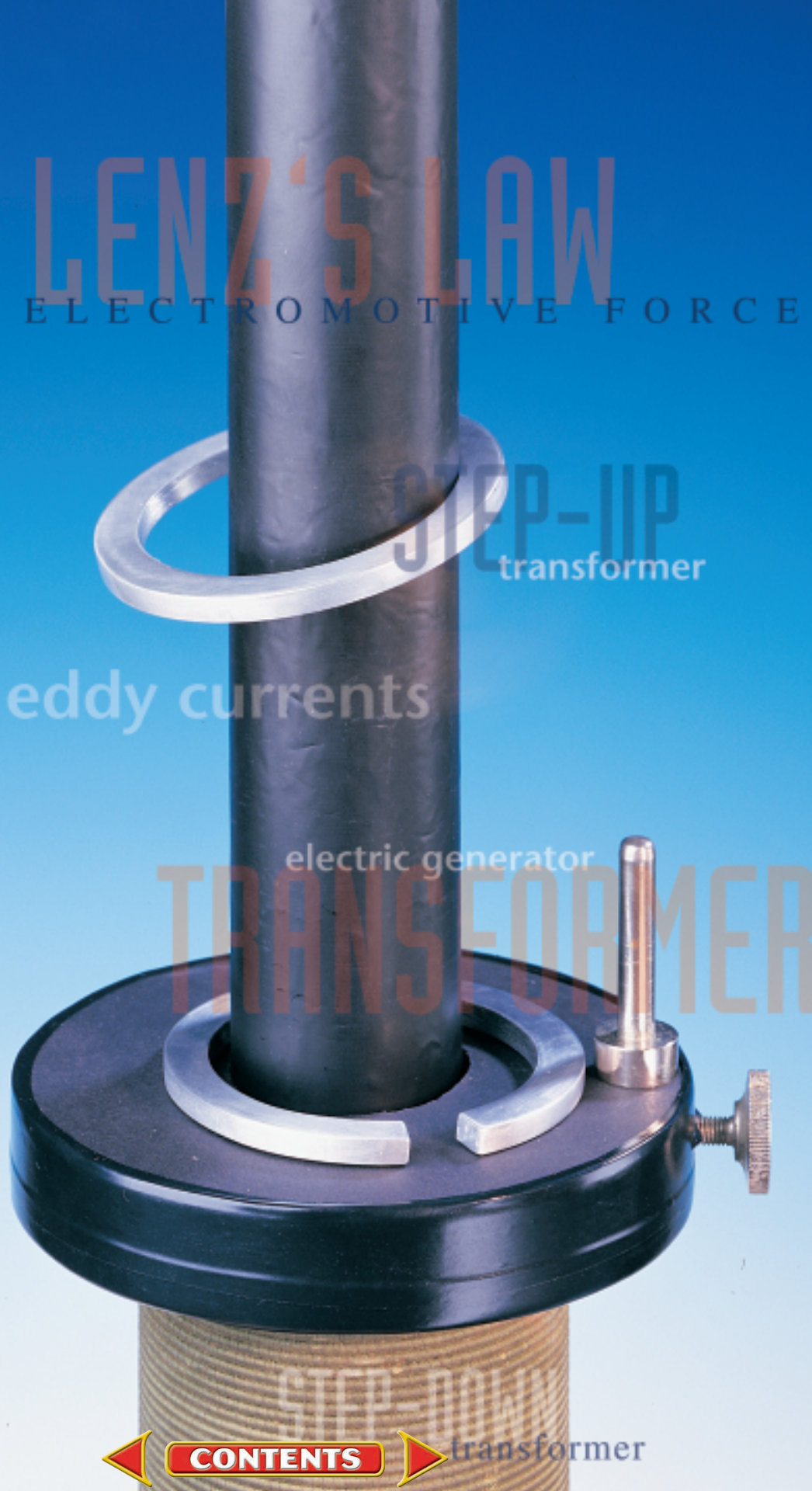


Go with the Flow

Two aluminum rings, one with a slit and one a continuous ring, are placed over a magnetic field generator that is producing a constantly changing magnetic field. Why does one ring float while the other does not?

➔ *Look at the text on page 592 for the answer.*



CHAPTER

25

Electromagnetic Induction



What unseen force levitates the top ring in the photo at the left? What upward force could be pushing the ring up, balancing the downward force of gravity? Why isn't the lower ring also floating? Why is there no upward force acting on the cut ring?

You've learned that superconductors and permanent magnets can cause objects to float. There is, however, no superconductor or permanent magnet in this photograph. You also know that if a current passes through the coil of wire around the central rod, it produces a continually changing magnetic field that can affect magnetic substances. However, the rings are made of aluminum, a nonmagnetic substance. A magnet will not attract a piece of aluminum much less push it up.

Yet the photo clearly shows an upward force being exerted on the top, uncut ring. The physical principle that explains why the ring floats associates a magnetic field with a changing electric field as well as with electric current. This same principle forms the foundation for producing continuous currents. It's at the heart of electric generators, and it's at the core of alternating current transformers.

As you study this chapter, you'll learn about this amazing principle that explains why the ring floats, how electricity is generated, and how electric energy is delivered to your home and school.

WHAT YOU'LL LEARN

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

WHY IT'S IMPORTANT

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

PHYSICS *Online*

To find out more about electromagnetic induction, visit the Glencoe Science Web site at science.glencoe.com



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25.1

Creating Electric Current from Changing Magnetic Fields



OBJECTIVES

- **Explain** how a changing magnetic field produces an electric current.
- **Define** electromotive force, and **solve** problems involving wires moving in a magnetic field.
- **Describe** how an electric generator works and how it differs from a motor.
- **Recognize** the difference between peak and effective voltage and current.

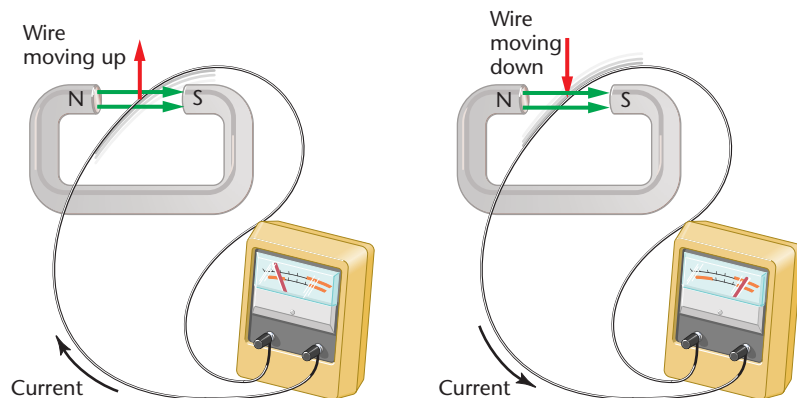
In 1822, Michael Faraday wrote a goal in his notebook: “Convert Magnetism into Electricity.” After nearly ten years of unsuccessful experiments, he was able to show that a changing magnetic field could produce electric current. In the same year, Joseph Henry, an American high school teacher, made the same discovery.

Faraday’s Discovery

In Chapter 24 you read about 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. Faraday tried many combinations of magnetic fields and wires without success, until he found that he could induce current by moving a wire through a magnetic field. **Figure 25–1** shows one of Faraday’s experiments. A wire loop that is part of a closed circuit is placed in a magnetic field. 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. When the wire is held stationary or is moved parallel to the magnetic field, there is no current. An electric current is generated in a wire only when the wire cuts magnetic field lines.

Creating current Faraday found that to generate current, either the conductor can move through a magnetic field or the magnetic field can move past a 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**.

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 the wire is moving through the field. The arrows indicate the direction of conventional current.



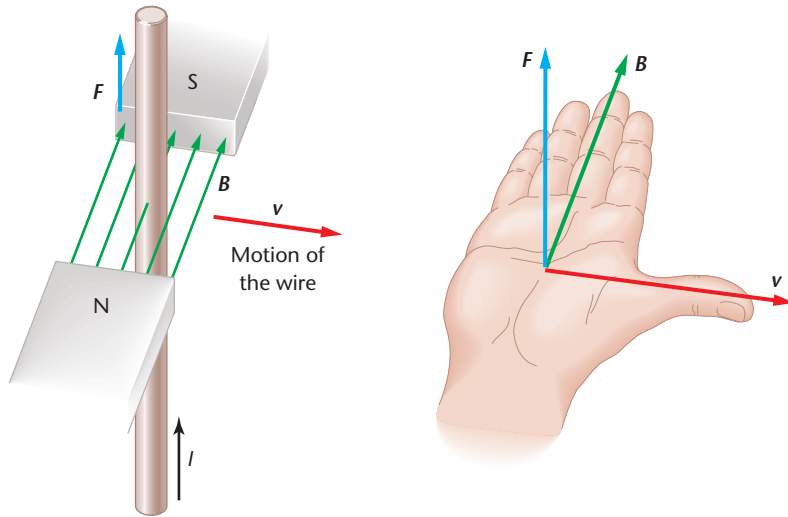


FIGURE 25-2 The right-hand rule can be used to find the direction of the forces on the charges in a conductor that is moving in a magnetic field.

In what direction is the current? To find the force on the charges in the wire, use the third right-hand rule described in Chapter 24. 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**.

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 a force; it is a potential difference and is measured in volts. Thus, the term *EMF* is misleading. Like many other historical terms still in use, it originated before electricity was well understood.

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*. The *EMF*, measured in volts, depends on the magnetic field, \mathbf{B} , the length of the wire in the magnetic field, L , and the velocity of the wire in the field, \mathbf{v} . If \mathbf{B} , \mathbf{v} , and the direction of the length of the wire are mutually perpendicular, then *EMF* is the product of the three.

Electromotive Force $EMF = BLv$

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*.

HISTORY CONNECTION

Transmitting Power

In the late 1800s, there was much debate in the United States over the best way to transmit power from power plants to consumers. The existing plants transmitted direct current (DC), but DC had serious limitations. A key decision was made to use alternating current (AC) in the new hydroelectric power plant at Niagara Falls. With the first successful transmission of AC to Buffalo, New York in 1896, the Niagara Falls plant paved the way for the development of AC power plants across the country.



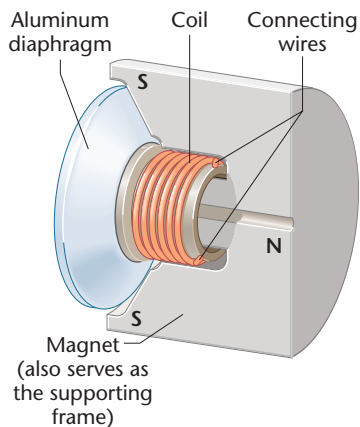


FIGURE 25-3 In this schematic of a moving coil microphone, the aluminum diaphragm is connected to a coil in a magnetic field. When sound waves vibrate the diaphragm, the coil moves in the magnetic field, generating a current proportional to the sound wave.

Checking the units of the *EMF* equation will help you work algebra correctly in problems. The units for *EMF* are volts, V. In Chapter 24, *B* was defined as F/IL ; therefore, the units for *B* are $N/A \cdot m$. Following is the unit equation for *EMF*.

$$\text{variables: } EMF = BLv$$

$$\text{units: } V = \left(\frac{N}{A \cdot m} \right) (m) (m/s) = \frac{N \cdot m}{A \cdot s} = \frac{J}{C} = V$$

From previous chapters, recall that $J = N \cdot m$, $A = C/s$, and that $V = J/C$.

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 loud-speaker. The microphone 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.

Example Problem

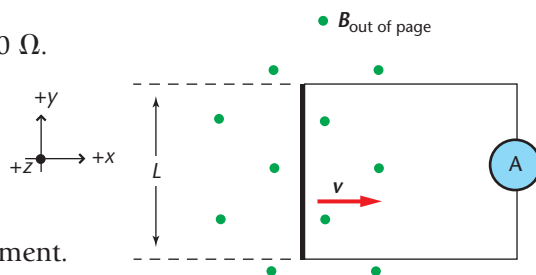
Induced *EMF*

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

- What *EMF* is induced in the wire?
- The wire is part of a circuit that has a resistance of 0.50Ω . What is the current through the wire?

Sketch the Problem

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



Calculate Your Answer

Known:

$$v = 7.0 \text{ m/s}$$

$$L = 0.20 \text{ m}$$

$$B = 8.0 \times 10^{-2} \text{ T}$$

$$R = 0.50 \Omega$$

Unknown:

$$EMF = ?$$

$$I = ?$$

Strategy:

- For motion at a right angle through a field, start with the EMF equation. Keep track of units. It is helpful to remember that $B = F/IL$, $energy = Fd$, $I = q/t$, and $V = energy/q$.
- Use the current equation. Recall that voltage and EMF are equivalent. Use the right-hand rule to determine current direction. The thumb is \mathbf{v} ($+x$), fingers are \mathbf{B} ($+z$), and palm is current, which points down ($-y$). Downward current corresponds to a counterclockwise current in the loop.

Check Your Answer

- Are the units correct? **a.** The answer is in volts, which is the correct unit for electromotive force. **b.** Ohms are defined as V/A . Perform the algebra with the units to confirm that I is measured in A.
- Does the direction make sense? The direction obeys the right-hand rule: \mathbf{v} is the thumb, \mathbf{B} is the fingers, \mathbf{F} is the palm. Current is in the direction of the force.
- Is the magnitude realistic? The answers are near 10^{-1} . This agrees with the quantities given and the algebra performed.

Calculations:

$$EMF = BLv$$

$$EMF = (8.0 \times 10^{-2} \text{ T})(0.20 \text{ m})(7.0 \text{ m/s})$$

$$EMF = 0.11 \text{ T} \cdot \text{m}^2/\text{s} = 0.11 \text{ J/C} = 0.11 \text{ V}$$

$$I = \frac{V}{R} = \frac{EMF}{R}$$

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

Practice Problems

- 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.
 - What EMF is induced in the wire?
 - The wire is part of a circuit of total resistance of 6.0Ω . What is the current in the circuit?
- 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 ($B = 5.0 \times 10^{-5} \text{ T}$). What EMF is induced in the wire?
- A straight wire, 30.0 m long, moves at 2.0 m/s in a perpendicular direction through a 1.0-T magnetic field.
 - What EMF is induced in the wire?
 - The total resistance of the circuit of which the wire is a part is 15.0Ω . What is the current?
- 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 N-pole of the magnet?

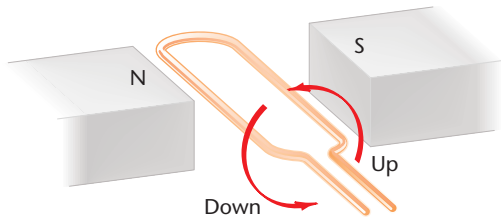
Pocket Lab

Making Currents

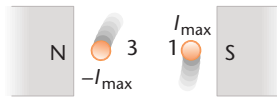


Hook the ends of a 1-m length of wire to the binding posts of a galvanometer (or microammeter). Make several overlapping loops in the wire. Watch the readings on the wire as you move a pair of neodymium magnets (or a strong horseshoe magnet) near the loops. Record your observations.

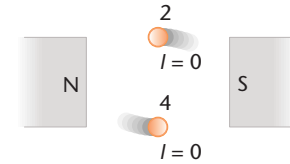
Analyze and Conclude What can you do to increase the current? Replace the 1-m length of wire with a preformed coil and see how much current you can produce. Describe your results.



a
FIGURE 25-4 An electric current is generated in a wire loop as the loop rotates **(a)**. The cross-sectional view shows the position of the loop when maximum current is generated **(b)**. The numbered positions correspond to the numbered points on the graph in **Figure 25-5**.



b



c

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 form 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, inducing 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*.

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. The direction of the induced current can be found from the third right-hand rule described in Chapter 24. As the loop rotates, the strength and direction of the current change. The current is greatest when the motion of the loop is perpendicular to the magnetic field—when the loop is in the horizontal position. 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, it moves through the magnetic field lines at an ever-increasing angle. Thus, it cuts through fewer magnetic field lines per unit 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, reversing 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. The graph of current versus time is shown in **Figure 25-5**.

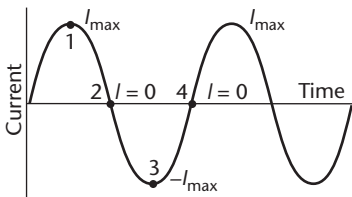


FIGURE 25-5 This graph shows the variation of current with time as the loop in **Figure 25-4** rotates. The variation of *EMF* with time can be shown with a similar graph.

Generators and motors are almost identical in construction, but they convert energy in opposite directions. A generator converts mechanical energy to electrical energy, while a motor converts electrical energy to mechanical energy.

Electromagnetic Fields (EMFs)

Alternating currents produce both electric and magnetic fields, EMFs. These low-frequency fields, 60 Hz, are generated by nearly all electrical appliances as well as by outdoor power lines and indoor electrical wiring. About two decades ago, some doctors suggested that there was a direct link between EMFs and childhood leukemia, a rare form of cancer. This possibility spurred many studies on the topic both in physics and biology. In addition to the cost of the studies, concern about EMF health risks are costing the U.S. society an estimated \$1 billion a year in lawsuits, rerouting of power lines, and redesigning of products such as computer monitors and household appliances. In 1995, the American Physical Society issued a statement that its review of scientific literature found “no consistent, significant link between cancer and power line fields.” But there are still questions to be resolved because of the subtle effects of EMFs on cell membranes.

Cells, Tissues, and EMFs

To date, studies on human cells and tissues and on laboratory animals have shown that exposure to EMFs at the low frequencies common in most households does not alter cell functions. Research also has shown that EMFs tens or hundreds of times stronger than those in residential structures do cause changes in the chemical signals that cells send to each other. This correlation, however, doesn't seem to have adverse effects on health.

Furthermore, current research indicates that exposure to even very high EMFs does not affect a cell's DNA. Damaged DNA is currently thought to be the cause of most cancers. In 1997, the National Cancer Institute finished an exhaustive, seven-year study with the

conclusion “that if there is any link at all, it's far too weak to be concerned about.”

Toss the toaster and bag the blanket?

Although current research indicates that the EMF issue is no cause for alarm, some people (including some scientists and physicians) are not convinced that their toasters, electric blankets, alarm clocks, computer terminals, televisions, and other commonly used household items are truly safe.

Investigating the Issue

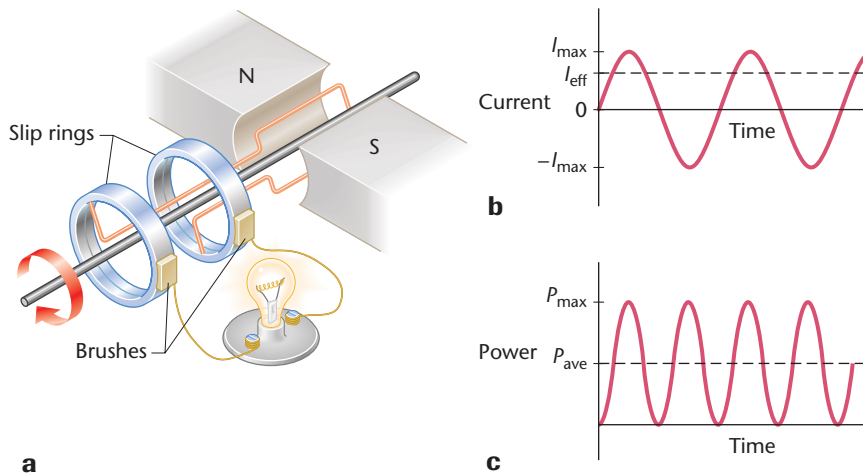
- 1. Acquiring Information** Read current articles about EMFs. Review the major points made in each article. While reading, look for bias and evidence of factual documentation.
- 2. Analyzing and Critiquing** What do you think should be done? Do you think there is sufficient and conclusive evidence that links health hazards and EMFs? Should people limit their exposure to EMFs? Should companies, including government, continue to spend millions of dollars to research the bio-effects of EMFs, redesign products to emit less, and move or bury power lines? Explain your reasoning.
- 3. Recognizing Cause and Effect** While there appears to be no correlation between exposure to EMFs and certain cancers, some studies have suggested a possible link between the two. What might be the reasons for this inconsistency?

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To find out more about EMFs, visit the Glencoe Science Web site at science.glencoe.com

FIGURE 25–6 Alternating-current generators transmit 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)**.



Alternating-Current Generator

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. The current goes from one direction to the other and back to the first, 60 times a second. **Figure 25–6a** 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 25–6b**.

Average power The power produced by a generator is the product of the current and the voltage. Because both I and V vary, the power associated with an alternating current varies. **Figure 25–6c** 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 defined as half the maximum power, $P_{AC} = 1/2 P_{AC \text{ max}}$.

Effective voltage and currents 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 $P = I^2R$. Thus, you can relate effective current, I_{eff} , in terms of the average AC power.

$$P_{AC} = I_{\text{eff}}^2 R$$

To determine I_{eff} in terms of maximum current, I_{max} , start with the power relationship and substitute in I^2R , then solve for I_{eff} .

$$P_{AC} = 1/2 P_{AC \text{ max}}$$

$$I_{\text{eff}}^2 R = 1/2 I_{\text{max}}^2 R$$

Pocket Lab

Motor and Generator



Make a series circuit with a Genecon (or efficient DC motor), a miniature lamp, and an ammeter. Rotate the handle (or motor shaft) to try to light the lamp.

Analyze and Conclude

Describe your results. Predict what might happen if you connect your Genecon to the Genecon from another lab group and crank yours. Try it. Describe what happens. Can more than two be connected?

$$I_{\text{eff}} = \sqrt{1/2 I_{\text{max}}^2}$$

$$\text{Effective Current } I_{\text{eff}} = 0.707 I_{\text{max}}$$

Similarly, it can be shown that

$$\text{Effective Voltage } V_{\text{eff}} = 0.707 V_{\text{max}}$$

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.

Practice Problems

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 effective voltage of an AC household outlet is 117 V.
 - a. What is the maximum voltage across a lamp connected to the outlet?
 - b. The effective 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 of the circuit is $5.0 \times 10^2 \Omega$. What is the effective current?
8. If the average power dissipated by an electric light is 100 W, what is the peak power?

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25.1 Section Review

1. Could you make a generator by mounting permanent magnets on a rotating shaft and keeping the coil stationary? Explain.
2. A bike generator lights the headlamp. What is the source of the energy for the bulb when the rider travels along a flat road?
3. Consider the microphone shown in **Figure 25–3**. When the diaphragm is pushed in, what is the direction of the current in the coil?
4. **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.

25.2

Changing Magnetic Fields Induce *EMF*



OBJECTIVES

- **State** Lenz's law, and **explain** back-*EMF* and how it affects the operation of motors and generators.
- **Explain** self-inductance and how it affects circuits.
- **Describe** a transformer and **solve** problems involving voltage, current, and turn ratios.

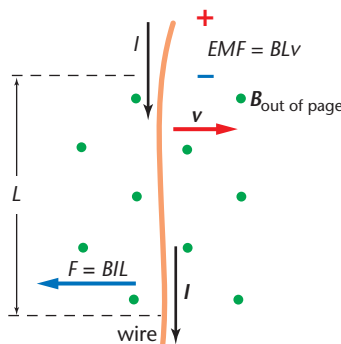


FIGURE 25–7 A wire, length L , moving through a magnetic field, \mathbf{B} , induces an electromotive force. If the wire is part of a circuit, then there will be a current, I . This current will now interact with the magnetic field producing force, \mathbf{F} . Notice that the resulting force opposes the motion, \mathbf{v} , of the wire.

In a generator, current begins when the armature turns through a magnetic field. You learned in Chapter 24 that when there is a current through a wire in a magnetic field, a force is exerted on the wire. Thus, the act of generating current produces a force on the wires in the armature.

Lenz's Law

In what direction is the force on the wires of the armature? To determine the direction, consider a section of one loop that moves through a magnetic field, as shown in **Figure 25–7**. In the last section, you learned that an *EMF* will be induced in the wire governed by the equation $EMF = BLv$. If the magnetic field is out of the page and velocity is to the right, then the right-hand rule shows a downward *EMF*, 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 the force, use the third right-hand rule: if current I is down and magnetic field B is out, then the resulting force is to the left. 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 25–8** is an example of how Lenz's law works. The N-pole of a magnet is moved toward the left end of a coil. To oppose the approach of the N-pole, the left end of the coil also must become an N-pole. In other words, the magnetic field lines must emerge from the left end of the coil. Using the second right-hand rule you learned in Chapter 24, you will see that if Lenz's law is correct, the induced current must be in a counterclockwise direction. Experiments have shown that this is so. If the magnet is turned so that an S-pole approaches the coil, the induced current will flow in a clockwise direction.



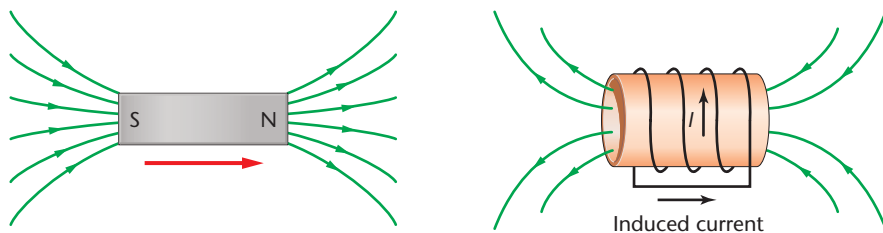


FIGURE 25-8 The magnet approaching the coil causes an induced current to flow. Lenz's law predicts the direction of flow shown.

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 electrical energy. The opposing force on the armature means that mechanical energy must be supplied to the generator to produce the electrical 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.

The heavy current required when a motor is started can cause voltage drops across the resistance of the wires that carry current to the motor. The voltage drop across the wires reduces the voltage across the motor. If a second device, such as a lightbulb, is in a parallel circuit with the motor, the voltage at the bulb also will drop when the motor is started. The bulb will dim. As the motor picks up speed, the voltage will rise again and the bulb will brighten.

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.

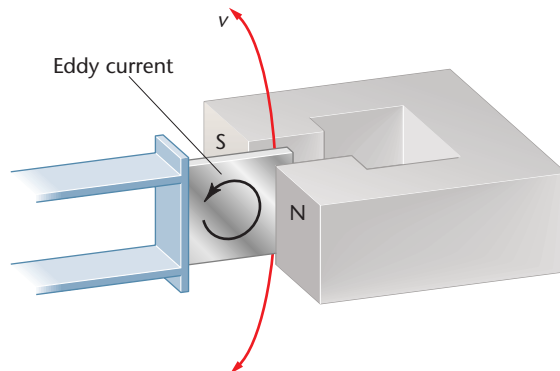
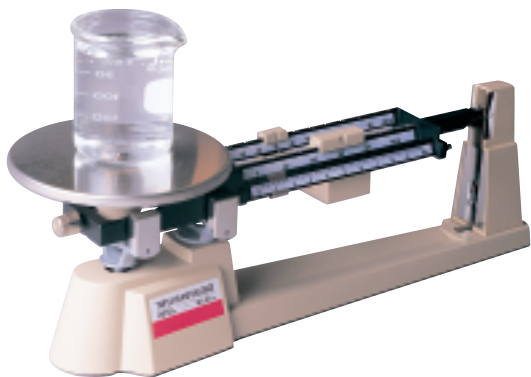
Pocket Lab

Slow Motor



Make a series circuit with a miniature DC motor, an ammeter, and a DC power supply. Hook up a voltmeter in parallel across the motor. Adjust the setting on the power supply so that the motor is running at medium speed. Make a data table to show the readings on the ammeter and voltmeter.

Analyze and Conclude Predict what will happen to the readings on the circuit when you hold the shaft and keep it from turning. Try it. Explain the results.



a
FIGURE 25–9 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)**.

Go with the Flow

➔ *Answers question from page 580.*

Application of Lenz’s law A sensitive balance, such as the kind used in chemistry laboratories, shown in **Figure 25–9**, uses Lenz’s law to stop its oscillation when an object is placed on the pan. 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. These currents 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, it does not change the mass read by the balance. This effect is called eddy current damping.

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. How



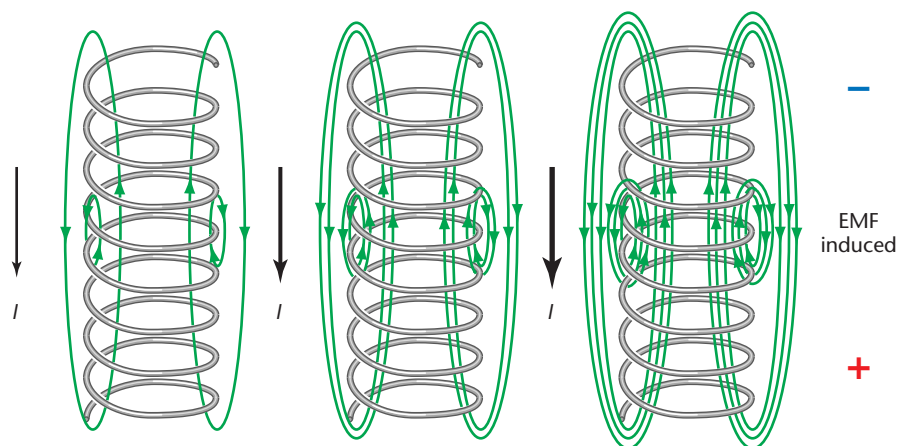


FIGURE 25-10 As the current in the coil increases from left to right, the magnetic field generated by the current also increases. This increase in magnetic field produces an *EMF* that opposes the current direction.

from left to right. The current generates a magnetic field, shown by magnetic field lines. As the current and magnetic field increase, you can imagine that new lines are created. As the lines expand, they cut through the coil wires, generating 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**. 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 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 a charged capacitor stores energy in the electric field between its plates.

Transformers

Inductance between coils is the basis for the operation of a transformer. A **transformer** is a device used to increase or decrease AC voltages. Transformers are widely used because they change voltages with relatively little loss of energy.

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 varying magnetic field. The varying magnetic field is carried through the core to the secondary coil. In the secondary coil, the varying field induces a varying *EMF*. This effect is called **mutual inductance**.

Pocket Lab

Slow Magnet



Lay a 1-m length of copper tube on the lab table. Try to pull the copper with a pair of neodymium magnets. Can you feel any force on the copper? Hold the tube by one end so that it hangs straight down. Drop a small steel marble through the tube. Use a stopwatch to measure the time needed for first the marble and then for the pair of magnets to fall through the tube. Catch the magnets in your hand. If they hit the table or floor, they will break.

Analyze and Conclude

Devise a hypothesis that would explain the strange behavior of the falling magnets and suggest a method of testing your hypothesis.

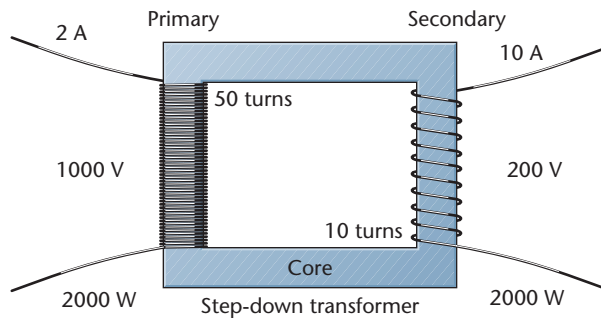
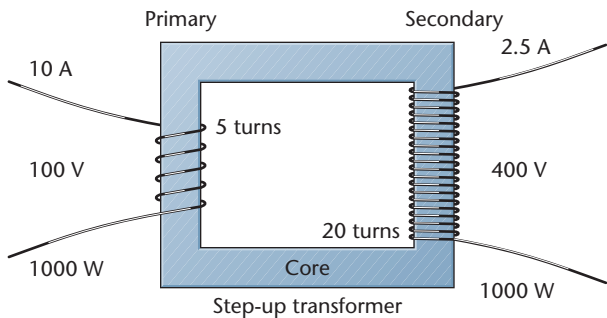


FIGURE 25–11 In a transformer, the ratio of input voltage to output voltage depends upon the ratio of the number of turns on the primary coil to the number of turns on the secondary coil.

The *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 turns on the secondary coil to turns on the primary coil.

$$\frac{\text{secondary voltage}}{\text{primary voltage}} = \frac{\text{number of turns on secondary coil}}{\text{number of turns on primary coil}}$$

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

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

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.

$$P_p = P_s$$

$$V_p I_p = V_s I_s$$

Rearrange the equation and you find the current in the primary circuit depends on how much current is required by the secondary circuit.

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

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.

Figure 25–11 illustrates the principles of step-up and step-down transformers.

Some transformers can function either as step-up transformers or step-down transformers depending on how they are hooked up. **Figure 25–12** shows an example of such a transformer.

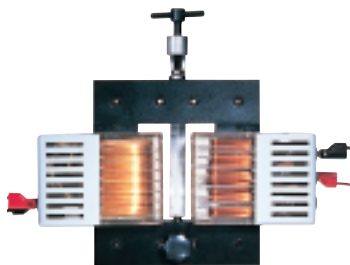


FIGURE 25–12 If the input voltage is connected to the coils on the left, where there is a larger number of turns, the transformer functions as a step-down transformer. If the input voltage is connected at the right, the transformer functions as a step-up transformer.



Swinging Coils

Problem

Electricity that you use in your everyday life comes from the wall socket or from chemical batteries. Modern theory suggests that current can be caused by the interactions of wires and magnets. Exactly how do coils and magnets interact?

Hypothesis

Form a testable hypothesis that relates to the interaction of magnets and coils. Be sure to include some symmetry tests in your hypothesis. Try to design a system of coils and magnets so that you can use one pair as a generator and one pair as a motor.

Possible Materials



coils of enameled wire
 identical sets of magnets
 masking tape
 supports and bars

Plan the Experiment

1. Devise a means to test stationary effects: those that occur when the magnet and coils are not moving.
2. Consider how to test moving effects: those that occur when the magnet moves in various directions in relation to the coil.
3. Include different combinations of connecting, or not connecting, the ends of the wires.
4. Consider polarity, magnetic strength, and any other variables that might influence the interaction of the coils and magnet.
5. **Check the Plan** Make sure that your teacher has approved your final plan before you proceed with your experiment.
6. When you have completed the lab, dispose of or recycle appropriate materials. Put away materials that can be reused.



Analyze and Conclude

1. **Organizing Results** Construct a list of tests that you performed and their results.
2. **Analyzing Data** Summarize the effects of the stationary magnet and the moving magnet. Explain how connecting the wires influenced your results.
3. **Relating Concepts** Describe and explain the effects of changing polarity, direction, number of coils, and any other variables you used.
4. **Checking Your Hypothesis** Did the experiment yield expected results? Did you determine any new interactions?

Apply

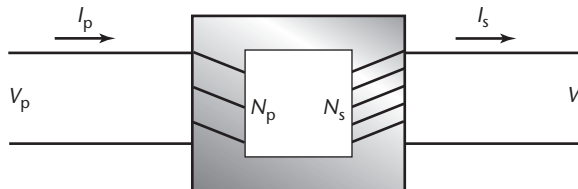
1. The current that you generated in this activity was quite small. List several factors that you could change to generate more current. (**Hint:** Think of a commercial generator.)

Example Problem

Step-Up Transformer

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

- What is the voltage in the secondary circuit?
- The current in the secondary circuit is 2.00 A. What is the current in the primary circuit?
- What is the power in the primary circuit?



Sketch the Problem

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

Calculate Your Answer

Known:

$$\begin{aligned}N_p &= 200 \\N_s &= 3000 \\V_p &= 90.0 \text{ V} \\I_s &= 2.00 \text{ A}\end{aligned}$$

Unknown:

$$\begin{aligned}V_s &= ? \\I_p &= ? \\P_p &= ?\end{aligned}$$

Strategy:

- Voltage and turn ratios are equal.

Solve for V_s .

- Assuming that the transformer is perfectly efficient, the power in the primary and secondary circuits is equal.

- Use the power relation to solve for P_p .

Calculations:

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

$$V_s = \frac{N_s}{N_p} V_p = \frac{3000}{200}(90.0 \text{ V}) = 1.35 \text{ kV}$$

$$P_p = P_s$$

$$V_p I_p = V_s I_s$$

$$I_p = \frac{V_s}{V_p} I_s = \frac{1350 \text{ V}}{90.0 \text{ V}}(2.00 \text{ A}) = 30.0 \text{ A}$$

$$P_p = V_p I_p = (90.0 \text{ V})(30.0 \text{ A}) = 2.70 \text{ kW}$$

Check Your Answer

- Are the units correct? Check the units with algebra. Voltage: V; Current: A; and Power: W.
- Do the signs make sense? All numbers are positive.
- Is the magnitude realistic? A large step-up ratio of turns results in a large secondary voltage yet a smaller secondary current. Answers agree.

Practice Problems

For all problems, effective currents and voltages are indicated.

- 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.

- a. What voltage is across the secondary circuit?
 - b. The current in the secondary circuit is 36 A. What is the current in the primary circuit?
10. 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?
11. 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.
- a. What is the EMF in the secondary circuit?
 - b. The current in the secondary circuit is 0.50 A. What current is in the primary circuit?



FIGURE 25–13 Step-down transformers are used to reduce the high voltage in transmission lines to levels appropriate for consumers at the points of use.

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. The high voltage reduces 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 the one shown in **Figure 25–13**, provide appropriately low voltages for consumer use. Transformers in your appliances further adjust voltages to useable levels.

25.2 Section Review

1. You hang a coil of wire with its ends joined so it can swing easily. If you now plunge a magnet into the coil, the coil will swing. Which way will it swing with respect to the magnet and why?
2. If you unplugged a running vacuum cleaner from the 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?
3. Frequently, transformer windings that have only a few turns are made of very thick (low-resistance) wire, while those with many turns are made of thin wire. Why?
4. **Critical Thinking** Would permanent magnets make good transformer cores? Explain.

CHAPTER 25 REVIEW



Summary

Key Terms

25.1

- electromagnetic induction
- electromotive force
- electric generator

25.2

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

25.1 Creating Electric Current from Changing Magnetic Fields

- 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, v , perpendicular to the field.
- A generator and a motor are similar devices. A generator converts mechanical

energy to electrical energy; a motor converts electrical energy to mechanical energy.

25.2 Changing Magnetic Fields Induce EMF

- 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.
- 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.

Key Equations

25.1

$$EMF = BLv \quad I_{\text{eff}} = 0.707 I_{\text{max}} \quad V_{\text{eff}} = 0.707 V_{\text{max}}$$

25.2

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

Reviewing Concepts

Section 25.1

1. How are Oersted's and Faraday's results similar? How are they different?
2. You have a coil of wire and a bar magnet. Describe how you could use them to generate an electric current.
3. What does EMF stand for? Why is the name inaccurate?
4. What is the armature of an electric generator?
5. Why is iron used in an armature?
6. What is the difference between a generator and a motor?

7. List the major parts of an AC generator.
8. Why is the effective value of an AC current less than its maximum value?
9. 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.

Section 25.2

10. State Lenz's law.
11. What produces the back- EMF of an electric motor?



12. Why is there no spark when you close a switch, putting current through an inductor, but there is a spark when you open the switch?
13. 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?
14. Explain why the word *change* appears so often in this chapter.
15. 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?

Applying Concepts

16. Substitute units to show that the units of BLv are volts.
17. When a wire is moved through a magnetic field, resistance of the closed circuit affects
 - a. current only.
 - b. *EMF* only.
 - c. both.
 - d. neither.
18. As Logan slows his bike, what happens to the *EMF* produced by his bike's generator? Use the term *armature* in your explanation.
19. The direction of AC voltage changes 120 times each second. Does that mean that a device connected to an AC voltage alternately delivers and accepts energy?
20. A wire is moved horizontally between the poles of a magnet, as shown in **Figure 25–14**. What is the direction of the induced current?

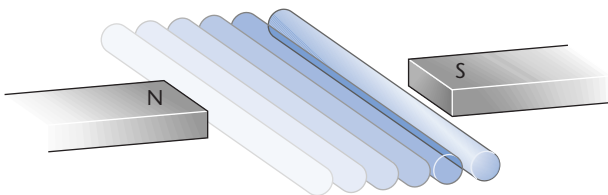


FIGURE 25–14

21. You make an electromagnet by winding wire around a large nail. 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.
22. A segment of a wire loop is moving downward through the poles of a magnet, as shown in **Figure 25–15**. What is the direction of the induced current?

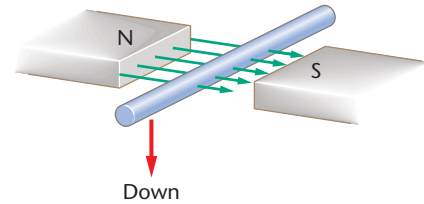


FIGURE 25–15

23. A transformer is connected to a battery through a switch. The secondary circuit contains a light-bulb. Which of the following statements best describes when the lamp will be lighted? Explain.
 - a. as long as the switch is closed
 - b. only the moment the switch is closed
 - c. only the moment the switch is opened
24. The direction of Earth's magnetic field in the northern hemisphere is downward and to the north. If an east-west wire moves from north to south, in which direction is the current?
25. You move a length of copper wire down through a magnetic field B , as shown in **Figure 25–15**.
 - 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?
26. A physics instructor drops a magnet through a copper pipe, as illustrated in **Figure 25–16**. The magnet falls very slowly, and the class concludes that there must be some force opposing gravity.

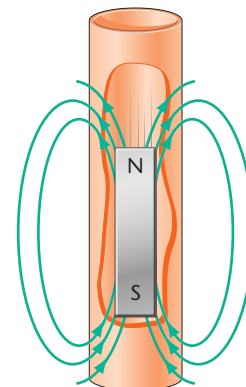


FIGURE 25–16

- a. What is the direction of the current induced in the pipe by the falling magnet if the S-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?
27. 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?

Problems

Section 25.1

28. 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?
29. 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?
30. A straight wire, 0.75 m long, moves upward through a horizontal 0.30-T magnetic field 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?
31. 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?
32. An AC generator develops a maximum EMF of 565 V. What effective EMF does the generator deliver to an external circuit?
33. 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 it deliver to the external circuit?
 - c. What is the effective power dissipated in the circuit?
34. 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?
35. 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?
36. 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- Ω resistance, what is the current?
37. You connect both ends of a copper wire, total resistance 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?
38. The direction of a 0.045-T magnetic field is 60° 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?
39. A generator at a dam can supply 375 MW (375×10^6 W) of electrical power. Assume that the turbine and generator are 85% 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, $U = mgh$. What is the change in U 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?

Section 25.2

40. 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 these voltages.
- a. 625 V b. 35 V c. 6.0 V
41. A step-up transformer has 80 turns on its primary coil. It has 1200 turns on its secondary coil. The primary circuit is supplied with an alternating current at 120 V.
- a. What voltage is across the secondary circuit?
 - b. The current in the secondary circuit is 2.0 A. What current is in the primary circuit?

- c. What is the power input and output of the transformer?
42. A laptop computer requires an effective voltage of 9.0 volts from the 120-V line.
- If the primary coil has 475 turns, how many does the secondary coil have?
 - A 125-mA current is in the computer. What current is in the primary circuit?
43. A hair dryer uses 10 A at 120 V. It is used with a transformer in England, where the line voltage is 240 V.
- What should be the ratio of the turns of the transformer?
 - What current will the hair dryer now draw?
44. A 150-W transformer has an input voltage of 9.0 V and an output current of 5.0 A.
- Is this a step-up or step-down transformer?
 - What is the ratio of V_{output} to V_{input} ?
45. 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?



Extra Practice For more practice solving problems, go to **Extra Practice Problems, Appendix B.**

Critical Thinking Problems

46. Suppose an “anti-Lenz’s law” existed that meant a force was exerted to increase the change in 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.
47. Real transformers are not 100% efficient. That is, the efficiency, in percent, is represented by $e = (100)P_s/P_p$. A step-down transformer that has an efficiency of 92.5% is used to obtain 28.0 V from the 125-V household voltage. The current in the secondary circuit is 25.0 A. What is the current in the primary circuit?
48. A transformer that supplies eight homes has an efficiency of 95%. All eight homes have electric ovens running that 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?

Going Further



Graphing Calculator Show that the average power in an AC circuit is half the peak power.

Figure 25–5 shows how the current produced by a generator varies in time. The equation that describes this variation is $I = I_{\text{max}}\sin(2\pi ft)$. In the U.S., $f = 60$ Hz. If a resistor is connected across a generator, then the voltage drop across the resistor will be given by $V = I_{\text{max}}R \sin(2\pi ft)$. The power dissipated by the resistor is $P = I_{\text{max}}^2 R \sin^2(2\pi ft)$. Suppose that $R = 10 \Omega$, $I_{\text{max}} = 1$ A.

- Plot the power as a function of time from $t = 0$ to $t = 1/60$ s (one complete cycle).
- Determine the energy transfer to the resistor. When the power is constant, the energy is the product of the power and the time interval. When the power varies, the energy can be calculated as the area under the curve of the graph of power versus time. There are different ways you can find this, depending on the tools you have. You could transfer the plot to a large piece of graph paper and count squares under the curve. Or, you could calculate the power every $1/1200$ s and multiply by the time interval ($1/1200$ s) to find the incremental energy transfer, then add up all the small increments of energy. Or, you might use a computer.
- The average power is given by the total energy transferred divided by the time interval. Find the average power from your result above and compare with the peak power, 10 W.

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