25 Electromagnetic Induction

What You'll Learn

- You will describe how changing magnetic fields can generate electric potential differences.
- You will apply this phenomenon to the construction of generators and transformers.

Why It's Important

The relationship between magnetic fields and current makes possible the three cornerstones of electrical technology: motors, generators, and transformers.

Hydroelectric Generators Dams commonly are built on rivers to provide a source of power for nearby communities. Within the dam, the potential and kinetic energy of water is turned into electric energy.

Think About This >

How do the generators located inside the dam convert the kinetic and potential energy of the water into electric energy?



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What happens in a changing magnetic field?

Question

LAUNCH Lab 🧏

How does a changing magnetic field affect a coil of wire passed through it?

Procedure 🖾 📼 👻

- 1. Place two bar magnets about 8 cm apart.
- **2.** Attach a sensitive galvanometer to either end of a piece of coiled copper wire.
- **3.** Slowly move the wire between the magnets. Note the galvanometer reading.
- Vary the angle of the movement of the copper wire and the velocity of the wire. Note your results.

Analysis

What causes the galvanometer to move? What situation makes the galvanometer deflect the most?

Critical Thinking When the wire is moved between the magnets, what is happening to the wire?



25.1 Electric Current from Changing Magnetic Fields

n Chapter 24, you learned how Hans Christian Oersted discovered that an electric current produces a magnetic field. Michael Faraday thought that the reverse must also be true: that a magnetic field produces an electric current. In 1822, Michael Faraday wrote a goal in his notebook: "Convert magnetism into electricity." Faraday tried many combinations of magnetic fields and wires without success. After nearly ten years of unsuccessful experiments, Faraday found that he could induce electric current by moving a wire through a magnetic field. In the same year, Joseph Henry, an American high-school teacher, also showed that a changing magnetic field could produce electric current. Henry took an idea developed by another scientist and broadened the application to other educational demonstration devices to make them more sensitive or powerful. Henry's versions of these devices were not new discoveries, but he made the devices more dramatic and effective as educational aids. However, Henry, unlike Faraday, chose not to publish his discoveries.

Objectives

- **Explain** how a changing magnetic field produces an electric current.
- Define electromotive force.
- **Solve** problems involving wires moving in magnetic fields.
- Vocabulary

electromagnetic induction fourth right-hand rule electromotive force electric generator average power **Figure 25-1** When a wire is moved in a magnetic field, there is an electric current in the wire, but only while the wire is moving. The direction of the current depends on the direction in which the wire is moving through the field. The arrows indicate the direction of conventional current.

concepts In MOtion

Interactive Figure To seee an animation on electromagnetic induction, visit physicspp.com.





Electromagnetic Induction

Figure 25-1 shows one of Faraday's experiments, in which a wire loop that is part of a closed circuit is placed in a magnetic field. When the wire is held stationary or is moved parallel to the magnetic field, there is no current, but when the wire moves up through the field, the current is in one direction. When the wire moves down through the field, the current is in the opposite direction. An electric current is generated in a wire only when the wire cuts magnetic field lines.

Faraday found that to generate current, either the conductor can move through a magnetic field or a magnetic field can move past the conductor. It is the relative motion between the wire and the magnetic field that produces the current. The process of generating a current through a circuit in this way is called **electromagnetic induction**.

How can you tell the direction of the current? To find the force on the charges in the wire, use the **fourth right-hand rule** to hold your right hand so that your thumb points in the direction in which the wire is moving and your fingers point in the direction of the magnetic field. The palm of your hand will point in the direction of the conventional (positive) current, as illustrated in **Figure 25-2.**

Figure 25-2 The fourth right-hand rule can be used to find the direction of the forces on the charges in a conductor that is moving in a magnetic field.



Electromotive Force

When you studied electric circuits, you learned that a source of electrical energy, such as a battery, is needed to produce a continuous current. The potential difference, or voltage, given to the charges by a battery is called the **electromotive force**, or *EMF*. Electromotive force, however, is not actually a force; instead, it is a potential difference and is measured in volts. Thus, the term electromotive force is misleading. Like many other historical terms still in use, it originated before the related principles—in this case, those of electricity—were well understood. The *EMF* is the influence that makes current flow from lower to higher potential, like a water pump in a water fountain.

What created the potential difference that caused an induced current in Faraday's experiment? When you move a wire through a magnetic field, you exert a force on the charges and they move in the direction of the force. Work is done on the charges. Their electrical potential energy, and thus their potential, is increased. The difference in potential is called the induced *EMF*. *EMF* depends on the magnetic field, *B*, the length of the wire in the magnetic field, *L*, and the velocity of the wire in the field that is perpendicular to the field, $v(\sin \theta)$.

Electromotive Force $EMF = BLv(\sin \theta)$

Electromotive force is equal to the magnitude of the magnetic field, times the length of the wire times the component of the velocity of the wire in the field perpendicular to the field.

If a wire moves through a magnetic field at an angle to the field, only the component of the wire's velocity that is perpendicular to the direction of the magnetic field generates *EMF*. If the wire moves through the field with a velocity that is exactly perpendicular to the field, then the above equation reduces to EMF = BLv, because $\sin 90^\circ = 1$. Checking the units of the *EMF* equation will help you work algebra correctly in related problems. The unit for measuring *EMF* is the volt, V. In Chapter 24, *B* was defined as *F/IL*; therefore, the units for *B* are N/A·m. Velocity is measured in m/s.

Using dimensional analysis, $(N/A \cdot m)(m)(m/s) = N \cdot m/A \cdot s = J/C = V$. Recall from previous chapters that $J = N \cdot m$, A = C/s, and V = J/C.

Application of induced *EMF* A microphone is a simple application that depends on an induced *EMF*. A dynamic microphone is similar in construction to a loudspeaker. The microphone shown in **Figure 25-3** has a diaphragm attached to a coil of wire that is free to move in a magnetic field. Sound waves vibrate the diaphragm, which moves the coil in the magnetic field. The motion of the coil, in turn, induces an *EMF* across the ends of the coil. The induced *EMF* varies as the frequency of the sound varies. In this way, the sound wave is converted to an electrical signal. The voltage generated is small, typically 10^{-3} V, but it can be increased, or amplified, by electronic devices.

■ Figure 25-3 In this drawing of a moving coil microphone, the aluminum diaphragm is connected to a coil in a magnetic field. When sound waves vibrate the diaphragm, the coil moves in the magnetic field and generates a current that is proportional to the sound wave.



EXAMPLE Problem 1

Induced *EMF* A straight wire, 0.20 m long, moves at a constant speed of 7.0 m/s perpendicular to a magnetic field of strength 8.0×10^{-2} T.

- a. What EMF is induced in the wire?
- **b.** The wire is part of a circuit that has a resistance of 0.50 Ω . What is the current through the wire?
- c. If a different metal was used for the wire, which has a resistance of 0.78 Ω , what would the new current be?

Analyze and Sketch the Problem

- Establish a coordinate system.
- Draw a straight wire of length *L*. Connect an ammeter to the wire to represent a measurement of current.
- Choose a direction for the magnetic field that is perpendicular to the length of wire.
- Choose a direction for the velocity that is perpendicular to both the length of the wire and the magnetic field.



- $B = 0.0 \times 10$ $R_1 = 0.50 \Omega$
- $n_1 = 0.30.32$
- $R_2=0.78~\Omega$

2 Solve for the Unknown

a. EMF = BLv





Personal Tutor For an online tutorial on induced EMF, visit <u>physicspp.com</u>.

 $= (8.0 \times 10^{-2} \text{ T})(0.20 \text{ m})(7.0 \text{ m/s})$ Substitute $B = 8.0 \times 10^{-2}$, L = 0.20 m, v = 7.0 m/s $= 0.11 \text{ T} \cdot \text{m}^2/\text{s}$ = 0.11 V **b.** $I = \frac{V}{R}$ $= \frac{EMF}{R}$ Substitute V = EMF

 $= \frac{0.11 \text{ V}}{0.50 \Omega}$ = 0.22 A

Using the fourth right-hand rule, the direction of the current is counterclockwise.

Substitute EMF = 0.11 V, R_1 = 0.50 Ω

c.
$$I = \frac{EMF}{R}$$

= $\frac{0.11 \text{ V}}{0.78 \Omega}$ Substitute *EMF* = 0.11 V, R_2 = 0.78 Ω
= 0.14 A

The current is counterclockwise.

3 Evaluate the Answer

- **Are the units correct?** Volt is the correct unit for *EMF*. Current is measured in amperes.
- **Does the direction make sense?** The direction obeys the fourth right-hand rule: *v* is the direction of the thumb, *B* is the same direction as the fingers, and *F* is the direction that the palm faces. Current is in the same direction as the force.
- **Is the magnitude realistic?** The answers are near 10⁻¹. This agrees with the quantities given and the algebra performed.



PRACTICE Problems

Additional Problems, Appendix II Solutions to Selected Problems, Appendix C

1. A straight wire, 0.5 m long, is moved straight up at a speed of 20 m/s through a 0.4-T magnetic field pointed in the horizontal direction.

a. What EMF is induced in the wire?

- **b.** The wire is part of a circuit of total resistance of 6.0 Ω . What is the current in the circuit?
- **2.** A straight wire, 25 m long, is mounted on an airplane flying at 125 m/s. The wire moves in a perpendicular direction through Earth's magnetic field ($B = 5.0 \times 10^{-5}$ T). What *EMF* is induced in the wire?
- **3.** A straight wire, 30.0 m long, moves at 2.0 m/s in a perpendicular direction through a 1.0-T magnetic field.
 - a. What EMF is induced in the wire?
 - **b.** The total resistance of the circuit of which the wire is a part is 15.0 Ω . What is the current?
- **4.** A permanent horseshoe magnet is mounted so that the magnetic field lines are vertical. If a student passes a straight wire between the poles and pulls it toward herself, the current flow through the wire is from right to left. Which is the north pole of the magnet?

Electric Generators

The **electric generator**, invented by Michael Faraday, converts mechanical energy to electrical energy. An electric generator consists of a number of wire loops placed in a strong magnetic field. The wire is wound around an iron core to increase the strength of the magnetic field. The iron and wires are called the armature, which is similar to that of an electric motor.

The armature is mounted so that it can rotate freely in the magnetic field. As the armature turns, the wire loops cut through the magnetic field lines and induce an *EMF*. Commonly called the voltage, the *EMF* developed by the generator depends on the length of wire rotating in the field. Increasing the number of loops in the armature increases the wire length, thereby increasing the induced *EMF*. Note that you could have a length of wire with only part of it in the magnetic field. Only the portion within the magnetic field induces an *EMF*.

Current from a generator When a generator is connected in a closed circuit, the induced *EMF* produces an electric current. **Figure 25-4** shows a single-loop generator without an iron core. The direction of the induced current can be found from the third right-hand rule. As the loop rotates, the strength and the direction of the current change.





Figure 25-4 An electric current is generated in a wire loop as the loop rotates.



Figure 25-5 The cross-sectional view of a rotating wire loop shows the position of the loop when maximum current is generated **(a).** When the loop is vertical, the current is zero **(b).** The current varies with time as the loop rotates **(c).** The variation of *EMF* with time can be shown with a similar graph.



Figure 25-6 Only the segments *bc* and *ad* have current induced through them. This can be shown using the fourth right-hand rule.

Ν

I (induced)

h

θ

Axis

v

S

I (induced)

В

d

а



The current is greatest when the motion of the loop is perpendicular to the magnetic field; that is, when the loop is in the horizontal position, as shown in **Figure 25-5a.** In this position, the component of the loop's velocity perpendicular to the magnetic field is greatest. As the loop rotates from the horizontal to the vertical position, as shown in **Figure 25-5b**, it moves through the magnetic field lines at an ever-increasing angle. Thus, it cuts through fewer magnetic field lines per unit of time, and the current decreases. When the loop is in the vertical position, the wire segments move parallel to the field and the current is zero. As the loop continues to turn, the segment that was moving up begins to move down and reverses the direction of the current in the loop. This change in direction takes place each time the loop turns through 180°. The current changes smoothly from zero to some maximum value and back to zero during each half-turn of the loop. Then it reverses direction. A graph of current versus time is shown in **Figure 25-5c.**

Does the entire loop contribute to the induced *EMF*? Look at **Figure 25-6**, where all four sides of the loop are depicted in the magnetic field. If the fourth right-hand rule is applied to segment *ab*, the direction of the induced current is toward the side of the wire. The same applies to segment *cd*. Thus, no current is induced along the length of the wire in *ab* or *cd*. But in segment *bc*, the direction of the induced current is from *b* to *c*, and in segment *ad*, the current is from *d* to *a*.

Because the conducting loop is rotating in a circular motion, the relative angle between a point on the loop and the magnetic field constantly changes. The electromotive force can be calculated by the electromotive force equation given earlier, $EMF = BLv(\sin \theta)$, except that *L* is now the length of segment *bc*. The maximum voltage is induced when a conductor is moving perpendicular to the magnetic field and thus $\theta = 90^{\circ}$.





Figure 25-7 An alternatingcurrent generator transmits current to an external circuit by way of a brush-slip-ring arrangement **(a)**. The alternating current produced varies with time **(b)**. The resulting power is always positive and also is sinusoidal **(c)**.

they convert energy in opposite directions. A generator converts mechanical energy to electrical energy, while a motor converts electrical energy to mechanical energy.

Alternating-Current Generators

An energy source turns the armature of a generator in a magnetic field at a fixed number of revolutions per second. In the United States, electric utilities use a 60-Hz frequency, in which the current goes from one direction to the other and back to the first 60 times per second. **Figure 25-7a** shows how an alternating current, AC, in an armature is transmitted to the rest of the circuit. The brush-slip-ring arrangement permits the armature to turn freely while still allowing the current to pass into the external circuit. As the armature turns, the alternating current varies between some maximum value and zero, as shown in the graph in **Figure 25-7b**.

Average power The power produced by a generator is the product of the current and the voltage. Because both current and voltage vary, the power associated with an alternating current varies. **Figure 25-7c** shows a graph of the power produced by an AC generator. Note that power is always positive because *I* and *V* are either both positive or both negative. **Average power**, $P_{AC'}$ is half the maximum power; thus, $P_{AC} = \frac{1}{2}P_{AC \max}$.

Effective voltage and current It is common to describe alternating current and voltage in terms of effective current and voltage, rather than referring to their maximum values. Recall from Chapter 22 that $P = I^2 R$. Thus, you can express effective current, $I_{eff'}$ in terms of the average AC power as $P_{AC} = I_{eff}^2 R$. To determine I_{eff} in terms of maximum current, $I_{max'}$ start with the power relationship, $P_{AC} = \frac{1}{2}P_{AC max'}$ and substitute in $I^2 R$. Then solve for I_{eff} .

Effective Current $I_{\text{eff}} = \frac{\sqrt{2}}{2} I_{\text{max}} = 0.707 I_{\text{max}}$ Effective current is equal to $\frac{\sqrt{2}}{2}$ times the maximum current.



Similarly, the following equation can be used to express effective voltage.

Effective Voltage $V_{\text{eff}} = \left(\frac{\sqrt{2}}{2}\right)V_{\text{max}} = 0.707 V_{\text{max}}$ Effective voltage is equal to $\frac{\sqrt{2}}{2}$ times the maximum voltage.

Effective voltage, also is commonly referred to as RMS (root mean square) voltage. In the United States, the voltage generally available at wall outlets is described as 120 V, where 120 V is the magnitude of the effective voltage, not the maximum voltage. The frequency and effective voltage that are used vary in different countries.

PRACTICE Problems *Additional Problems, Appendix B • Solutions to Selected Problems, Appendix C

- 5. A generator develops a maximum voltage of 170 V.
 - a. What is the effective voltage?
 - **b.** A 60-W lightbulb is placed across the generator with an I_{max} of 0.70 A. What is the effective current through the bulb?
 - c. What is the resistance of the lightbulb when it is working?
- **6.** The RMS voltage of an AC household outlet is 117 V. What is the maximum voltage across a lamp connected to the outlet? If the RMS current through the lamp is 5.5 A, what is the maximum current in the lamp?
- 7. An AC generator delivers a peak voltage of 425 V.
 - **a.** What is the V_{eff} in a circuit placed across the generator?
 - **b.** The resistance is $5.0 \times 10^2 \ \Omega$. What is the effective current?
- **8.** If the average power dissipated by an electric light is 75 W, what is the peak power?

In this section you have explored how moving wires in magnetic fields can induce current. However, as Faraday discovered, changing magnetic fields around a conductor also can induce current in the conductor. In the next section, you will explore changing magnetic fields and the applications of induction by changing magnetic fields.

25.1 Section Review

- **9. Generator** Could you make a generator by mounting permanent magnets on a rotating shaft and keeping the coil stationary? Explain.
- **10. Bike Generator** A bike generator lights the headlamp. What is the source of the energy for the bulb when the rider travels along a flat road?
- **11. Microphone** Consider the microphone shown in Figure 25-3. When the diaphragm is pushed in, what is the direction of the current in the coil?
- **12. Frequency** What changes to the generator are required to increase the frequency?

- **13. Output Voltage** Explain why the output voltage of an electric generator increases when the magnetic field is made stronger. What else is affected by strengthening the magnetic field?
- **14. Generator** Explain the fundamental operating principle of an electric generator.
- **15. Critical Thinking** A student asks, "Why does AC dissipate any power? The energy going into the lamp when the current is positive is removed when the current is negative. The net is zero." Explain why this reasoning is wrong.

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n a generator, current is produced when the armature turns through a magnetic field. The act of generating current produces a force on the wires in the armature. In what direction is the force on the wires of an armature?

Lenz's Law

Consider a section of one loop that moves through a magnetic field, as shown in **Figure 25-8a.** An *EMF*, equal to *BLv*, will be induced in the wire. If the magnetic field is out of the page and velocity is to the right, then the fourth right-hand rule shows a downward *EMF*, as illustrated in **Figure 25-8b**, and consequently a downward current is produced. In Chapter 24, you learned that a wire carrying a current through a magnetic field will experience a force acting on it. This force results from the interaction between the existing magnetic field and the magnetic field generated around all currents. To determine the direction of this force, use the third right-hand rule: if current, *I*, is down and the magnetic field, *B*, is out, then the resulting force is to the left, as shown in **Figure 25-8c**. This means that the direction of the force on the wire opposes the original motion of the wire, *v*. That is, the force acts to slow down the rotation of the armature. The method of determining the direction of a force was first demonstrated in 1834 by H.F.E. Lenz and is therefore called Lenz's law.

Lenz's law states that the direction of the induced current is such that the magnetic field resulting from the induced current opposes the change in the field that caused the induced current. Note that it is the change in the field and not the field itself that is opposed by the induced magnetic effects.

Opposing change Figure 25-9, on the next page, is an example of how Lenz's law works. The north pole of a magnet is moved toward the left end of a coil of wire. To create a force that will oppose the approach of the north pole, the left end of the coil also must become a north pole. In other words, the magnetic field lines must emerge from the left end of the coil. Using the second right-hand rule, which you learned in Chapter 24, you will see that if Lenz's law is correct, the induced current must be in a counterclockwise direction as viewed from the end of the coil where the magnet is inserted. Experiments have shown that this is so. If the magnet is turned so that a south pole approaches the coil, the induced current will flow in a clockwise direction.

Objectives

- Apply Lenz's law.
- Explain back-EMF and how it affects the operation of motors and generators.
- Explain self-inductance and how it affects circuits.
- Solve transformer problems involving voltage, current, and turn ratios.
- Vocabulary

Lenz's law eddy current self-inductance transformer primary coil secondary coil mutual inductance step-up transformer step-down transformer

Figure 25-8 A wire, length *L*, moving through a magnetic field, *B*, induces an electromotive force. If the wire is part of a circuit, then there will be a current, *I*. This current will interact with the magnetic field and produce a force, *F*. Notice that the resulting force opposes the motion, *v*, of the wire.



Figure 25-9 The magnet approaching the coil causes an induced current to flow. Lenz's law predicts the direction of flow shown.





Figure 25-10 Sensitive balances use eddy-current damping to control oscillations of the balance beam **(a).** As the metal plate on the end of the beam moves through the magnetic field, a current is generated in the metal. This current, in turn, produces a magnetic field that opposes the motion that caused it, and the motion of the beam is dampened **(b).**

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Interactive Figure To see an animation on the application of Lenz's Law, visit physicspp.com.





If a generator produces only a small current, then the opposing force on the armature will be small, and the armature will be easy to turn. If the generator produces a larger current, the force on the larger current will be greater, and the armature will be more difficult to turn. A generator supplying a large current is producing a large amount of electric energy. The opposing force on the armature means that mechanical energy must be supplied to the generator to produce the electric energy, consistent with the law of conservation of energy.

Motors and Lenz's law Lenz's law also applies to motors. When a current-carrying wire moves in a magnetic field, an *EMF* is generated. This *EMF*, called the back-*EMF*, is in a direction that opposes the current. When a motor is first turned on, there is a large current because of the low resistance of the motor. As the motor begins to turn, the motion of the wires across the magnetic field induces a back-*EMF* that opposes the current. Therefore, the net current through the motor is reduced. If a mechanical load is placed on the motor, as in a situation in which work is being done to lift a weight, the rotation of the motor will slow. This slowing down will decrease the back-*EMF*, which will allow more current through the motor. Note that this is consistent with the law of conservation of energy: if current increases, so does the rate at which electric power is being sent to the motor. This power is delivered in mechanical form to the load. If the mechanical load stops the motor, current can be so high that wires overheat.

As current draw varies with the changing speed of an electric motor, the voltage drop across the resistance of the wires supplying the motor also varies. Another device, such as a lightbulb, that is in parallel with the motor, also would experience the drop in voltage. This is why you may have noticed some lights in a house dimming when a large motorized appliance, such as an air conditioner or a table saw, starts operating.

When the current to the motor is interrupted by a switch in the circuit being turned off or by the motor's plug being pulled from a wall outlet, the sudden change in the magnetic field generates a back-*EMF*. This reverse voltage can be large enough to cause a spark across the switch or between the plug and the wall outlet.

Application of Lenz's law A sensitive balance, such as the kind used in laboratories, uses Lenz's law to stop its oscillation when an object is placed on the pan. As shown in **Figure 25-10**, a piece of metal attached to the balance arm is located between the poles of a horseshoe magnet.



When the balance arm swings, the metal moves through the magnetic field. Currents called **eddy currents** are generated in the metal and produce a magnetic field that acts to oppose the motion that caused the currents. Thus, the metal piece is slowed down. The force opposes the motion of the metal in either direction but does not act if the metal is still. Thus, the force does not change the mass read by the balance. This effect is called eddy-current damping. A practical motor or transformer core is constructed from thin laminations, or layers, each one insulated from the other, to reduce the circulation of eddy currents.

Eddy currents are generated when a piece of metal moves through a magnetic field. The reverse is also true: a current is generated when a metal loop is placed in a changing magnetic field. According to Lenz's law, the current generated will oppose the changing magnetic field. The current generates a magnetic field of its own in the opposite direction that causes the uncut, aluminum ring in Figure 25-11 to float. An AC current is in the coil, so a constantly changing magnetic field is generated. This changing magnetic field induces an EMF in the rings. If these rings were constructed from a nonconducting material such as nylon or brass, an EMF could not be induced. For the uncut ring, the EMF causes a current that produces a magnetic field that will oppose the change in the generating magnetic field. The interaction of these two magnetic fields causes the ring to push away from the coil, similar to the way in which the north poles of two magnets push away from each other. For the lower ring, which has been sawed through, an EMF is generated, but no current can result because of an incomplete path. Hence, no opposing magnetic field is produced by the ring.

Self-Inductance

Back-*EMF* can be explained in another way. As Faraday showed, *EMF* is induced whenever a wire cuts the lines of a magnetic field. The current through the wire shown in **Figure 25-12** increases from **Figure 25-12a** to **Figure 25-12c**. The current generates a magnetic field, shown by magnetic field lines. As the current and magnetic field increase, new lines are created. As more lines are added, they cut through the coil wires and generate an *EMF* to oppose the current changes. The *EMF* will make the potential of the top of the coil more negative than the bottom. This induction of *EMF* in a wire carrying changing current is called **self-inductance**.





Figure 25-11 Current is induced in the continuous metal ring, while there is no current in the cut ring.



Figure 25-12 As the current in the coil increases from **(a)** on the left to **(c)** on the right, the magnetic field generated by the current also increases. This increase in the magnetic field produces an *EMF* that opposes the current direction.



MINI LAB

Motor and Generator

Motors and generators differ, mainly in the way they convert energy–electric to mechanical compared to mechanical to electric.

1. Make a series circuit with an efficient DC motor, a miniature lamp, and an ammeter.

2. Rotate the handle, or motor shaft, to try to light the lamp.

Analyze and Conclude

3. What happens if you vary the speed at which you rotate the handle?

4. Predict what will happen if you connect your motor to a second motor.

■ Figure 25-13 In a transformer, the ratio of input voltage to output voltage depends upon the ratio of the number of turns on the primary coil to the number of turns on the secondary coil. The output voltage can be the same as the input, greater than the input (a), or less than the input (b). The size of the induced *EMF* is proportional to the rate at which field lines cut through the wires. The faster the current is changed, the larger the opposing *EMF*. If the current reaches a steady value, the magnetic field is constant, and the *EMF* is zero. When the current is decreased, an *EMF* is generated that tends to prevent the reduction in the magnetic field and current. Because of self-inductance, work has to be done to increase the current flowing through the coil. Energy is stored in the magnetic field. This is similar to the way in which a charged capacitor stores energy in the electric field between its plates.

Transformers

Transformers are used to increase or decrease AC voltages. Usage of transformers is common because they change voltages with relatively little loss of energy. In fact, many of the devices in your home, such as game systems, printers, and stereos, have transformers inside their casings or as part of their cords.

How transformers work Self-inductance produces an *EMF* when current changes in a single coil. A transformer has two coils, electrically insulated from each other, but wound around the same iron core. One coil is called the **primary coil.** The other coil is called the **secondary coil.** When the primary coil is connected to a source of AC voltage, the changing current creates a changing magnetic field, which is carried through the core to the secondary coil. In the secondary coil, the changing field induces a varying *EMF*. This effect is called **mutual inductance**.

The *EMF* induced in the secondary coil, called the secondary voltage, is proportional to the primary voltage. The secondary voltage also depends on the ratio of the number of turns on the secondary coil to the number of turns on the primary coil, as shown by the following expressions.

$$\frac{\text{secondary voltage}}{\text{primary voltage}} = \frac{\text{number of turns on secondary coil}}{\text{number of turns on primary coil}}$$
$$\frac{V_{\text{s}}}{V_{\text{p}}} = \frac{N_{\text{s}}}{N_{\text{p}}}$$

If the secondary voltage is larger than the primary voltage, the transformer is called a **step-up transformer**, as shown in **Figure 25-13a**. If the voltage coming out of the transformer is smaller than the voltage put in, then it is called a **step-down transformer**, as shown in **Figure 25-13b**.



In an ideal transformer, the electric power delivered to the secondary circuit equals the power supplied to the primary circuit. An ideal transformer dissipates no power itself, and can be represented by the following equations:

$$P_{\rm p} = P_{\rm s}$$
$$V_{\rm p}I_{\rm p} = V_{\rm s}I_{\rm s}$$

Rearranging the equation to find the ratio V_p/V_s shows that the current in the primary circuit depends on how much current is required by the secondary circuit. This relationship can be combined with the relationship shown earlier between voltage and the number of turns to result in the following.

Transformer Equation
$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

The ratio of the current in the secondary coil to the current in the primary coil is equal to the ratio of the voltage in the primary coil to the secondary coil, which is also equal to the ratio of the number of turns on the voltage in the primary coil to the number of turns on the secondary coil.

As mentioned previously, a step-up transformer increases voltage. Because transformers cannot increase the power output, there must be a corresponding decrease in current through the secondary circuit. Similarly, in a step-down transformer, the current is greater in the secondary circuit than it is in the primary circuit. A voltage decrease corresponds to a current increase, as shown in the Connecting Math to Physics. Another way to understand this is to consider a transformer as 100 percent efficient, as is typically assumed in industry. Therefore, in most cases, it may be assumed that the input power and the output power are the same. Figure 25-13 illustrates the principles of step-up and step-down transformers. As shown in **Figure 25-14**, some transformers, depending on how they are hooked up.

Connecting Math to Physics

Inequalities Study the following expressions to help you understand the relationships among voltage, current, and the number of coils in step-up and step-down transformers.

| Step-Up Transformer | Step-Down Transformer |
|-------------------------|-------------------------|
| $V_{\rm p} < V_{\rm s}$ | $V_{\rm p} > V_{\rm s}$ |
| $I_{\rm p} > I_{\rm s}$ | $I_{\rm p} < I_{\rm s}$ |
| $N_{\rm p} < N_{\rm s}$ | $N_{\rm p} > N_{\rm s}$ |



Figure 25-14 If the input voltage is connected to the coils on the left, where there is a larger number of turns, the transformer functions as a step-down transformer. If the input voltage is connected at the right, the transformer functions as a step-up transformer.

APPLYING PHYSICS

► **Common Units** Transformers typically are rated in volt-amps reactive (VA, kilo-VA, mega-VA). Technically, only pure resistivetype loads have their power expressed in watts and reactive loads in volt-amps.

EXAMPLE Problem 2

Step-Up Transformers A step-up transformer has a primary coil consisting of 200 turns and a secondary coil consisting of 3000 turns. The primary coil is supplied with an effective AC voltage of 90.0 V.

- a. What is the voltage in the secondary circuit?
- b. The current in the secondary circuit is 2.0 A. What is the current in the primary circuit?

Unknown:

Analyze and Sketch the Problem

- · Draw an iron core with turns of wire.
- Label the variables *I*. *V*. and *N*.

Known:
$$\begin{split} N_{\rm p} &= 200 \qquad V_{\rm p} = 90.0 \ {\sf V} \qquad V_{\rm s} = ? \\ N_{\rm s} &= 3000 \qquad I_{\rm s} = 2.0 \ {\sf A} \qquad I_{\rm p} = ? \end{split}$$

200





2 Solve for the Unknown

a. Solve for $V_{\rm s}$. 17 17

$$\frac{V_{s}}{V_{p}} = \frac{N_{s}}{N_{p}}$$
$$V_{s} = \frac{N_{s}V_{p}}{N_{p}}$$
$$= \frac{(3000)(90.0 \text{ V})}{(3000)(90.0 \text{ V})}$$

= 1350 V

Substitute $N_{\rm s} = 3000$, $V_{\rm n} = 90.0$ V, $N_{\rm n} = 200$

Substitute $P_{\rm p} = V_{\rm p}I_{\rm p}, P_{\rm s} = V_{\rm s}I_{\rm s}$

b. The power in the primary and secondary circuits are equal assuming 100 percent efficiency.

$$P_{p} = P_{s}$$

$$V_{p}I_{p} = V_{s}I_{s}$$
Solve for I_{p} .

I_p

$$= \frac{V_s V_s}{V_p}$$

= $\frac{(1350 \text{ V})(2.0 \text{ A})}{900 \text{ V}}$ Substitute $V_s = 1350 \text{ V}, I_s = 2.0 \text{ A}, V_p = 90.0 \text{ V}$

Math Handbook Significant Digits pages 833-834

3 Evaluate the Answer

 $= 3.0 \times 10^{1} \text{ A}$

- Are the units correct? Voltage should be in volts and current in amps.
- Is the magnitude realistic? A large step-up ratio of turns results in a large secondary voltage yet a smaller secondary current. The answers agree with this.

PRACTICE Problems

 Additional Problems, Appendix II Solutions to Selected Problems, Appendix C

For the following problems, effective currents and voltages are indicated.

- 16. A step-down transformer has 7500 turns on its primary coil and 125 turns on its secondary coil. The voltage across the primary circuit is 7.2 kV. What voltage is being applied across the secondary circuit? If the current in the secondary circuit is 36 A, what is the current in the primary circuit?
- 17. A step-up transformer has 300 turns on its primary coil and 90,000 turns on its secondary coil. The EMF of the generator to which the primary circuit is attached is 60.0 V. What is the EMF in the secondary circuit? The current in the secondary circuit is 0.50 A. What current is in the primary circuit?



CHALLENGE PROBLEM

A distribution transformer (T₁) has its primary coil connected to a 3.0-kV AC source. The secondary coil is connected to the primary coil of a second transformer (T₂) by copper conductors. Finally, the secondary coil of transformer T₂ connects to a load that uses 10.0 kW of power. Transformer T_1 has a turn ratio of 5:1, and T_2 has a load voltage of 120 V. The transformer efficiencies are 100.0 percent and 97.0 percent, respectively.

- 1. Calculate the load current.
- **2.** How much power is being dissipated by transformer T_2 ?
- **3.** What is the secondary current of transformer T₁?
- **4.** How much current is the AC source supplying to T_1 ?

Everyday uses of transformers As you learned in Chapter 22, long-distance transmission of electrical energy is economical only if low currents and very high voltages are used. Step-up transformers are used at power sources to develop voltages as high as 480,000 V. High voltages reduce the current required in the transmission lines, keeping the energy lost to resistance low. When the energy reaches the consumer, step-down transformers, such as those shown in Figure 25-15, provide appropriately low voltages for consumer use.

Transformers in home appliances further adjust voltages to useable levels. If you have ever had to charge a toy or operate a personal electronic device, you probably had to plug a large "block" into the wall outlet. A transformer of the type discussed in this chapter is contained inside of that block. In this case, it is probably reducing the household voltage of about 120 V to something in the 3-V to 26-V range.

Not all transformers are step-up or step-down. Transformers can be used to isolate one circuit from another. This is possible because the wire of the primary coil never makes direct contact with the wire of the secondary coil. This type of transformer would most likely be found in some small electronic devices.



Figure 25-15 Step-down transformers are used to reduce the high voltages in transmission lines to levels appropriate for consumers at the points of use.

25.2 Section Review

- 18. Coiled Wire and Magnets You hang a coil of wire with its ends joined so that it can swing easily. If you now plunge a magnet into the coil, the coil will swing. Which way will it swing relative to the magnet and why?
- **19.** Motors If you unplugged a running vacuum cleaner from a wall outlet, you would be much more likely to see a spark than you would be if you unplugged a lighted lamp from the wall. Why?
- 20. Transformers and Current Explain why a transformer may only be operated on alternating current.

- 21. Transformers Frequently, transformer coils that have only a few turns are made of very thick (lowresistance) wire, while those with many turns are made of thin wire. Why?
- 22. Step-Up Transformers Refer to the step-up transformer shown in Figure 25-13. Explain what will happen to the primary current if the secondary coil is short-circuited.
- 23. Critical Thinking Would permanent magnets make good transformer cores? Explain.

Section 25.2 Changing Magnetic Fields Induce EMF 685 Matt Meadows

PHYSICSLAB

Induction and Transformers

A transformer is an electric device without any moving components. It is made of two electric circuits interlinked by a magnetic field. A transformer is used to increase or decrease an AC potential difference, which often is called *voltage*. Transformers can be found everywhere. Every electronic device that plugs into your household electric circuits incorporates a transformer, usually to lower the voltage going to the device. Televisions that have standard cathode-ray picture tubes incorporate high-voltage transformers, which raise the standard household voltage to tens of thousands of volts. This accelerates electrons from the rear of the tube to the screen. In this experiment, you will use two coils with a removable iron core. One coil is called the primary coil, the other the secondary coil. When an AC voltage is applied to the primary coil, the changing magnetic field induces a current, and thus, a voltage in the secondary coil. This induced voltage is expressed by $V_s/V_p = N_s/N_{p'}$ where N refers to the number of turns in the coils.

QUESTION

What is the relationship between voltages in the two coils of a transformer?

Objectives

- **Describe** how a transformer works.
- Observe the effect of DC voltage on a transformer.
- **Observe** the effect of AC voltage on a transformer.

Safety Precautions



Materials

primary and secondary coil apparatus small AC power supply AC voltmeter DC power supply (0-6V, 0-5A) connecting wires with alligator clips small lightbulb with wires

Procedure

- 1. Estimate the number of coils of wire on the primary and secondary coils. Do this by counting the number of coils in 1 cm and multiplying by the coil's length in centimeters. The primary coil has one layer. The secondary coil has two layers of wire, so double the value for it. Record your results in the data table.
- Place a small lightbulb across the contacts of the secondary coil. Carefully place the secondary coil into the primary coil. Slowly insert the iron core into the center of the secondary coil.
- Attach two wires to the output of the DC power supply. Attach the positive wire from the power supply to one of the primary connections. Turn the power supply to nearly its maximum output setting. Holding the free end of the wire attached to the negative connection, gently tap its end to the other primary coil connection. Observe the area where you touch the wire to the connection. Record your observations in the data table.





| Data Table | | |
|---------------------------|--|--|
| Number of primary coils | | |
| Number of secondary coils | | |
| Step 3 observation | | |
| Step 4 observation | | |
| Step 5 observation | | |
| Step 6 observation | | |
| Step 7 coil volts (V) | | |
| Step 8 observation | | |
| Step 9 iron core | | |

- **4.** Observe the lightbulb while you are gently tapping the connection. What happens as the wire makes contact and then breaks the electric contact? Record your observation in the data table.
- **5.** Hold the negative wire to the primary coil connection for 5 s and observe the lightbulb. Record your observation in the data table.
- **6.** Disconnect the DC power supply and put it away while leaving the small lightbulb attached to the secondary coil. Attach the AC power supply to the two primary coil connections. Plug in the AC power supply and observe the lightbulb. Record your observations in the data table.
- **7.** Select the AC scale for your voltmeter. Insert the probes into the voltmeter and carefully touch them to the primary coil and measure the applied voltage. Move the probe from the primary coil and measure the secondary coil voltage. Record both readings in the data table.
- 8. Repeat step 7, but slowly remove the iron core from the secondary coil. What happens to the lightbulb? Measure both primary and secondary coil voltages while the core is being removed. Record your observations in the data table.
- **9.** Carefully feel the iron core. What is your observation? Record it in the data table.

Analyze

- **1.** Calculate the ratio of $N_{\rm s}/N_{\rm p}$ from your data.
- **2.** Calculate the ratio of $V_{\rm s}/V_{\rm p}$ from your data.

- **3. Interpret Data** How do the ratios N_s/N_p and V_s/V_p compare?
- **4. Recognize Cause and Effect** Based on the data for step 7, is this transformer a step-up or a step-down transformer? What evidence do you have to support this conclusion?

Conclude and Apply

- **1. Infer** How can you explain your observation of the lightbulb in step 4?
- **2. Infer** How can you explain the phenomena you observed at the negative connection of the primary coil in step 3?
- **3. Infer** How can you explain your observations of the primary and the secondary coil voltages as you removed the iron core in step 8?
- **4. Explain** Explain the temperature of the iron core you observed in step 9.

Going Further

Why does the transformer work only with alternating and not direct current?

Real-World Physics

Discuss the use of transformers to assist in the delivery of electricity from the power plant to your home.

Physics nline

To find out more about induction and transformers, visit the Web site: **physicspp.com**

How it Wiks How a Credit-Card Reader Works

The magnet can be turned

Credit cards have revolutionized the world's economies by enabling money to be transferred quickly and easily. The credit-card reader, which captures data from a magnetic strip on the back of a card, is one of the most important links in the electronic transfer of money.



Study Guide

25.1 Electric Current from Changing Magnetic Fields

Vocabulary

(p. 672)

(p. 672)

· electromagnetic induction

electromotive force (p. 673)
electric generator (p. 675)

average power (p. 677)

· fourth right-hand rule

Chapter

- **Key Concepts**
- Michael Faraday discovered that if a wire moves through a magnetic field, an electric current can flow.
- The current produced depends upon the angle between the velocity of the wire and the magnetic field. Maximum current occurs when the wire is moving at right angles to the field.
- Electromotive force, *EMF*, is the potential difference created across the moving wire. *EMF* is measured in volts.
- The *EMF* in a straight length of wire moving through a uniform magnetic field is the product of the magnetic field, *B*, the length of the wire, *L*, and the component of the velocity of the moving wire through the field that is perpendicular to the field, $v(\sin \theta)$.

$$EMF = BLv \sin \theta$$

• Effective current and voltage can be used to describe alternating current and voltage.

$$I_{\rm eff} = 0.707 \ I_{\rm max}$$

 $V_{\rm eff} = 0.707 V_{\rm max}$

• A generator and a motor are similar devices. A generator converts mechanical energy to electric energy, whereas a motor converts electric energy to mechanical energy.

25.2 Changing Magnetic Fields Induce EMF

Vocabulary

- Lenz's law (p. 679)
- eddy current (p. 681)
- self-inductance (p. 681)
- transformer (p. 682)
- primary coil (p. 682)
- secondary coil (p. 682)
- mutual inductance (p. 682)
- step-up transformer (p. 682)
- step-down transformer (p. 682)

Key Concepts

- Lenz's law states that an induced current is always produced in a direction such that the magnetic field resulting from the induced current opposes the change in the magnetic field that is causing the induced current.
- Back-*EMF* is created by a current-carrying wire moving in a magnetic field. Back-*EMF* opposes the current.
- Self-inductance is a property of a wire carrying a changing current. The faster the current is changing, the greater the induced *EMF* that opposes that change.
- A transformer has two coils wound about the same core. An AC current through the primary coil induces an alternating *EMF* in the secondary coil. The voltages in alternating-current circuits may be increased or decreased by transformers.

$$\frac{I_{\rm s}}{I_{\rm p}} = \frac{V_{\rm p}}{V_{\rm s}} = \frac{N_{\rm p}}{N_{\rm s}}$$

Concept Mapping

24. Complete the following concept map using the following terms: *generator, back-EMF, Lenz's law.*



Mastering Concepts

- **25.** What is the armature of an electric generator? (25.1)
- 26. Why is iron used in an armature? (25.1)

For problems 27–29, refer to Figure 25-16.

- **27.** A single conductor moves through a magnetic field and generates a voltage. In what direction should the wire be moved, relative to the magnetic field to generate the minimum voltage? (25.1)
- **28.** What is the polarity of the voltage induced in the wire when it passes the south pole of the magnetic field? (25.1)
- **29.** What is the effect of increasing the net conductor length in an electric generator? (25.1)



- **30.** How were Oersted's and Faraday's results similar? How were they different? (25.1)
- **31.** You have a coil of wire and a bar magnet. Describe how you could use them to generate an electric current. (25.1)
- **32.** What does *EMF* stand for? Why is the name inaccurate? (25.1)
- **33.** What is the difference between a generator and a motor? (25.1)
- 34. List the major parts of an AC generator. (25.1)
- **35.** Why is the effective value of an AC current less than its maximum value? (25.1)
- **36. Hydroelectricity** Water trapped behind a dam turns turbines that rotate generators. List all the forms of energy that take part in the cycle that includes the stored water and the electricity produced. (25.1)
- 37. State Lenz's law. (25.2)
- **38.** What causes back-*EMF* in an electric motor? (25.2)
- **39.** Why is there no spark when you close a switch and put current through an inductor, but there is a spark when you open the switch? (25.2)
- **40.** Why is the self-inductance of a coil a major factor when the coil is in an AC circuit but a minor factor when the coil is in a DC circuit? (25.2)
- **41.** Explain why the word *change* appears so often in this chapter. (25.2)
- **42.** Upon what does the ratio of the *EMF* in the primary circuit of a transformer to the *EMF* in the secondary circuit of the transformer depend? (25.2)

Applying Concepts

- **43.** Use unit substitution to show that the units of *BLv* are volts.
- **44.** When a wire is moved through a magnetic field, does the resistance of the closed circuit affect current only, *EMF* only, both, or neither?
- **45. Biking** As Logan slows his bike, what happens to the *EMF* produced by his bike's generator? Use the term *armature* in your explanation.
- **46.** The direction of AC voltage changes 120 times each second. Does this mean that a device connected to an AC voltage alternately delivers and accepts energy?

47. A wire is moved horizontally between the poles of a magnet, as shown in **Figure 25-17.** What is the direction of the induced current?



48. You make an electromagnet by winding wire around a large nail, as shown in **Figure 25-18.** If you connect the magnet to a battery, is the current larger just after you make the connection or several tenths of a second after the connection is made? Or, is it always the same? Explain.



Figure 25-18

49. A segment of a wire loop is moving downward through the poles of a magnet, as shown in **Figure 25-19.** What is the direction of the induced current?



Figure 25-19

50. A transformer is connected to a battery through a switch. The secondary circuit contains a lightbulb, as shown in **Figure 25-20.** Will the lamp be lighted as long as the switch is closed, only at the moment the switch is closed, or only at the moment the switch is opened? Explain.



51. Earth's Magnetic Field The direction of Earth's magnetic field in the northern hemisphere is downward and to the north as shown in Figure 25-21. If an east-west wire moves from north to south, in which direction is the current?



- **52.** You move a length of copper wire down through a magnetic field, *B*, as shown in Figure 25-19.
 - **a.** Will the induced current move to the right or left in the wire segment in the diagram?
 - **b.** As soon as the wire is moved in the field, a current appears in it. Thus, the wire segment is a current-carrying wire located in a magnetic field. A force must act on the wire. What will be the direction of the force acting on the wire as a result of the induced current?
- **53.** A physics instructor drops a magnet through a copper pipe, as illustrated in **Figure 25-22.** The magnet falls very slowly, and the students in the class conclude that there must be some force opposing gravity.
 - **a.** What is the direction of the current induced in the pipe by the falling magnet if the south pole is toward the bottom?
 - **b.** The induced current produces a magnetic field. What is the direction of the field?
 - **c.** How does this field reduce the acceleration of the falling magnet?



54. Generators Why is a generator more difficult to rotate when it is connected to a circuit and supplying current than it is when it is standing alone?

- **55.** Explain why the initial start-up current is so high in an electric motor. Also explain how Lenz's law applies at the instant t > 0.
- **56.** Using Figure 25-10 in conjunction with Lenz's law, explain why all practical transformer cores incorporate a laminated core.
- **57.** A practical transformer is constructed with a laminated core that is not a superconductor. Because the eddy currents cannot be completely eliminated, there is always a small core loss. This results, in part, in a net loss of power within the transformer. What fundamental law makes it impossible to bring this loss to zero?
- **58.** Explain the process of mutual induction within a transformer.
- **59.** Shawn drops a magnet, north pole down, through a vertical copper pipe.
 - **a.** What is the direction of the induced current in the copper pipe as the bottom of the magnet passes?
 - **b.** The induced current produces a magnetic field. What is the direction of the induced magnetic field?

Mastering Problems

25.1 Electric Current from Changing Magnetic Fields

- **60.** A wire, 20.0-m long, moves at 4.0 m/s perpendicularly through a magnetic field. An *EMF* of 40 V is induced in the wire. What is the strength of the magnetic field?
- **61. Airplanes** An airplane traveling at 9.50×10^2 km/h passes over a region where Earth's magnetic field is 4.5×10^{-5} T and is nearly vertical. What voltage is induced between the plane's wing tips, which are 75 m apart?
- **62.** A straight wire, 0.75-m long, moves upward through a horizontal 0.30-T magnetic field, as shown in **Figure 25-23**, at a speed of 16 m/s.
 - **a.** What *EMF* is induced in the wire?
 - **b.** The wire is part of a circuit with a total resistance of 11 Ω . What is the current?



63. At what speed would a 0.20-m length of wire have to move across a 2.5-T magnetic field to induce an *EMF* of 10 V?

- **64.** An AC generator develops a maximum *EMF* of 565 V. What effective *EMF* does the generator deliver to an external circuit?
- **65.** An AC generator develops a maximum voltage of 150 V. It delivers a maximum current of 30.0 A to an external circuit.
 - **a.** What is the effective voltage of the generator?
 - **b.** What effective current does the generator deliver to the external circuit?
 - **c.** What is the effective power dissipated in the circuit?
- **66. Electric Stove** An electric stove is connected to an AC source with an effective voltage of 240 V.
 - **a.** Find the maximum voltage across one of the stove's elements when it is operating.
 - **b.** The resistance of the operating element is 11 Ω . What is the effective current?
- **67.** You wish to generate an *EMF* of 4.5 V by moving a wire at 4.0 m/s through a 0.050-T magnetic field. How long must the wire be, and what should be the angle between the field and direction of motion to use the shortest wire?
- **68.** A 40.0-cm wire is moved perpendicularly through a magnetic field of 0.32 T with a velocity of 1.3 m/s. If this wire is connected into a circuit of 10.0-Ω resistance, what is the current?
- **69.** You connect both ends of a copper wire with a total resistance of 0.10 Ω to the terminals of a galvanometer. The galvanometer has a resistance of 875 Ω . You then move a 10.0-cm segment of the wire upward at 1.0 m/s through a 2.0×10^{-2} -T magnetic field. What current will the galvanometer indicate?
- **70.** The direction of a 0.045-T magnetic field is 60.0° above the horizontal. A wire, 2.5-m long, moves horizontally at 2.4 m/s.
 - **a.** What is the vertical component of the magnetic field?
 - **b.** What *EMF* is induced in the wire?
- **71. Dams** A generator at a dam can supply 375 MW $(375 \times 10^6 \text{ W})$ of electrical power. Assume that the turbine and generator are 85 percent efficient.
 - **a.** Find the rate at which falling water must supply energy to the turbine.
 - **b.** The energy of the water comes from a change in potential energy, *PE* = *mgh*. What is the change in *PE* needed each second?
 - **c.** If the water falls 22 m, what is the mass of the water that must pass through the turbine each second to supply this power?

- **72.** A conductor rotating in a magnetic field has a length of 20 cm. If the magnetic-flux density is 4.0 T, determine the induced voltage when the conductor is moving perpendicular to the line of force. Assume that the conductor travels at a constant velocity of 1 m/s.
- **73.** Refer to Example Problem 1 and **Figure 25-24** to determine the following.
 - a. induced voltage in the conductor
 - **b.** current (*I*)

c. direction of flux rotation around the conductor **d.** polarity of point A relative to point B



Figure 25-24

25.2 Changing Magnetic Fields Induce EMF

- **74.** The primary coil of a transformer has 150 turns. It is connected to a 120-V source. Calculate the number of turns on the secondary coil needed to supply the following voltages.
 - **a.** 625 V
 - **b.** 35 V
 - **c.** 6.0 V
- **75.** A step-up transformer has 80 turns on its primary coil and 1200 turns on its secondary coil. The primary circuit is supplied with an alternating current at 120 V.
 - **a.** What voltage is being applied across the secondary circuit?
 - **b.** The current in the secondary circuit is 2.0 A. What current is in the primary circuit?
 - **c.** What are the power input and output of the transformer?
- **76. Laptop Computers** The power supply in a laptop computer requires an effective voltage of 9.0 V from a 120-V line.
 - **a.** If the primary coil has 475 turns, how many does the secondary coil have?
 - **b.** A 125-mA current is in the computer. What current is in the primary circuit?

- **77. Hair Dryers** A hair dryer manufactured for use in the United States uses 10 A at 120 V. It is used with a transformer in England, where the line voltage is 240 V.
 - **a.** What should be the ratio of the turns of the transformer?
 - **b.** What current will the hair dryer now draw?
- **78.** A 150-W transformer has an input voltage of 9.0 V and an output current of 5.0 A.
 - **a.** Is this a step-up or step-down transformer?
 - **b.** What is the ratio of V_{output} to V_{input} ?
- **79.** Scott connects a transformer to a 24-V source and measures 8.0 V at the secondary circuit. If the primary and secondary circuits were reversed, what would the new output voltage be?

Mixed Review

- **80.** A step-up transformer's primary coil has 500 turns. Its secondary coil has 15,000 turns. The primary circuit is connected to an AC generator having an *EMF* of 120 V.
 - **a.** Calculate the *EMF* of the secondary circuit.
 - **b.** Find the current in the primary circuit if the current in the secondary circuit is 3.0 A.
 - **c.** What power is drawn by the primary circuit? What power is supplied by the secondary circuit?
- **81.** With what speed must a 0.20-m-long wire cut across a magnetic field for which *B* is 2.5 T if it is to have an *EMF* of 10 V induced in it?
- **82.** At what speed must a wire conductor 50-cm long be moved at right angles to a magnetic field of induction 0.20 T to induce an *EMF* of 1.0 V in it?
- **83.** A house lighting circuit is rated at 120-V effective voltage. What is the peak voltage that can be expected in this circuit?
- **84. Toaster** A toaster draws 2.5 A of alternating current. What is the peak current through this toaster?
- **85.** The insulation of a capacitor will break down if the instantaneous voltage exceeds 575 V. What is the largest effective alternating voltage that may be applied to the capacitor?
- **86. Circuit Breaker** A magnetic circuit breaker will open its circuit if the instantaneous current reaches 21.25 A. What is the largest effective current the circuit will carry?
- **87.** The electricity received at an electrical substation has a potential difference of 240,000 V. What should the ratio of the turns of the step-down transformer be to have an output of 440 V?

- **88.** An alternating-current electric generator supplies a 45-kW industrial electric heater. If the system voltage is 660 V_{rms'} what is the peak current supplied?
- **89.** A certain step-down transformer has 100 turns on the primary coil and 10 turns on the secondary coil. If a 2.0-kW resistive load is connected to the transformer, what is the effective primary current that flows? Assume that the secondary voltage is $60.0 V_{pk'}$.
- **90.** A transformer rated at 100 kVA has an efficiency of 98 percent.
 - **a.** If the connected load consumes 98 kW of power, what is the input power to the transformer?
 - **b.** What is the maximum primary current with the transformer consuming its rated reactive power? Assume that $V_{\rm p} = 600$ V.
- **91.** A wire, 0.40-m long, cuts perpendicularly across a magnetic field for which *B* is 2.0 T at a velocity of 8.0 m/s.
 - **a.** What *EMF* is induced in the wire?
 - **b.** If the wire is in a circuit with a resistance of 6.4 Ω, what is the size of the current in the wire?
- **92.** A coil of wire, which has a total length of 7.50 m, is moved perpendicularly to Earth's magnetic field at 5.50 m/s. What is the size of the current in the wire if the total resistance of the wire is $5.0 \times 10^{-2} \Omega$? Assume Earth's magnetic field is 5×10^{-5} T.
- **93.** The peak value of the alternating voltage applied to a 144- Ω resistor is 1.00×10² V. What power must the resistor be able to handle?
- **94. Television** The CRT in a television uses a step-up transformer to change 120 V to 48,000 V. The secondary side of the transformer has 20,000 turns and an output of 1.0 mA.

a. How many turns does the primary side have?**b.** What is the input current?

Thinking Critically

- **95. Apply Concepts** Suppose that an "anti-Lenz's law" existed that meant a force was exerted to increase the change in a magnetic field. Thus, when more energy was demanded, the force needed to turn the generator would be reduced. What conservation law would be violated by this new "law"? Explain.
- **96. Analyze** Real transformers are not 100 percent efficient. Write an expression for transformer efficiency in percent using power. A step-down transformer that has an efficiency of 92.5 percent is used to obtain 28.0 V from a 125-V household voltage. The current in the secondary circuit is 25.0 A. What is the current in the primary circuit?

97. Analyze and Conclude A transformer that supplies eight homes has an efficiency of 95 percent. All eight homes have operating electric ovens that each draw 35 A from 240-V lines. How much power is supplied to the ovens in the eight homes? How much power is dissipated as heat in the transformer?

Writing in Physics

98. Common tools, such as an electric drill, are typically constructed using a universal motor. Using your local library, and other sources, explain how this type of motor may operate on either AC or DC current.

Cumulative Review

- **99.** Light is emitted by a distant star at a frequency of 4.56×10^{14} Hz. If the star is moving toward Earth at a speed of 2750 km/s, what frequency light will be detected by observers on Earth? (Chapter 16)
- **100.** A distant galaxy emits light at a frequency of 7.29×10^{14} Hz. Observers on Earth receive the light at a frequency of 6.14×10^{14} Hz. How fast is the galaxy moving, and in what direction? (Chapter 16)
- **101.** How much charge is on a $22-\mu$ F capacitor with 48 V applied to it? (Chapter 21)
- **102.** Find the voltage across a 22- Ω , 5.0-W resistor operating at half of its rating. (Chapter 22)
- **103.** Determine the total resistance of three, $85-\Omega$ resistors connected in parallel and then series-connected to two $85-\Omega$ resistors connected in parallel, as shown in **Figure 25-25.** (Chapter 23)



Figure 25-25

104. An electron with a velocity of 2.1×10^6 m/s is at right angles to a 0.81-T magnetic field. What is the force on the electron produced by the magnetic field? What is the electron's acceleration? The mass of an electron is 9.11×10^{-31} kg. (Chapter 24)

Standardized Test Practice

Multiple Choice

- **1.** Which dimensional analysis is correct for the calculation of *EMF*?
 - \bigcirc (N·A·m)(J)

 - © J·C
 - \bigcirc (N·m·A/s)(1/m)(m/s)
- **2.** An electromotive force of 4.20×10^{-2} V is induced on a 427-mm-long piece of wire that is moving at a rate of 18.6 cm/s. What is the magnetic field that induced the *EMF*?

| A | 5.29 T | C | $3.34 \times 10^{-3} \mathrm{T}$ |
|---|--------|---|----------------------------------|
| B | 1.89 T | D | $5.29 \times 10^{-1} \text{ T}$ |

3. Which of the following will fail to induce an electric current in the wire?



4. 15 cm of wire is moving at the rate of 0.12 m/s through a perpendicular magnetic field of strength 1.4 T. Calculate the *EMF* induced in the wire.

| A | 0 V | © | 0.025 V |
|---|---------|---|---------|
| B | 0.018 V | | 2.5 V |

5. A transformer uses a 91-V supply to operate a 13-V device. If the transformer has 130 turns on the primary coil and the device uses 1.9 A of current from the transformer, what is the current supplied to the primary coil?

| A | 0.27 A | C | 4.8 A |
|---|--------|---|--------|
| B | 0.70 A | | 13.3 A |

6. An AC generator that delivers a peak voltage of 202 V connects to an electric heater with a resistance of $4.80 \times 10^2 \Omega$. What is the effective current in the heater?

| A | 0.298 A | \bigcirc | 2.38 A |
|---|---------|------------|--------|
| B | 1.68 A | | 3.37 A |



Extended Answer

7. Compare the power lost in transmission for an 800-W line at 160 V to the same power on a line at 960 V. Assume the resistance of the line is 2 Ω. What conclusion can you draw?

Test-Taking TIP

Investigate

Ask your instructor what kinds of questions to expect on the test. Also ask for practice tests so that you can become familiar with the test-taking materials.