21

Electrical Safety

21.1 Introduction

Electrical safety is a very broad and diverse topic that would require several volumes for a comprehensive treatment. Instead, we will limit our discussion to a few introductory concepts and illustrate them with examples.

It would be difficult to imagine that anyone in our society could have reached adolescence without having experienced some form of electrical shock. Whether that shock was from a harmless electrostatic discharge or from accidental contact with an energized electrical circuit, the response was probably the same—an immediate and involuntary muscular reaction. In either case, the cause of the reaction is current flowing through the body. The severity of the shock depends on several factors, the most important of which are the magnitude, the duration, and the pathway of the current through the body.

21.2 Human Response To Electric Shock

The effect of electrical shock varies widely from person to person. Figure 21.1 shows the general reactions that occur as a result of 60 Hz ac current flow through the body from hand to hand, with the heart in the conduction pathway. Observe that there is an intermediate range of current, from about 0.1 to 0.2 A, which is most likely to be fatal. Current levels in this range are apt to produce ventricular fibrillation, a disruption of the orderly contractions of the heart muscle. Recovery of the heartbeat generally does not occur without immediate medical intervention. Current levels above that fatal range tend to cause the heart muscle to contract severely, and if the shock is removed soon enough, the heart may resume beating on its own.
The voltage required to produce a given current depends on the quality of the contact to the body and the impedance of the body between the points of contact. The electrostatic voltage such as might be produced by sliding across a car seat on a dry winter day may be on the order of 20,000 to 40,000 V, and the current surge upon touching the door handle, on the order of 40 A. However, the pathway for the current flow is mainly over the body surface and its duration is for only a few microseconds. Although that shock could be disastrous for some electronic components, it causes nothing more than mild discomfort and aggravation to a human being.

Electrical appliances found about the home typically require 120 or 240 V rms for operation. Although the voltage level is small compared with that of the electrostatic shock,
the potential for harm to the individual and to property is much greater. Accidental contact is more apt to result in current flow either from hand to hand or from hand to foot—either of which will subject the heart to shock. Moreover, the relatively slowly changing (low-frequency) 60 Hz current tends to penetrate more deeply into the body as opposed to remaining on the surface as a rapidly changing (high-frequency) current would tend to do. Additionally, the energy source has the capability of sustaining a current flow without depletion. Thus, subsequent discussion will concentrate primarily on hazards associated with the 60 Hz ac power system.

21.3
Ground-Fault Interrupter

The single-phase three-wire system shown in Fig. 21.2 is commonly, although not exclusively, used for electrical power distribution in residences. Two important aspects of this, or any, system that relate to safety are circuit fusing and grounding.

Each branch circuit, regardless of the type loads it serves, is protected from excessive current flow by circuit breakers or fuses. Receptacle circuits are generally limited to 20 amps and lighting circuits to 15 amps. Clearly, these cannot protect persons from lethal shock. The primary purpose of these current limiting devices is to protect equipment.

The neutral conductor of the power system is connected to ground (earth) at a multitude of points throughout the system and, in particular, at the service entrance to the residence. The connection to earth may be by way of a driven ground rod or by contact to a cold water pipe of a buried metallic water system. The 120 V branch circuits radiating from the distribution panel (fuse or breaker box) generally consist of three conductors rather than only two, as shown in Fig. 21.2. The third conductor is the ground wire, as shown in Fig. 21.3.

The ground conductor may appear to be redundant, since it plays no role in the normal operation of a load that might be connected to the receptacle. Its role is illustrated by the following example.

EXAMPLE 21.1
Joe College has a workshop in his basement where he uses a variety of power tools such as drills, saws, and sanders. The basement floor is concrete and being below ground level, it is usually damp. Damp concrete is a relatively good conductor. Unknown to Joe, the insulation on a wire in his electric drill has been nicked and the wire is in contact with (or shorted to) the metal case of the drill, as shown in Fig. 21.4.

![Figure 21.2](image-url) Single-phase three-wire system shown without circuit breakers.
Without the ground conductor connected to the metal case of the tool, Joe would receive a severe, perhaps fatal shock when he attempts to use the drill. The voltage between his hand and his feet would be 120 V and the current through his body would be limited by the resistance of his body and of the concrete floor. Typically, the circuit breakers would not operate. However, if the ground conductor is present and properly connected to the drill case, the case will remain at ground potential, the 120 V conductor becomes shorted to ground, the circuit breaker operates, and Joe lives to drill another hole.

It was mentioned that the circuit breaker or fuse cannot provide effective protection against shock. There is, however, a special type of device called a ground-fault interrupter (GFI) which can provide protection for personnel. This device detects current flow outside the normal circuit. Consider the circuit of Fig. 21.4. In the absence of a fault condition, the current in the neutral conductor must be the same as that in the line conductor. If a fault occurs, the neutral and line currents will differ by the current flowing to ground through the fault. The GFI detects that imbalance of currents between the neutral and line conductor and opens the circuit in response. Its principle of operation is illustrated by the following example.

**EXAMPLE 21.2**
Consider the action of the magnetic circuit in Fig. 21.5. Under normal operating conditions, \( i_1 \) and \( i_2 \) are equal and, if the coils in the neutral and line conductors are identical, as we learned in Chapter 18, the magnetic flux in the case will be zero. Consequently, no voltage will be induced in the sensing coil.

If a fault should occur at the load, current will flow in the ground conductor and per-
haps in the earth, thus $i_1$ and $i_2$ will no longer be equal, the magnetic flux will not be zero, and a voltage will be induced in the sensing coil. That voltage can be used to activate a circuit breaker. This is the essence of the GFI device.

Ground-fault interrupters are available in the form of circuit breakers and also as receptacles. They are now required in branch circuits that serve outlets in areas such as bathrooms, basements, garages, and outdoor sites. The devices will operate at ground-fault currents on the order of a few milliampere. Unfortunately, the GFI is a relatively new device and electrical code requirements are generally not retroactive. Thus, few older residences have them.

Requirements for the installation and maintenance of electrical systems are meticulously defined by various codes that have been established to provide protection of personnel and property. Installation, alteration, or repair of electrical devices and systems should be undertaken only by qualified persons. The subject matter that we study in this book does not provide that qualification.

We now provide some modeling techniques which help us quantify the danger involved in the potential misuse of electrical devices and systems.

The following examples illustrate the potential hazards that can be encountered in a variety of everyday situations. We begin by revisiting a situation described in a previous example.

**EXAMPLE 21.3**

Suppose that a man is working on the roof of a mobile home with a hand drill; the mobile home is tied to ground with metal straps. It is early in the day, the man is barefoot, and dew covers the mobile home. The ground prong on the electrical plug of the drill has been removed. Will the man be shocked if the "hot" electrical line shorts to the case of the drill?

To analyze this problem, we must construct a model that adequately represents the situation described. In his book *Medical Instrumentation* (Houghton Mifflin Company, Boston, 1978), John G. Webster suggests the following values for resistance of the human body:

\[ R_{skin\ (dry)} = 15 \, k\Omega, \quad R_{skin\ (wet)} = 150 \, \Omega, \quad R_{limb\ (arm\ or\ leg)} = 100 \, \Omega, \quad \text{and} \quad R_{trunk} = 200 \, \Omega. \]
The network model is shown in Fig. 21.6. Note that since the ground line is open circuited, a closed path exists from the hot wire through the short, the human body, the mobile home, and the ground. For the conditions stated above, we assume that the surface contact resistance $R_{sc1}$ and $R_{sc2}$ are 150 $\Omega$ each. The body resistance, $R_{body}$, consisting of arm, trunk, and leg, is 400 $\Omega$. The mobile home resistance is assumed to be zero, and the ground resistance, $R_{gnd}$, from the mobile home ground to the actual source ground is assumed to be 1 $\Omega$. Therefore, the magnitude of the current through the body from hand to foot would be

$$I_{body} = \frac{120}{R_{sc1} + R_{body} + R_{sc2} + R_{gnd}}$$

$$= \frac{120}{701}$$

$$= 171 \text{ mA}$$

A current of this magnitude can easily cause heart failure.

It is important to note that additional protection would be provided if the circuit breaker were a ground-fault interrupter.

**EXAMPLE 21.4**

Two boys are playing basketball in their backyard. In order to cool off, they decide to jump into their pool. The pool has a vinyl lining, so the water is electrically insulated from the earth. Unknown to the boys, there is a ground fault in one of the pool lights. One boy jumps in and while standing in the pool with water up to his chest, reaches up to pull in the other boy, who is holding onto a grounded hand rail as shown in Fig. 21.7.

What is the impact of this action?

The action in Fig. 21.7(a) is modeled as shown in Fig. 21.7(b). Note that since a ground fault has occurred, there exists a current path through the two boys. Assuming that the fault, pool, and railing resistances are approximately zero, the magnitude of the current
through the two boys would be

\[ I = \frac{120}{3R_{arm} + 3R_{wet\,contact} + R_{trunk}} \]

\[ = \frac{120}{950} \]

\[ = 126 \text{ mA} \]

This current level would cause severe shock in both boys. The boy outside the pool would be more likely to experience heart failure.

**EXAMPLE 21.5**

A patient in a medical laboratory has a muscle stimulator attached to his left forearm. His heart rate is being monitored by an EKG machine with two differential electrodes over the heart and the ground electrode attached to his right ankle. This activity is illustrated in Fig. 21.8(a). The stimulator acts as a current source that drives 150 mA through the muscle from the active electrode to the passive electrode. If the laboratory technician mistakenly decides to connect the passive (ground) electrode of the stimulator to the ground electrode of the EKG system to achieve a common ground, is there any risk?

When the passive electrode of the stimulator is connected to the ground electrode of the EKG system, the equivalent network in Fig. 21.8(b) illustrates the two paths for the
The magnitude of the body current is
\[ I_{\text{body}} = \frac{(150)(10^{-3})(100)}{100 + 100 + 200 + 100} \]
\[ = 30 \text{ mA} \]

Therefore, a dangerously high level of current will flow from the stimulator through the body to the EKG ground.

**EXAMPLE 21.6**

A cardiac care patient with a pacing electrode has ignored the hospital rules and is listening to a cheap stereo. The stereo has an amplified 60 Hz hum that is very annoying. The patient decides to dismantle the stereo partially in an attempt to eliminate the hum. In the process, while he is holding one of the speaker wires, the other touches the pacing electrode. What are the risks in this situation?

Let us suppose that the patient’s skin is damp and that the 60 Hz voltage across the speaker wires is only 10 mV. Then the circuit model in this case would be shown in Fig. 21.9. The magnitude of the current through the heart would be
\[ I = \frac{(10)(10^{-3})}{150 + 100 + 200} \]
\[ = 22.2 \mu\text{A} \]

It is known that 10 µA delivered directly to the heart is potentially lethal.
EXAMPLE 21.7
While maneuvering in a muddy area, a crane operator accidentally touched a high-voltage line with the boom of the crane as illustrated in Fig. 21.10. The line potential was 7200 V. The neutral conductor was grounded at the pole. When the crane operator realized what had happened, he jumped from the crane and walked in the direction of the
pole, which was approximately 10 m away. He was electrocuted as he walked. Can we explain this very tragic accident?

The conditions depicted in Fig. 21.10(a) can be modeled as shown in Fig. 21.10(b). The crane was at 7200 V with respect to earth. Therefore, a gradient of 720 V/m existed along the earth between the crane and the power pole. This earth between the crane and the pole is modeled as a resistance. If the man’s stride was about 1 m, the difference in potential between his feet was approximately 720 V. A man standing in the same area with his feet together was unharmed.

EXAMPLE 21.8
Two adjacent homes, A and B, are fed from different transformers as shown in Fig. 21.11(a). A surge on the line feeding house B has caused the circuit breaker X–Y to open. House B is now left without power. In an attempt to help his neighbor, the resident of house A volunteers to connect a long extension cord between a wall plug in house A and wall plug in house B, as shown in Fig. 21.11(b). Later, the lineman from the utility company comes to reconnect the circuit breaker. Unaware of the extension cord connection, the lineman

![Figure 21.11](https://example.com/figure.png)

**Figure 21.11** Diagrams used in Example 21.8.
believes that there is no voltage between points X and Z. However, because of the electrical connection between the two homes, 7200 V exists between the points and the lineman could be seriously injured or even killed if he comes in contact with this high voltage.

DRILL EXERCISE

D21.1. A young lady is driving her car in a violent rainstorm. While she is waiting at an intersection, a power line falls across her car and makes contact. The power line voltage is 7200 V.

(a) Assuming that the resistance of the car is negligible, what is the potential current through her body if while holding the door handle with a dry hand, she steps out onto the wet ground?

(b) If she remained in the car, what would happen?

Ans: (a) $I = 463 \text{ mA}$, extremely dangerous; (b) She will probably be safe.

21.5 Some Guidelines for Avoiding Injury

The examples of this section have been provided in an attempt to illustrate some of the potential dangers that exist when working or playing around electric power. In the worst case, failure to prevent an electrical accident can result in death. However, even nonlethal electrical contacts can cause such things as burns or falls. Therefore, we must always be alert to ensure not only our own safety, but also that of others who work and play with us.

The following guidelines will help us minimize the chances of injury.

1. Avoid working on energized electrical systems.
2. Always assume that an electrical system is energized unless you can absolutely verify that it is not.
3. Never make repairs or alterations which are not in compliance with the provisions of the prevailing code; have such repairs made by a licensed professional.
4. Do not work on potentially hazardous electrical systems alone.
5. If another person is “frozen” to an energized electrical circuit, deenergize the circuit if possible. If that cannot be done, use nonconductive material such as dry wooden boards, sticks, belts, and articles of clothing to separate the body from the contact. Act quickly but take care to protect yourself.
6. When handling long metallic equipment such as ladders, antennas, and so on, outdoors, be continuously aware of overhead power lines and avoid any possibility of contact with them.

Safety when working with electric power must always be a primary consideration. Regardless of how efficient or expedient an electrical network is for a particular application, it is worthless if it is also hazardous to human life.

In addition to the numerous deaths that occur each year due to electrical accidents, fire damage that results from improper use of electrical wiring and distribution equipment amounts to millions of dollars per year.

To prevent the loss of life and damage to property, very detailed procedures and spec-
ifications have been established for the construction and operation of electrical systems to ensure their safe operation. *The National Electrical Code ANSI C1* (ANSI—American National Standards Institute) is the primary guide. There are other codes, however; for example, *The National Electric Safety Code, ANSI C2*, which deals with safety requirements for public utilities. The Underwriters' Laboratory (UL) tests all types of devices and systems to ensure that they are safe for use by the general public. We find the UL label on all types of electrical equipment that is used in the home, such as appliances and extension cords.

Electric energy plays a very central role in our lives. It is extremely important to our general health and well-being. However, if not properly used, it can be lethal.

### 21.6 Summary

- Electrical shock can be fatal to human beings.
- Circuit breakers and fuses are designed to protect equipment, not humans.
- Ground-fault interrupters are used to protect humans from electric shock.
- Electrical modeling techniques can be used to help quantify the danger involved in the misuse of electrical systems.
- There are a number of guidelines that help minimize the chances of injury from electrical systems.
- The National Electrical Code is the primary guide for the construction and operation of electrical systems for safe operation.

### PROBLEMS

**21.1.** A man accidentally let his parakeet out the door. The bird flew up to a power line and sat there. Unable to coax the bird down, the man stood on an aluminum ladder and reached for the bird with an aluminum pole. Is there any potential danger in this situation? If so, what, and if not, why not?

**21.2.** In order to test a light socket, a young lady, while standing on cushions that insulate her from the ground, sticks her finger into the socket, as shown in Fig. P21.2. The tip of her finger makes contact with one side of the line and the side of her finger makes contact with the other side of the line. Assuming that any portion of a limb has

![Figure P21.2](image-url)
a resistance of 100 Ω, is there any current in the body? Is there any current in the vicinity of the heart?

21.3. A young mechanic is installing a 12 V battery in a car. The negative terminal has been connected. He is currently tightening the bolts on the positive terminal. With a tight grip on the wrench, he turns it so that the gold ring on his finger makes contact with the frame of the car. This situation is modeled in Fig. P21.3, where we assume that the resistance of the wrench is negligible and the resistance of the contact is as follows:

- \( R_1 = R_{\text{bolt to wrench}} = 0.01 \, \Omega \)
- \( R_2 = R_{\text{wrench to ring}} = 0.01 \, \Omega \)
- \( R_3 = R_{\text{ring}} = 0.01 \, \Omega \)
- \( R_4 = R_{\text{ring to frame}} = 0.01 \, \Omega \)

What power is quickly dissipated in the gold ring, and what is the impact of this power dissipation?

21.4. A man and his son are flying a kite. The kite becomes entangled in a 7200 V power line close to a power pole. The man crawls up the pole to remove the kite. While trying to remove the kite, the man accidentally touches the 7200 V line. Assuming the power pole is well grounded, what is the potential current through the man’s body?