How Circuits Operate. When understanding the operation of a circuit is called for, a bulleted list is used to summarize its operation. The lists are used in place of paragraphs and are especially helpful for explaining the sequenced steps of a motor control operation.

Integration of Diagrams and Photos. When the operation of a piece of equipment is illustrated by means of a diagram, a photo of the device is included. This feature is designed to increase the level of recognition of devices associated with motor and control systems.

Troubleshooting Scenarios. Troubleshooting is an important element of any motors and controls course. The chapter troubleshooting scenarios are designed to help students with the aid of the instructor to develop a systematic approach to troubleshooting.

Discussion and Critical Thinking Questions. These open-ended questions are designed to give students an opportunity to reflect on the material covered in the chapter. In most cases, they allow for a wide range of responses and provide an opportunity for the student to share more than just facts.

The second edition has been revised to include the following:

- **Key concepts** and terms, which are now **highlighted** the first time they appear.
- New/updated **photos** and **line art** for **every chapter**.
- An expanded use of **bulleted lists** for lengthy explanations.
- **Additional review questions** for new topics.
- **Additional** end of chapter **Troubleshooting Scenarios** with suggested solutions.
- **Additional** end of chapter **Discussion topics** with suggested talking points.
- Updated **PowerPoint** slides for instructors.

The following content has been added to the chapters listed below:

Chapter 1 - Arc flash hazards.

Chapter 2 - DC motor applications.
- Reverse phase relay operation.

Chapter 3 - Transformer power losses.
- Transformer performance.
- Current and potential transformer connections.

Chapter 4 - Pushbutton assembly.
- Ultrasonic wind sensors.
- Thermowells.
- Double-break and dry contacts.
- Stepper motor operation.

Chapter 5 - AC and DC generators.
- Industrial motor applications.
- Asynchronous motor.
- Instruments used for troubleshooting motors.

Chapter 6 - Auxiliary contact blocks.
- Inductive loads and voltage spikes.
- Solid-state contactors.
- Microprocessor -based modular overload relay.
- Comparison of NEMA and IEC symbols and circuits.

Chapter 7 - DIN rail mounting
- Solid-state relay issues
- Relay timing diagrams

Chapter 8 - Multiple motor start-stop stations
- IEC reversing motor starter power and control circuit.
- HOA motor control circuit.
- E-stop motor control circuit.
- Soft starter versus variable frequency drive.
- Limit switch motor control applications.

Chapter 9 - Diode Testing.
- Bipolar junction transistor testing.
- Field-effect transistor testing.
- SCR testing.
- Triac testing.

Chapter 10 - Open and closed loop control.
- Vector drives.
- Four-quadrant control.
- Fixed PLC controllers.

Ancillaries

- **Activities Manual for *Electric Motors and Control Systems.*** This manual contains quizzes, practical assignments, and computer-generated simulated circuit analysis assignments.

  Quizzes made up of multiple choice, true/false, and completion-type questions are provided for each part of each chapter. These serve as an excellent review of the material presented.

  Practical assignments are designed to give the student an opportunity to apply the information covered in the text in a hands-on motor installation.

  The Constructor motor control simulation software is included as part of the manual. This special edition of the program contains some 45 preconstructed simulated motor control circuits constructed using both NEMA and IEC symbols. The Constructor analysis assignments provide students with the opportunity to test and troubleshoot the motor control circuits discussed in the text. The Constructor simulation engine visually displays power flow to each component and using animation and sound effects, each component will react accordingly once power is supplied.

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- **Instructor's Resources** are available to instructors who adopt *Electric Motors and Control Systems*. They can be found on the Instructor Library on Connect and include:

  Answers to the textbook review questions and the Activities Manual quizzes and assignments.

  PowerPoint presentations that feature enhanced graphics along with explanatory text and objective-type questions.

  EZ Test testing software with text-coordinated question banks.

  ExamView text coordinated question banks.

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Once you have your password, please go to connect.mheducation.com, and log in. Click on the course for which you are using *Electric Motors and Control Systems.* If you have not added a course, click "Add Course," and select "Engineering Technology" from the drop-down menu. Select *Electric Motors and Control Systems,* 2e and click "Next."

Once you have added the course, Click on the "Library" link, and then click "Instructor Resources."

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About the Author

Frank D. Petruzella has extensive practical experience in the electrical motor control field, as well as many years of experience teaching and authoring textbooks. Before becoming a full time educator, he was employed as an apprentice and electrician in areas of electrical installation and maintenance. He holds a Master of Science degree from Niagara University, a Bachelor of Science degree from the State University of New York College–Buffalo, as well as diplomas in Electrical Power and Electronics from the Erie County Technical Institute.

Electric Motors and Control Systems provides . . .

***Electric Motors and Control Systems*, 2e contains the most up-to-date information on electric motor operation, selection, installation, control and maintenance. The text provides a balance between concepts and applications to offer students an accessible framework to introduce a broad range of motor types and control systems.**

CHAPTER OBJECTIVES provide an outline of the concepts that will be presented in the chapter. These objectives provide a roadmap to students and instructors on what new material will be presented.

Chapter Objectives

This chapter will help you:

1. Recognize symbols frequently used on motor and control diagrams.
2. Read and construct ladder diagrams.
3. Read wiring, single-line, and block diagrams.
4. Become familiar with the terminal connections for different types of motors.
5. Interpret information found on motor nameplates.
6. Become familiar with the terminology used in motor circuits.
7. Understand the operation of manual and magnetic motor starters.

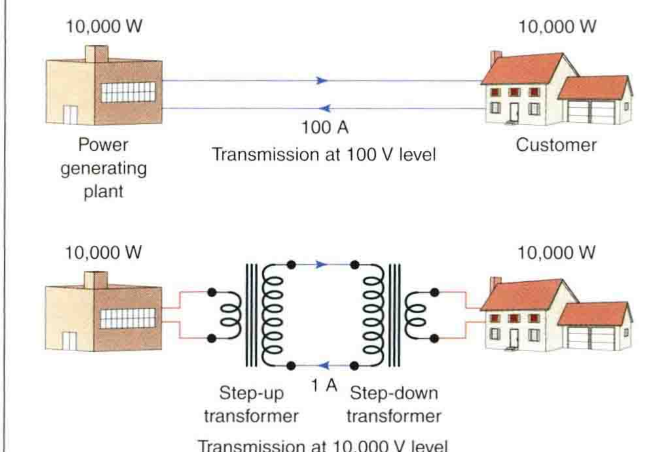

Figure 3-2 High voltage reduces the required amount of transmission current required.

CIRCUIT LISTS When a new operation of a circuit is presented, a bulleted list is used to summarize the operation. The lists are used in place of paragraphs to provide a more accessible summary of the necessary steps of a motor control operation.

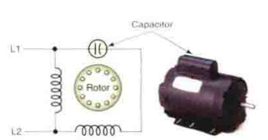

Figure 2-32 Permanent-split capacitor motor.
Photo courtesy Leeson www.leeson.com

three-phase motors. In addition, single-phase motors are not self-starting on their running windings, as are three-phase motors.

Large horsepower AC motors are usually three-phase. All three-phase motors are constructed internally with a number of individually wound coils. Regardless of how many individual coils there are, the individual coils will always be wired together (series or parallel) to produce three distinct windings, which are referred to as phase A, phase B, and phase C. All three-phase motors are wired so that the phases are connected in either **wye (Y)** or **delta (Δ)** configuration, as illustrated in Figure 2-33.

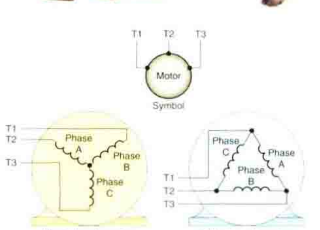

Figure 2-33 Three-phase wye and delta motor connections
Photo courtesy Leeson www.leeson.com

DIAGRAMS AND PHOTOS When the operation of a piece of equipment is illustrated, a photo of the device is included. The integration of diagrams and photos increases the students' recognition of devices associated with motor and control systems.

an engaging framework in every chapter to help students master concepts and realize success beyond the classroom.

REVIEW QUESTIONS

Each chapter is divided into parts designed to represent individual lessons. These parts provide professors and students the flexibility to pick and choose topics that best represent their needs. Review questions follow each part to reinforce the new concepts that have been introduced.

PART 1 *Review Questions*

1. Define the term *motor control circuit*.
2. Why are symbols used to represent components on electrical diagrams?
3. An electrical circuit contains three pilot lights. What acceptable symbol could be used to designate each light?
4. Describe the basic structure of an electrical ladder diagram schematic.
5. Lines are used to represent electrical wires on diagrams.
   a. How are wires that carry high current differentiated from those that carry low current?
   b. How are wires that cross but do not electrically connect differentiated from those that connect electrically?
6. The contacts of a pushbutton switch open when the button is pressed. What type of push button would this be classified as? Why?
7. A relay coil labeled TR contains three contacts. What acceptable coding could be used to identify each of the contacts?
8. A rung on a ladder diagram requires that two loads, each rated for the full line voltage, be energized when a switch is closed. What connection of loads must be used? Why?
9. One requirement for a particular motor application is that six pressure switches be closed before the motor is allowed to operate. What connections of switches should be used?
10. The wire identification labels on several wires of an electrical panel are examined and found to have the same number. What does this mean?
11. A broken line representing a mechanical function on an electrical diagram is mistaken for a conductor and wired as such. What two types of problems could this result in?

TROUBLESHOOTING SCENARIOS

These scenarios are designed to help students develop a systematic approach to troubleshooting which is vital in this course.

TROUBLESHOOTING *SCENARIOS*

Photo courtesy Fluke, www.fluke.com. Reproduced with Permission.

1. Heat is the greatest enemy of a motor. Discuss in what way nonadherence to each of the following motor nameplate parameters could cause a motor to overheat: (*a*) voltage rating; (*b*) current rating; (*c*) ambient temperature; (*d*) duty cycle.
2. Two identical control relay coils are incorrectly connected in series instead of parallel across a 230 V source. Discuss how this might affect the operation of the circuit.
3. A two-wire magnetic motor control circuit controlling a furnace fan uses a thermostat to automatically operate the motor on and off. A single-pole switch is to be installed next to the remote thermostat and wired so that, when closed, it will override the automatic control and allow the fan to operate at all times regardless of the thermostat setting. Draw a ladder control diagram of a circuit that will accomplish this.
4. A three-wire magnetic motor control circuit uses a remote start/stop pushbutton station to operate the motor on and off. Assume the start button is pressed but the starter coil does not energize. List the possible causes of the problem.
5. How is the control voltage obtained in most motor control circuits?
6. Assume you have to purchase a motor to replace the one with the specifications shown below. Visit the website of a motor manufacturer and report on the specifications and price of a replacement motor.

Horsepower	10
Voltage	200
Hertz	60
Phase	3
Full-load amperes	33
RPM	1725
Frame size	215T
Service factor	1.15
Rating	40C AMB-CONT
Locked rotor code	J
NEMA design code	B
Insulation class	B
Full-load efficiency	85.5
Power factor	76
Enclosure	OPEN

DISCUSSION TOPICS AND CRITICAL THINKING QUESTIONS

These open-ended questions are designed to give students an opportunity to review the material covered in the chapter. These questions cover all the parts presented in each chapter and provide an opportunity for the student to show comprehension of the concepts covered.

DISCUSSION TOPICS *AND CRITICAL THINKING QUESTIONS*

1. Why are contacts from control devices not placed in parallel with loads?
2. Record all the nameplate data for a given motor and write a short description of what each item specifies.
3. Search the Internet for electric motor connection diagrams. Record all information given for the connection of the following types of motors:
   a. DC compound motor
   b. AC single-phase dual-voltage induction motor
   c. AC three-phase two-speed induction motor
4. The AC squirrel-cage induction motor is the dominant motor technology in use today. Why?
5. In general, how do NEMA motor standards compare to IEC standards?

Contents

Safety in the Workplace

1

Photo Courtesy Honeywell, www.honeywell.com.

Chapter Objectives

This chapter will help you:

1. Identify the electrical factors that determine the severity of an electric shock.
2. Be aware of general principles of electrical safety including wearing approved protective clothing and using protective equipment.
3. Familiarity with arc flash hazard recognition and prevention.
4. Explain the safety aspects of grounding an electrical motor installation.
5. Outline the basic steps in a lockout procedure.
6. Be aware of the functions of the different organizations responsible for electrical codes and standards.

Safety is the number one priority in any job. Every year, electrical accidents cause serious injury or death. Many of these casualties are young people just entering the workplace. They are involved in accidents that result from carelessness, from the pressures and distractions of a new job, or from a lack of understanding about electricity. This chapter is designed to develop an awareness of the dangers associated with electrical power and the potential dangers that can exist on the job or at a training facility.

PART 1 Protecting against Electrical Shock

Electrical Shock

The human body conducts electricity. Even low currents may cause severe health effects. Spasms, burns, muscle paralysis, or death can result, depending on the amount of the current flowing through the body, the route it takes, and the duration of exposure.

The main factor for determining the severity of an electric shock is the amount of electric current that passes through the body. This current is dependent upon the voltage and the resistance of the path it follows through the body.

Electrical **resistance** (R) is the opposition to the flow of current in a circuit and is measured in ohms (Ω). The lower the body resistance, the greater the current flow and potential electric shock hazard. Body resistance can be divided into external (skin resistance) and internal (body tissues and blood stream resistance). Dry skin is a good insulator; moisture lowers the resistance of skin, which explains why shock intensity is greater when the hands are wet. Internal resistance is low owing to the salt and moisture content of the blood. There is a wide degree of variation in body resistance. A shock that may be fatal to one person may cause only brief discomfort to another. Typical body resistance values are:

- Dry skin—100,000 to 600,000 Ω
- Wet skin—1,000 Ω
- Internal body (hand to foot)—400 to 600 Ω
- Ear to ear—100 Ω

Thin or wet skin is much less resistant than thick or dry skin. When skin resistance is low, the current may cause little or no skin damage but severely burn internal organs and tissues. Conversely, high skin resistance can produce severe skin burns but prevent the current from entering the body.

Voltage (E) is the pressure that causes the flow of electric current in a circuit and is measured in units called volts (V). The amount of voltage that is dangerous to life varies with each individual because of differences in body resistance and heart conditions. Generally, any voltage *above 30 V* is considered dangerous.

Electric **current** (I) is the rate of flow of electrons in a circuit and is measured in amperes (A) or milliamperes (mA). One milliampere is one-thousandth of an ampere. The amount of current flowing through a person's body depends on the voltage and resistance. Body current can be calculated using the following Ohm's law formula:

$$\textbf{Current} = \frac{\textbf{Voltage}}{\textbf{Resistance}}$$

If you came into direct contact with 120 volts and your body resistance was 100,000 ohms, then the current that would flow would be:

$$I = \frac{120\text{ V}}{100{,}000\ \Omega} = 0.0012\text{ A} = 1.2\text{ mA } (0.0012 \times 1{,}000)$$

This is just about at the threshold of perception, so it would produce only a tingle.

If you were sweaty and barefoot, then your resistance to ground might be as low as 1,000 ohms. Then the current would be:

$$I = \frac{120\text{ V}}{1{,}000\ \Omega} = 0.12\text{ A} = 120\text{ mA}$$

This is a lethal shock, capable of producing ventricular fibrillation (rapid irregular contractions of the heart) and death!

Voltage is not as reliable an indication of shock intensity because the body's resistance varies so widely that it is impossible to predict how much current will result from a given voltage. The amount of current that passes through the body and the length of time of exposure are perhaps the two most reliable criteria of shock intensity. Once current enters the body, it follows through the circulatory system in preference to the external skin. Figure 1-1 illustrates the relative magnitude and effect of electric current. It doesn't take much current to cause a painful or even fatal shock. A current of 1 mA (1/1000 of an ampere) can be felt. A current of 10 mA will produce a shock of sufficient intensity to prevent voluntary control of muscles, which explains why, in some cases, the victim of electric shock is unable to release grip on the conductor while the current is flowing. A current of 100 mA passing through the body for a second or longer can be fatal. Generally, any current flow *above 0.005 A, or 5 mA,* is considered dangerous.

A 1.5 V flashlight cell can deliver more than enough current to kill a human being, yet it is safe to handle. This is because the resistance of human skin is high enough to limit greatly the flow of electric current. In lower voltage circuits, resistance restricts current flow to very low values. Therefore, there is little danger of an electric shock. Higher voltages, on the other hand, can force enough current though the skin to produce a shock. The danger of harmful shock increases as the voltage increases.

The pathway through the body is another factor influencing the effect of an electric shock. For example, a current from hand to foot, which passes through the heart and part of the central nervous system, is far more dangerous than a shock between two points on the same arm (Figure 1-2).

AC (alternating current) of the common 60 Hz frequency is three to five times more dangerous than DC (direct current) of the same voltage and current value. DC tends to cause a convulsive contraction of the muscles, often forcing the victim away from further current exposure. The effects of AC on the body depend to a great extent on the frequency: low-frequency currents (50–60 Hz) are usually more dangerous than high-frequency currents. AC causes muscle spasm, often "freezing" the hand (the most common part of the body to make contact) to the circuit. The fist clenches around the current source, resulting in prolonged exposure with severe burns.