THIRD EDITION

Electric Motors and Control Systems

Frank D. Petruzella

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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.

One unique feature with all of his texts is that they are all supported with the latest in related computer simulation software. Working in conjunction with National Instruments for Multisim, CMH Software for Constructor, and The Learning Pit for LogixPro, he has developed program files directly related to circuits explained in the text.

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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 following content has been added to the chapters listed below:

Chapter 1 - Safety light curtains
- Safety interlock switches
- Emergency stop controls
- Safety laser scanners

Chapter 2 - Comparison of common motor NEMA and IEC symbols
- Riser diagrams
- Dual voltage three-phase motor connections
- IEC three-phase motor connections
- IEC 2-wire and 3-wire control circuits

Chapter 3 - Motor control center three-phase full-voltage starter bucket
- Electrical grounding
- Transformer testing

Chapter 4 - IEC break-make pushbutton control circuit
- Two motor emergency stop control circuit
- Signal light towers
- Alternating pumping operation and control circuit
- Comparison of the features and application of sensors

Chapter 5 - DC brushless motor operation and applications

Chapter 6 - Capacitor switching contactor operation and applications
- DC inverter power contactors

Chapter 7 - Interposing relay operation and applications
- Analog-switching relay operation and applications
- Conveyor motor warning signal control circuit
- Timed and instantaneous relay timer contacts
- One-shot timer solenoid control circuit
- Symmetrical recycle timer flasher circuit

Chapter 8 - Three motor sequential motor starting interlocking circuit.
- Two motor sequential motor stopping interlocking circuit.
- Three-phase motor selector jogging circuit.
- Zero-speed switch operation.
- Antiplugging executed using time-delay relays.

Chapter 9 - Inverter applications and output waveforms.
- Building blocks of an electronic motor control system.
- Three-wire sourcing and sinking sensor connections.

Chapter 10 - Analog versus digital signals.
- 4–20 mA control loop.
- PLC processor module troubleshooting.
- PLC input module troubleshooting.
- PLC output module troubleshooting.

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 preconstructed simulated motor control circuits constructed using both NEMA and IEC symbols. The constructor analysis assignments provide students with the opportunity to test 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.

  The constructor troubleshooting mode includes a Test Probe that provides an indication of power or continuity. The test probe leads are inserted into the circuit to determine common preprogrammed motor faults.

- **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.

  Instructional videos for text motor control circuits.

ACKNOWLEDGMENTS

The efforts of many people are needed to develop and improve a text. Among these people are the reviewers and consultants who point out areas of concern, cite areas of strength, and make recommendations for change. In particular, I would like to acknowledge Don Pelster of Nashville Community College. Don has done an impeccable job of performing a technical edit of the text as well as all the additional Instructor resources.

E*lectric Motors and Control Systems,* 3e 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.

Electric Motors and Control Systems provides . . .

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

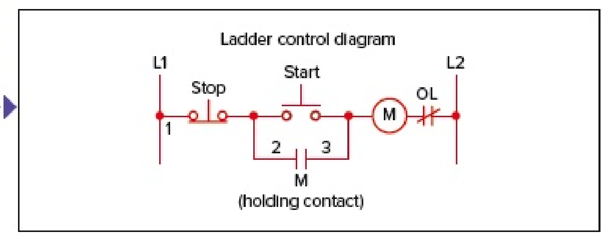
This chapter will help you:

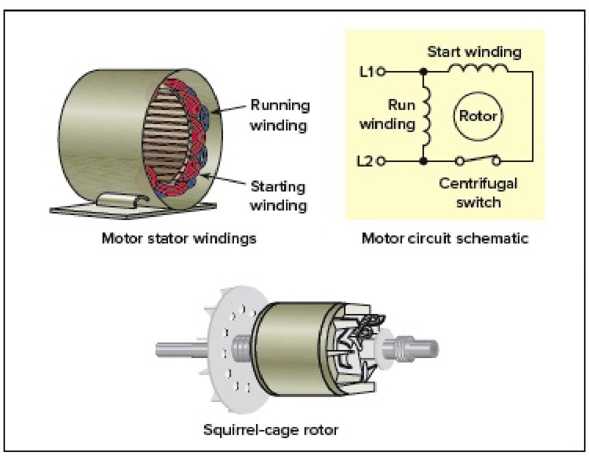
- Recognize symbols frequently used on motor and control diagrams.
- Differentiate between NEMA and IEC motor control symbols.
- Interpret and construct ladder diagrams.
- Interpret wiring, single-line, and block diagrams.
- Explain the terminal connections for different types of motors.
- Interpret connection schemes used for dual-voltage three-phase motors.
- Interpret information found on motor nameplates.
- Explain the terminology used in motor circuits.

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.

The operation of the circuit can be summarized as follows:

- Three-wires are run from the start/stop pushbutton station to the starter.
- When the momentary-contact start button is closed, line voltage is applied to the starter coil to energize it.
- The three main M contacts close to apply voltage to the motor.





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. Does the severity of an electric shock increase or decrease with each of the following changes?
   a. A decrease in the source voltage
   b. An increase in body current flow
   c. An increase in body resistance
   d. A decrease in the length of time of exposure
2. a. Calculate the theoretical body current flow (in amperes and milliamperes) of an electric shock victim who comes in contact with a 120 V energy source. Assume a total resistance of 15,000 Ω (skin, body, and ground contacts).
   b. What effect, if any, would this amount of current likely have on the body?
3. Normally a 6 volt lantern battery capable of delivering 2 A of current is considered safe to handle. Why?
4. Why is AC of a 60 Hz frequency considered to be potentially more dangerous than DC of the same voltage and current value?
5. What circuit fault can result in an arc flash?
8. State the piece of electrical safety equipment that should be used to perform each of the following tasks:
   a. A switching operation where there is a risk of injury to the eyes or face from an electric arc.
   b. Using a multimeter to verify the line voltage on a three-phase 480 volt system.
   c. Opening a manually operated high-voltage disconnect switch.
9. Outline the safety procedure to follow when you are connecting shorting probes across de-energized circuits.
10. List three pieces of personal protection equipment required to be worn on most job sites.
11. Explain the way in which safety light curtains operate.
12. a. Describe a typical example of point of operation light curtain control.
    b. Describe a typical example of perimeter access light curtain control.
13. What type of safety switch is used to monitor the

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

Troubleshooting Scenarios

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	32
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

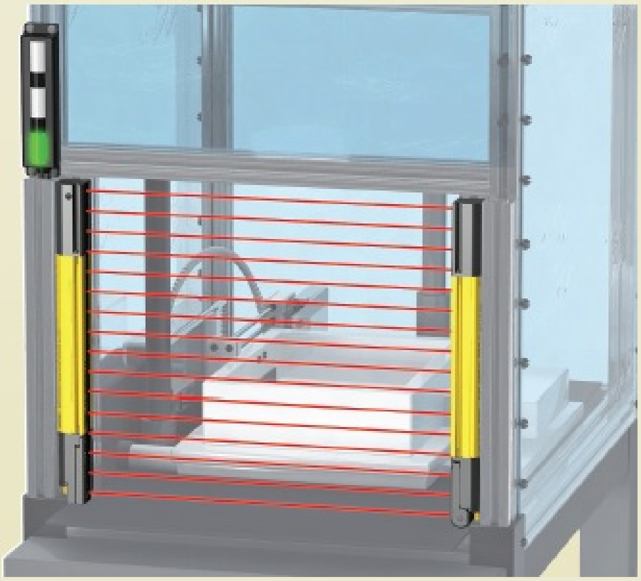
DISCUSSION TOPICS AND CRITICAL THINKING QUESTIONS These open-ended questions are designed to give students an opportunity to review the material covered in the chapter. These questions cover all the parts presented in each chapter and provide an opportunity for the student to show comprehension of the 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?

CHAPTER ONE

Safety in the Workplace



Banner Engineering

CHAPTER OBJECTIVES

This chapter will help you:

- Identify the electrical factors that determine the severity of an electric shock.
- Describe arc flash hazard recognition and prevention.
- List of general principles of electrical safety including wearing approved protective clothing and using protective equipment.
- Understand the application of different types of electrical machine safety devices.
- Explain the safety aspects of grounding an electrical motor installation.
- Outline the basic steps in a lockout procedure.
- Identify 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.

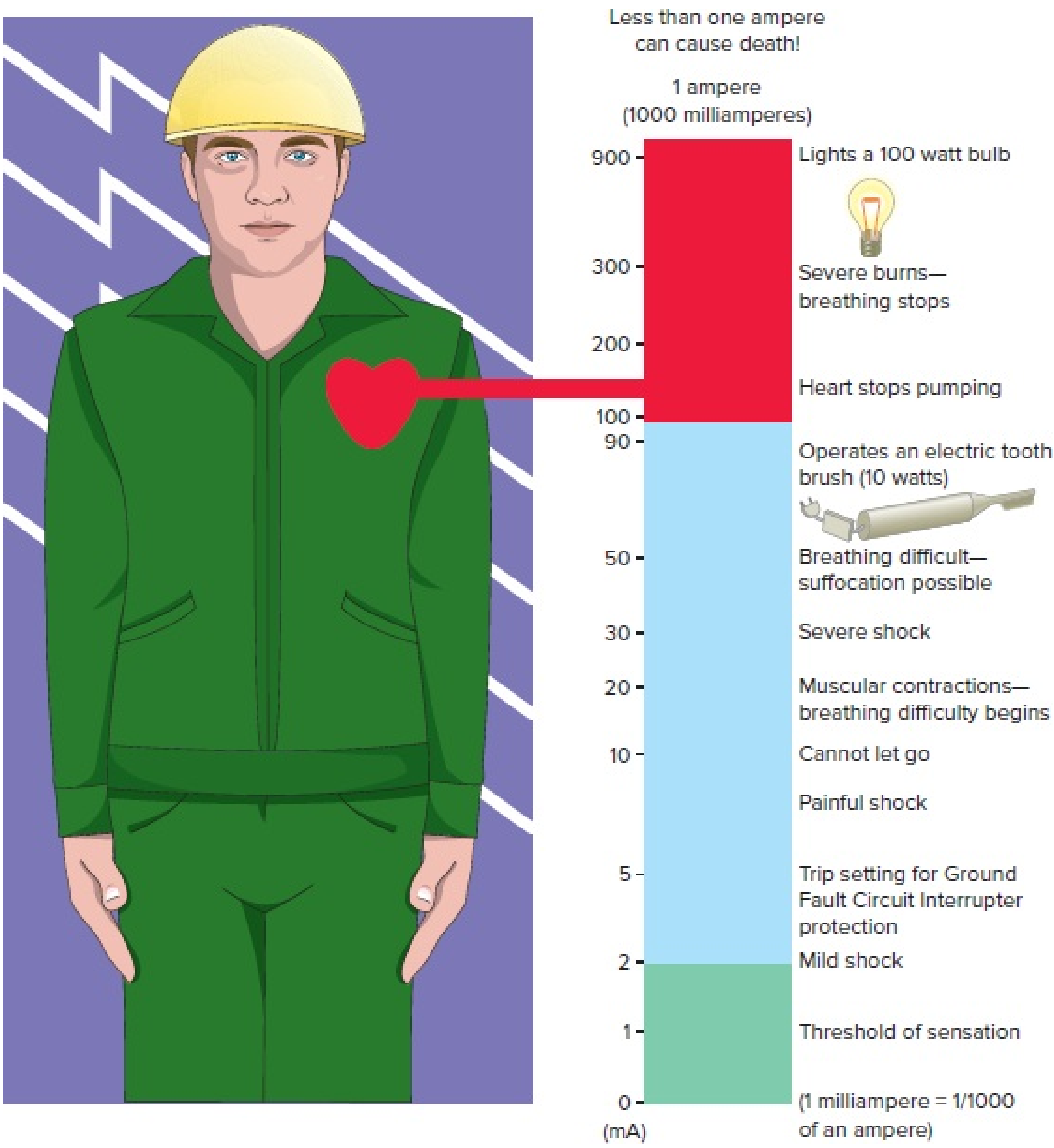


Figure 1-1 Relative magnitude and effect of electric current on the body.

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).

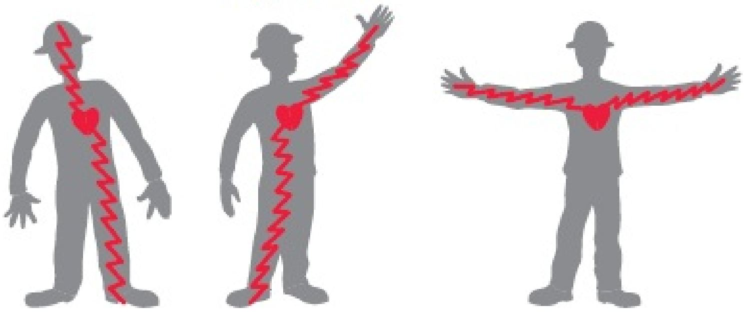


Figure 1-2 **Typical electric current pathways that stop normal pumping of the heart.**

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.

Page 3

The most common electric-related injury is a burn. The major types of burns:

- **Electrical burns,** which are a result of electric current flowing through the tissues or bones. The burn itself may be only on the skin surface or deeper layers of the skin may be affected.
- **Arc burns,** which are a result of an extremely high temperature caused by an electric arc (as high as 35,000°F) in close proximity to the body. Electric arcs can occur as a result of poor electrical contact or failed insulation.
- **Thermal contact burns,** which are a result of the skin coming in contact with the hot surfaces of overheated components. They can be caused by contact with objects dispersed as a result of the blast associated with an electric arc.

If a person does suffer a severe shock, it is important to free the victim from the current as quickly as can be done safely. Do not touch the person until the electric power is turned off. You cannot help by becoming a second victim. The victim should be attended to immediately by a person trained in CPR (cardiopulmonary resuscitation).

Page 4

Arc Flash Hazards

An **arc flash** is the ball of fire that explodes from an electrical **short circuit** between one exposed live conductor and another conductor or to ground. The arc flash creates an enormous amount of energy (Figure 1-3) that can damage equipment and cause severe injury or loss of life.

Figure 1-3 **Arc flash.**

Photo Courtesy of Honeywell, www.honeywell.com

An arc flash can be caused by dropped tools, unintentional contact with electrical systems, or the buildup of conductive dust, dirt, corrosion, and particles.

Electrical short circuits are either bolted faults or arcing faults. A **bolted fault** is current flowing through bolted bus bars or other electric conductors. An **arcing fault** is current flowing through the air. Because air offers opposition to electric current flow, the arc fault current is always lower than the bolted fault current. An **arc blast** is a flash that causes an explosion of air and metal that produces dangerous pressure waves, sound waves, and molten steel.

In order to understand the hazards associated with an arc flash incident, it is important to understand the difference between an arcing short circuit and a bolted short circuit. A bolted short circuit occurs when the normal circuit current bypasses the load through a very low conductive path, resulting in current flow that can be hundreds or thousands of times the normal load current. In this case, assuming all equipment remains intact, the fault energy is contained within the conductors and equipment, and the power of the fault is dissipated throughout the circuit from the source to the short. All equipment needs to have adequate interrupting ratings to safely contain and clear the high fault currents associated with bolted faults.

In contrast, an arcing fault is the flow of current through a higher-resistance medium, typically the air, between phase conductors or between phase conductors and neutral or ground. Arcing fault currents can be extremely high in current magnitude approaching the bolted short-circuit current but are typically between 38 and 89 percent of the bolted fault. The inverse characteristics of typical overcurrent protective devices generally result in substantially longer clearing times for an arcing fault due to the lower fault values.

Eighty percent of electrical workplace accidents are associated with arc flash and involve burns or injuries caused by intense heat or showers of molten metal or debris. In addition to toxic smoke, shrapnel, and shock waves, the creation of an arc flash produces an intense flash of blinding light. This flash is capable of causing immediate vision damage and can increase a worker's risk of future vision impairment.

An arc flash hazard exists when a person interacts with equipment in a way that could cause an electric arc. Such tasks may include testing or troubleshooting, application of temporary protective grounds, or the opening or closing of power circuit breakers as illustrated in Figure 1-4. ***Arcs can produce temperature four times hotter than the surface of the sun.*** To address this hazard, safety standards such as National Fire Protection Association (NFPA) 70E have been developed to minimize arc flash hazards. The NFPA standards require that any panel likely to be serviced by a worker be **surveyed** and **labeled**. Injuries can be avoided with training; with proper work practices; and by using protective face shields, hoods, and clothing that are NFPA-compliant.

Figure 1-4 An arc flash hazard exists when a person interacts with equipment.
Chemco Electrical Contractors Ltd.

Personal Protective Equipment

Construction and manufacturing worksites, by nature, are potentially hazardous places. For this reason, safety has become an increasingly large factor in the working environment. The electrical industry, in particular, regards **safety** to be unquestionably the most single important priority because of the hazardous nature of the business. A safe operation depends largely upon all personnel being informed and aware of potential hazards. Safety signs and tags indicate areas or tasks that can pose a hazard to personnel and/or equipment. Signs and tags may provide warnings specific to the hazard, or they may provide safety instructions (Figure 1-5).