FOURTH EDITION

Electrical Transformers and Rotating Machines

STEPHEN L. HERMAN

ELECTRICAL TRANSFORMERS AND ROTATING MACHINES

FOURTH EDITION

Stephen L. Herman

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Preface

Transformers and Rotating Machines, Fourth Edition combines theory and practical applications for those desiring employment in the industrial electrical field. This text assumes the student has knowledge of basic electrical theory. The text begins with a study of magnetism and magnetic induction and progresses through single-phase isolation transformers, current transformers, and autotransformers. A unit on three-phase power refreshes the student's knowledge of basic three-phase connections and calculations before proceeding into three-phase transformers. All the basic types of three-phase transformers are covered, such as delta-wye, delta-delta, wye-delta, wye-wye, and open-delta. Special transformer connections such as the Scott, T, and zig-zag are also presented. Examples of adding single-phase loads to three-phase transformers are included.

Transformers and Rotating Machines also provides information on direct current generators and motors. The basic types of DC machines (series, shunt, and compound) are discussed. The text also provides information on brushless motors, printed circuit motors, and permanent magnet motors.

Alternating current machines covered in this text include alternators, three-phase motors, and single-phase motors. The operating characteristics of squirrel cage, consequent pole, wound rotor, and synchronous motors are explained. Diagrams and explanations provide students with thorough coverage of both wye and delta high- and low-voltage connections for three-phase motors.

Single-phase alternating-current motors include split phase, repulsion, universal, and shaded pole. The operating characteristics of each type of motor are discussed.

Transformers and Rotating Machines includes a set of hands-on laboratory experiments for single-phase transformers, three-phase transformers, three-phase motors, and single-phase motors. All the transformer experiments require the use of common equipment such as 0.5 kVA control transformers, 6–150 ohm resistors with a minimum power rating of 100 watts, 1–100 ohm resistor with minimum power rating of 144 watts, voltmeters, ohmmeters, and ammeters.

NEW FOR THE FOURTH EDITION

The units covering the installation of transformers and motors have been updated to reflect the changes in the 2014 *National Electric Code (NEC)*®.

The fourth edition also contains:

- Extended coverage of magnetic measurements.
- Additional explanation of exponential curves.
- Extended coverage of control transformers.
- Transformer nameplate information.
- Transformer sizing calculations.
- Extended coverage of transformer installation.
- Coverage of three-phase variable autotransformers.

SUPPLEMENTS

An Instructor Companion Site for this text includes the Instructor's Guide, unit presentations, unit testbanks, and an image gallery.

ACCESSING AN INSTRUCTOR COMPANION WEBSITE FROM SSO FRONT DOOR

1. Go to http://login.cengage.com and log in using the instructor e-mail address and password.
2. Enter author, title, or ISBN in the **Add a title to your bookshelf** search.
3. Click **Add to my bookshelf** to add instructor resources.
4. At the Product page, click the **Instructor Companion site** link.

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UNIT 1 | Magnetism

Objectives

After studying this unit, you should be able to:

- Discuss the properties of permanent magnets.
- Discuss the difference between the axis poles and the magnetic poles of the earth.
- Discuss the operation of electromagnets.
- Determine the polarity of an electromagnet when the direction of the current is known.
- Discuss the different systems used to measure magnetism.
- Define terms used to describe magnetism and magnetic quantities.

Magnetism is one of the most important phenomena in the study of electricity. It is the force used to produce most of the electrical power in the world. The force of magnetism has been known for over 2000 years. It was first discovered by the Greeks when they noticed that a certain type of stone was attracted to iron. This stone was first found in Magnesia in Asia Minor and was named magnetite. In the Dark Ages, the strange powers of the magnet were believed to be caused by evil spirits or the devil.

THE EARTH IS A MAGNET

The first compass was invented when it was noticed that a piece of magnetite, a type of stone that is attracted to iron, placed on a piece of wood floating in water always aligned itself north and south *(Figure 1-1)*. Because they are always able to align themselves north and south, natural magnets became known as "leading stones" or **lodestones**. The reason that the lodestone aligned itself north and south is because the earth itself contains magnetic poles. *Figure 1-2* illustrates the position of the true North and South poles, or the axis, of the earth and the position of the magnetic poles. Notice that what is considered as *magnetic* north is not located at the true North Pole of the earth. This is the reason that navigators must distinguish between true north and magnetic north. The angular difference between the two is known as the angle of

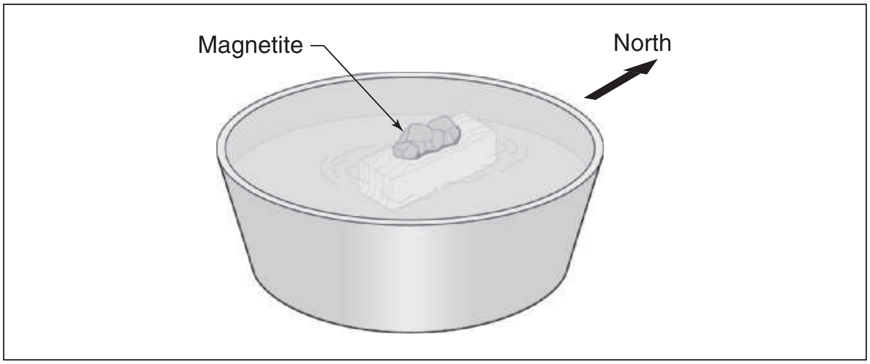


Figure 1-1 The first compass.

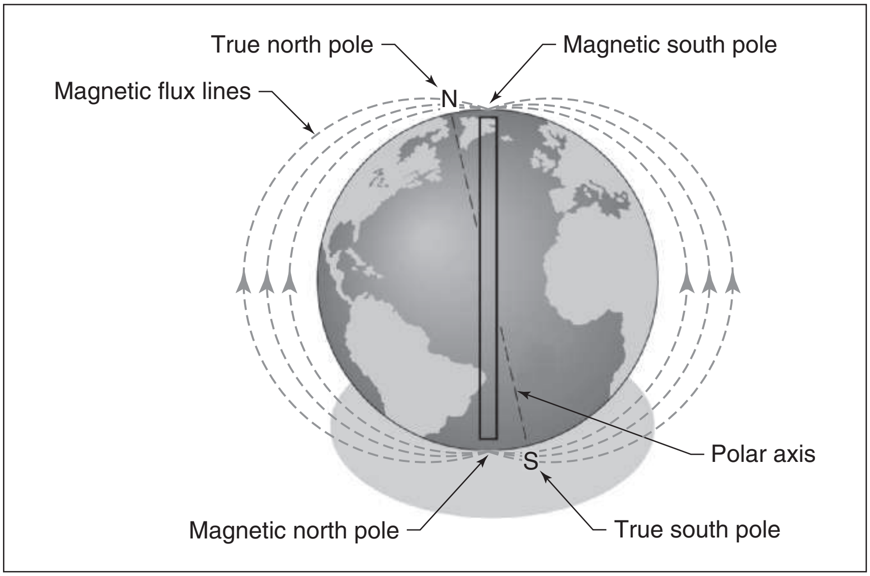


Figure 1-2 The earth is a magnet.

declination. Although the illustration shows the magnetic lines of force to be only on each side of the earth, the lines actually surround the entire earth like a magnetic shell.

Also notice that the magnetic north pole is located near the southern polar axis and the magnetic south pole is located near the northern polar axis. The reason that the geographic poles (axes) are called north and south is because the north pole of a compass needle points in the direction of the north *geographic* pole. Since unlike magnetic poles attract, the north magnetic pole of the compass needle is attracted to the south magnetic pole of the earth.

PERMANENT MAGNETS

Permanent magnets are magnets that do not require any power or force to maintain their field. They are an excellent example of one of the basic laws of magnetism, which states that **energy is required to create a magnetic field, but no energy is required to maintain a magnetic field**. Man-made permanent magnets are much stronger and can retain their magnetism longer than natural magnets.

THE ELECTRON THEORY OF MAGNETISM

There are actually only three substances that form natural magnets: iron, nickel, and cobalt. Why these materials form magnets has been the subject of complex scientific investigations, resulting in an explanation of magnetism based on **electron spin patterns**. It is believed that each electron spins on its axis as it orbits around the nucleus of the atom. This spinning motion causes each electron to become a tiny permanent magnet. Although all electrons spin, they do not all spin in the same direction. In most atoms, electrons that spin in opposite directions tend to form pairs *(Figure 1-3)*. Since the electron pairs spin in opposite directions, their magnetic effects cancel each other out as far as having any effect on distant objects. In a similar manner two horseshoe magnets connected together would be strongly attracted to each other, but would have little effect on surrounding objects *(Figure 1-4)*.

An atom of iron contains 26 electrons. Of these 26, 22 are paired and spin in opposite directions, canceling each other's magnetic effect. In the next-to-the-outermost shell, however, four electrons are not paired and spin in the same direction. These four electrons account for the magnetic properties of iron. At a temperature of 1420°F, or 771.1°C, the

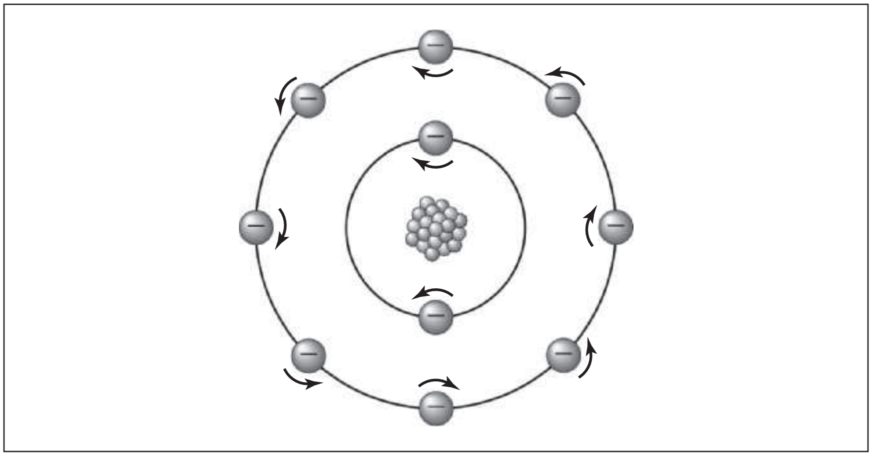


Figure 1-3 Electron pairs generally spin in opposite directions.

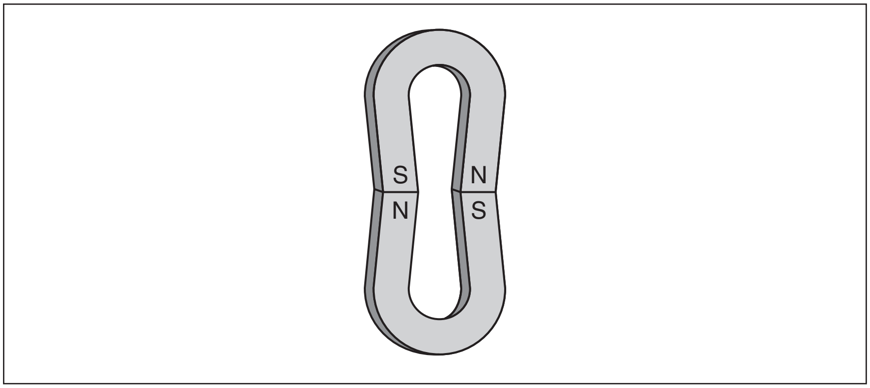


Figure 1-4 Two horseshoe magnets attract each other.

electron spin patterns rearrange themselves and iron loses its magnetic properties.

When the atoms of most materials combine to form molecules, they arrange themselves in a manner that produces a total of eight valence electrons. The electrons form a spin pattern that cancels the magnetic field of the material. When the atoms of iron, nickel, and cobalt combine, however, the magnetic field is not canceled. Their electrons combine so that they share valence electrons in such a way that their spin patterns are in the same direction, causing their magnetic fields to add instead of cancel. The additive effect forms regions in the molecular structure of the metal called **magnetic domains** or **magnetic molecules**. These magnetic domains act as small permanent magnets.

A piece of nonmagnetized metal has its molecules in a state of disarray as shown in *Figure 1-5*. When the metal is magnetized, its molecules align themselves in an orderly pattern as shown in *Figure 1-6*. In theory, each molecule of a magnetic material is itself a small magnet.

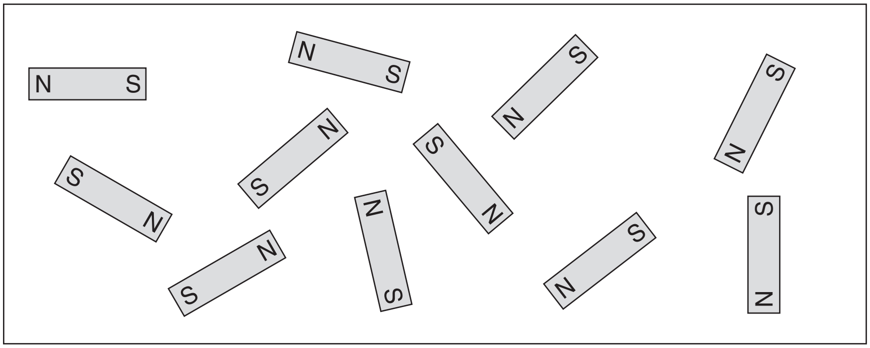


Figure 1-5 The molecules are disarrayed in a piece of nonmagnetized metal.

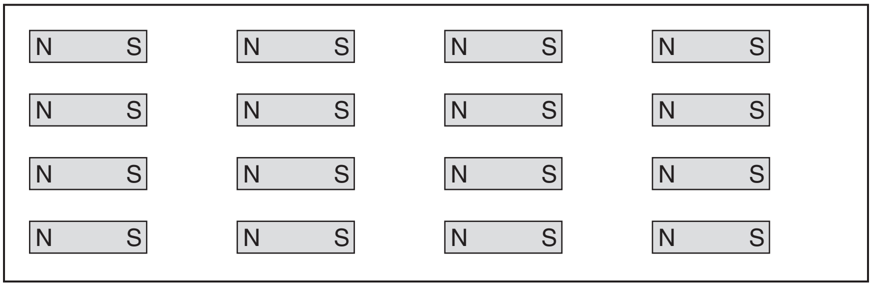


Figure 1-6 The molecules are aligned in an orderly fashion in a piece of magnetized metal.

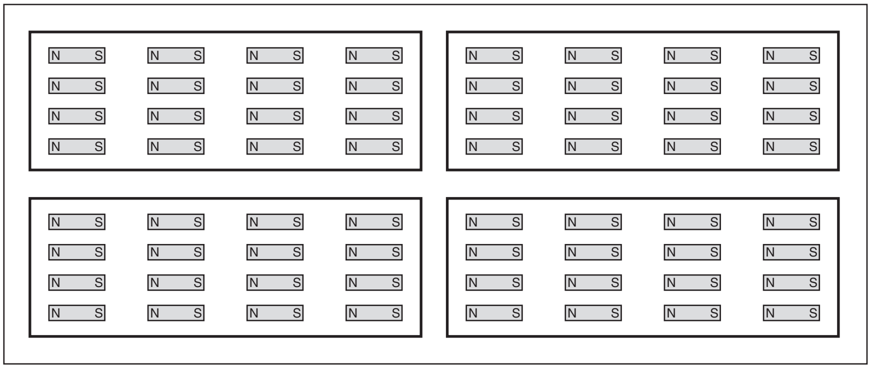


Figure 1-7 When a magnet is cut apart, each piece becomes a separate magnet.

If a permanent magnet were cut into pieces, each piece would be a separate magnet *(Figure 1-7)*.

MAGNETIC MATERIALS

Magnetic materials can be divided into three basic classifications, as follows:

> **Ferromagnetic** materials are metals that are easily magnetized. Examples of these materials are iron, nickel, cobalt, and manganese.
>
> **Paramagnetic** materials are metals that can be magnetized, but not as easily as ferromagnetic materials. Some examples of paramagnetic materials are platinum, titanium, and chromium.
>
> **Diamagnetic** materials are either metal or nonmetal materials that cannot be magnetized. The magnetic lines of force tend to go around them instead of through them. Some examples of these materials are copper, brass, and antimony.

Some of the best materials for the production of permanent magnets are alloys. One of the best permanent magnet materials is Alnico 5, which is made from a combination of aluminum, nickel, cobalt, copper, and iron. Another type of permanent magnet material is made from a combination of barium ferrite and strontium ferrite. Ferrites can have an advantage in some situations because they are insulators and not conductors. They have a resistance of approximately 1,000,000 Ω per centimeter. These two materials can be powdered. The powder is heated to the melting point and then rolled and heat-treated. This treatment changes the grain structure and magnetic properties of the material. The new type of material has a property more like stone than metal and is known as a ceramic magnet. Ceramic magnets can be powdered and mixed with rubber, plastic, or liquids. Ceramic magnetic materials mixed with liquids can be used to make magnetic ink, which is used on checks. Another frequently used magnetic material is iron oxide, which is used to make magnetic recording tape and computer diskettes.

MAGNETIC LINES OF FORCE

flux

Magnetic lines of force are called **flux**. The symbol used to represent flux is the Greek letter phi (Φ). Flux lines can be seen by placing a piece of cardboard on a magnet and sprinkling iron filings on the cardboard. The filings will align themselves in a pattern similar to the one shown in *Figure 1-8*. The pattern produced by the iron filings forms a two-dimensional figure, but the flux lines actually surround the entire magnet *(Figure 1-9)*. Magnetic **lines of flux** repel each other and never cross. Although magnetic lines of flux do not flow, it is assumed they are in a direction north to south.

A basic law of magnetism states that **unlike poles attract and like poles repel**. *Figure 1-10* illustrates what happens when a piece of cardboard is placed over two magnets with their north and south poles facing each other and iron filings are sprinkled on the cardboard. The filings form a pattern showing that the magnetic lines of flux are attracted to each other. *Figure 1-11* illustrates the pattern formed by the iron filings when the

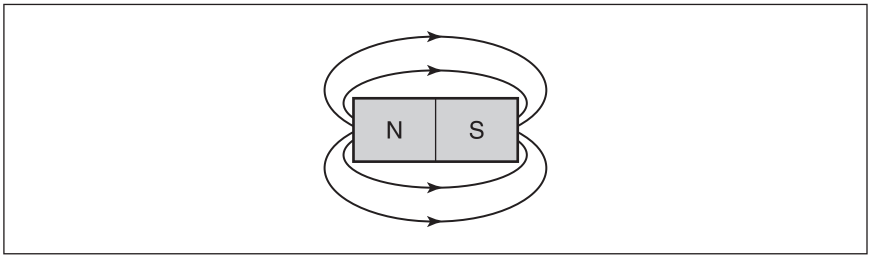


Figure 1-8 Magnetic lines of force are called flux lines.

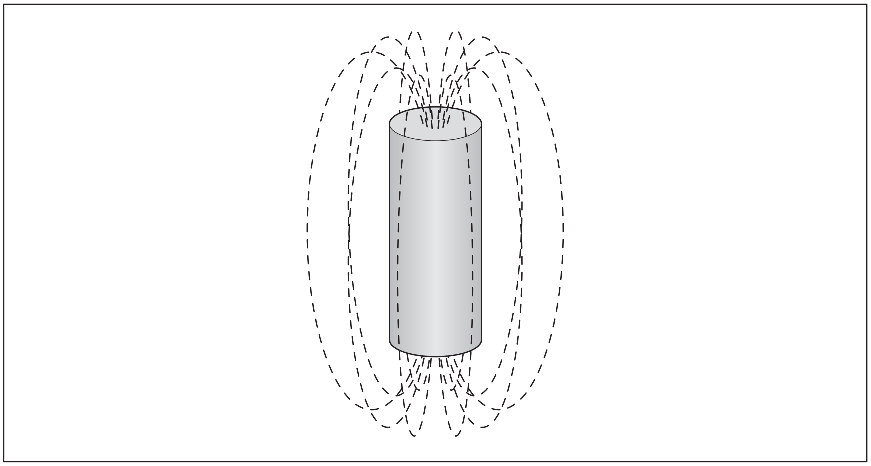


Figure 1-9 Magnetic lines of force surrounding the entire magnet.

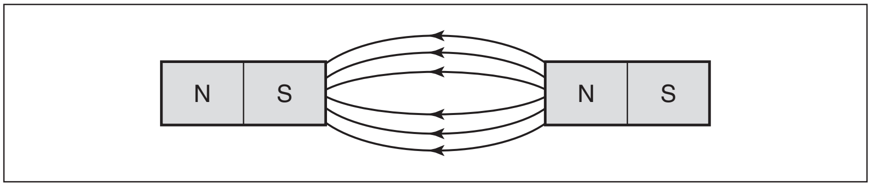


Figure 1-10 Opposite magnetic poles attract each other.

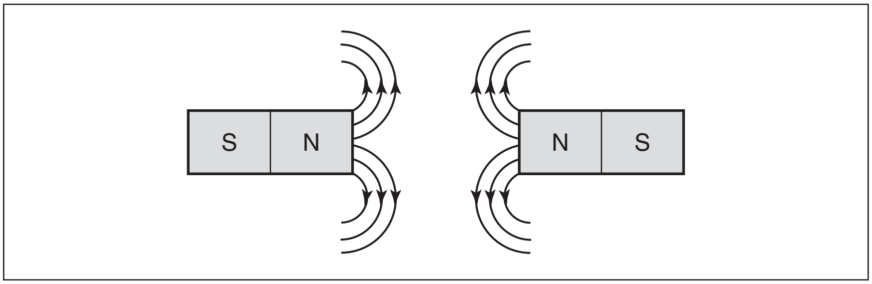


Figure 1-11 Like magnetic poles repel each other.

cardboard is placed over two magnets with like poles facing each other. The filings show that the magnetic lines of flux repel each other.

If the opposite poles of two magnets are brought close to each other, they will be attracted to each other as shown in *Figure 1-12*. If like poles of the two magnets are brought together, they will repel each other.

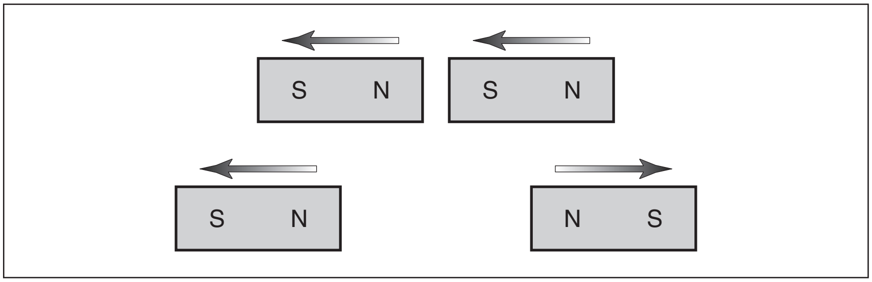


Figure 1-12 Opposite poles of a magnet attract, and like poles repel.

ELECTROMAGNETICS

A basic law of physics states that **whenever an electric current flows through a conductor, a magnetic field is formed around the conductor. Electromagnets** depend on electric current flow to produce a magnetic field. They are generally designed to produce a magnetic field only as long as the current is flowing; they do not retain their magnetism when current flow stops. Electromagnets operate on the principle that current flowing through a conductor produces a magnetic field around the conductor *(Figure 1-13)*. If the conductor is wound into a coil as shown in *Figure 1-14*, the magnetic lines of flux add to produce a stronger magnetic field. A coil with ten turns of wire will produce a magnetic field that is ten times as strong as the magnetic field around a single conductor.

Another factor that affects the strength of an electromagnetic field is the amount of current flowing through the wire. An increase in current flow will cause an increase in magnetic field strength. The two factors that determine the number of flux lines produced by an electromagnet are the number of turns of wire and the amount of current flow through the wire. The strength of an electromagnet is proportional to its **ampere-turns**. Ampere-turns are determined by multiplying the number of turns of wire by the current flow.

ampere-turns

Core Material

Coils can be wound around any type of material to form an electromagnet. The base material is called the core material. When a coil is wound around a nonmagnetic material such as wood or plastic, it is known as an *air-core* magnet. When a coil is wound around a magnetic material such as iron or soft steel, it is known as an *iron-core* magnet. The addition of magnetic material to the center of the coil can greatly increase the strength of the magnet. If the core material causes the magnetic field to become fifty times stronger, the core material has a permeability of 50 *(Figure 1-15)*. **Permeability** is a measure of a material's willingness to become magnetized. The number of flux

permeability

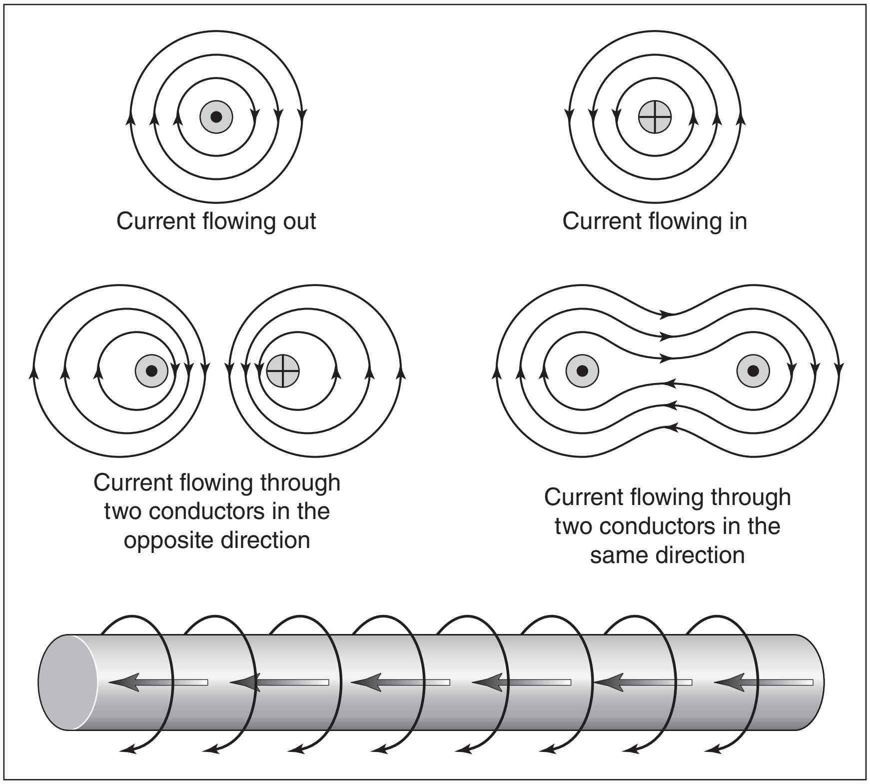


Figure 1-13 Current flowing through a conductor produces a magnetic field around the conductor.

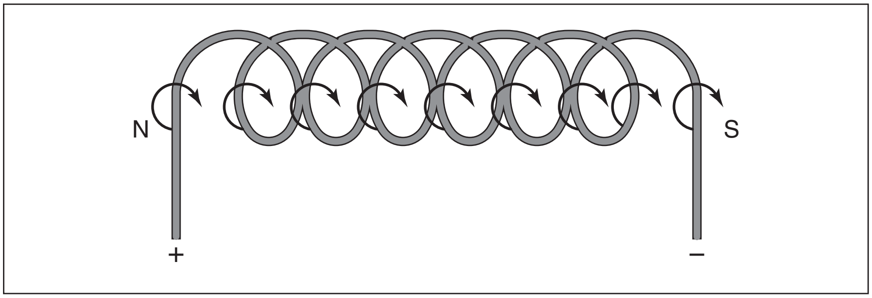


Figure 1-14 Winding the wire into a coil increases the strength of the magnetic field.

lines produced is proportional to the ampere-turns. The magnetic core material provides an easy path for the flow of magnetic lines in much the same way a conductor provides an easy path for the flow of electrons. This increased permeability permits the flux lines to be concentrated in

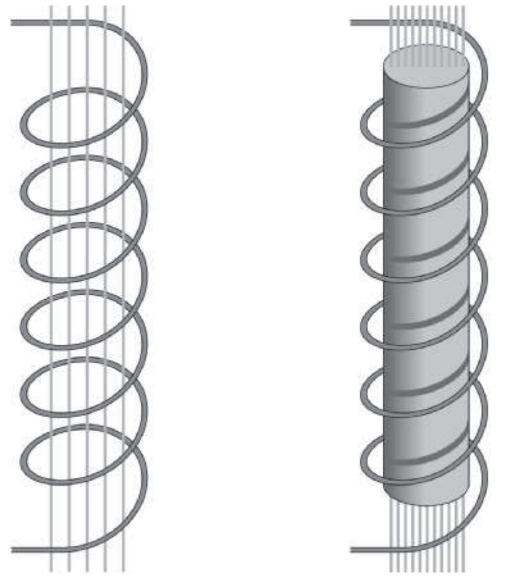


Figure 1-15 An iron core increases the number of flux lines per square inch.

a smaller area, which increases the number of flux lines per square inch or per square centimeter. In a similar manner, a person using a garden hose with an adjustable nozzle attached can adjust the nozzle to spray the water in a fine mist that covers a large area or in a concentrated stream that covers a small area.

reluctance

Another common magnetic measurement is reluctance. **Reluctance** is resistance to magnetism. A material such as soft iron or steel has a high permeability and low reluctance because it is easily magnetized. A material such as copper has a low permeability and high reluctance.

saturation

If the current flow in an electromagnet is continually increased, the magnet will eventually reach a point at which its strength will increase only slightly with an increase in current. When this condition occurs, the magnetic material is at a point of saturation. **Saturation** occurs when all the molecules of the magnetic material are lined up. Saturation is similar to pouring 5 gallons of water into a 5-gallon bucket. Once the bucket is full, it simply cannot hold any more water. If it became necessary to construct a stronger magnet, a larger piece of core material would be required.

residual magnetism

When the current flow through the coil of a magnet is stopped, there may be some magnetism left in the core material. The amount of magnetism left in a material after the magnetizing force has stopped is called **residual magnetism**. If the residual magnetism of a piece of core material is hard to remove, the material has a high coercive force. **Coercive force** is a measure of a material's ability to retain magnetism. A high coercive force is desirable in materials that are intended to be used as permanent magnets. A low coercive force is generally desirable for materials intended to be used as electromagnets. Coercive force is measured by determining the amount of current flow through the coil in the direction opposite to that required to remove the residual magnetism. Another term that is used to describe a material's ability to retain magnetism is **retentivity**.

retentivity

MAGNETIC MEASUREMENT

The terms used to measure the strength of a magnetic field are determined by the system that is being used. There are three different systems used to measure magnetism: the English system, the CGS system, and the MKS system.

The English System

In the English system of measure often called the Customary system of units, magnetic strength is measured in a term called flux density. **Flux density** is measured in lines per square inch. The Greek letter phi (Φ) is used to measure flux. The letter B is used to represent flux density. The following formula is used to determine flux density:

flux density

$$B\ (\text{flux density}) = \frac{\Phi\ (\text{flux lines})}{A\ (\text{area})}$$

In the English system, the term used to describe the total force producing a magnetic field, or flux, is **magnetomotive force (mmf)**. Magnetomotive force can be computed using the formula:

$$\text{mmf} = \Phi \times \text{rel (reluctance)}$$

The following formula can be used to determine the strength of the magnet.

$$\text{Pull (in pounds)} = \frac{B \times A}{72{,}000{,}000}$$

where B = flux density in lines per square inch
A = area of the magnet

METRIC UNITS OF MAGNETIC MEASUREMENT

There are two different metric system of magnetic measurement, the CGS and the MKS. The CGS system uses the metric unit Centimeter for length, Gram for mass, and Second for time. The MKS system uses the metric unit Meter for length, Kilogram for mass, and Second for time. The MKS system has become known as the SI (System International) system and has all but replaced both the English and CGS systems.

THE CGS SYSTEM

maxwell

gauss

gilbert

In the CGS system, one magnetic line of force is known as a **maxwell**. A maxwell is defined as the amount of magnetism induced through one square centimeter by a perpendicular magnetic field of 1 gauss. A **gauss** represents a magnetic force of one maxwell per square centimeter, or is equal to one ten thousandth of a tesla. In the English system, magnetomotive force (mmf) is measured in ampere-turns. In the CGS system, **gilberts** are used to represent the same measurement. Because the difference between these two systems of measurement is that one uses English units of measure and other uses metric units of measure, a conversion factor can be used to convert one set of units to the other.

$$1 \text{ gilbert} = 0.7955 \text{ ampere-turn}$$

$$1 \text{ ampere-turn} = 1.257 \text{ gilberts}$$

In the CGS system, the *Dyne* is the unit of force. The dyne is a very weak amount of force. One dyne is equal to 1/27,800 of an ounce, or it requires 27,800 dynes to equal a force of 1 ounce. The standard unit of magnetic measurement is the *Unit Magnetic Pole*. In *Figure 1-16*, two magnets are placed in a vacuum and separated by a distance of 1 cm. When these two magnets repel each other with a force of 1 dyne, they are considered to be a unit magnetic pole. Magnetic force can be determined using the formula

$$\textit{Force (in dynes)} = \frac{M_1 \times M_2}{D}$$

where M_1 = strength of first magnet in unit magnetic poles

M_2 = strength second magnet in unit magnetic poles

D = distance between the poles in centimeters

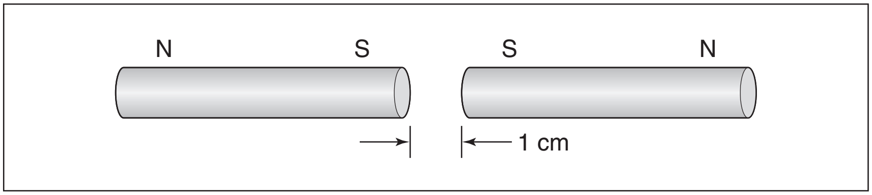


Figure 1-16 A unit magnetic pole produces a force of 1 dyne.

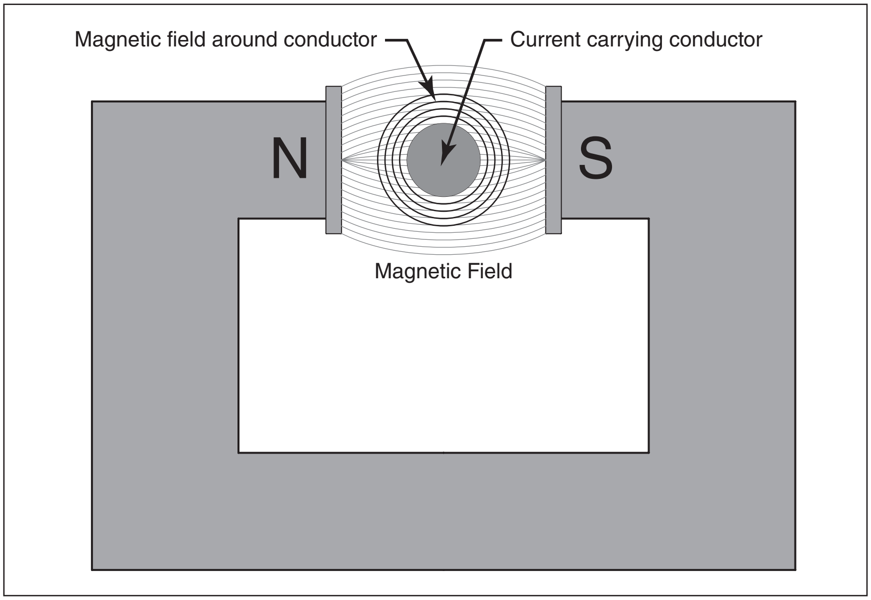


Figure 1-17 The intensity of a magnetic field can be determined by placing a current carrying conductor in the field.

THE MKS OR SI SYSTEM

In the MKS system, the *tesla* is the unit of magnetic field intensity. The intensity of a magnetic field can be determined by placing a current carrying conductor in a magnetic field *(Figure 1-17)*. Current flowing through the conductor produces a magnetic field around the conductor, causing a force to be produced against the conductor by the stationary magnetic field. The amount of force produced is determined by the strength of the stationary magnetic field, the amount of current flow through the conductor, and the length of the conductor. A magnetic field has the strength of 1 tesla when a current carrying conductor one meter in length having a current flow of one ampere exerts a force of 1 newton. One newton is the amount of force necessary to accelerate a mass of one kilogram at a rate of one meter per second per second. One tesla is equivalent to a flux density of one weber per square meter. One weber is equal to 100,000,000 lines of magnetic flux. One tesla is equal to 10,000 gauss. The Earth's magnetic flux density at its surface is about 50 microteslas (µT). Conversion factors for magnetic units are shown in *Table 1-1*.

MAGNETIC POLARITY

The polarity of an electromagnet can be determined using the **left-hand rule**. When the fingers of the left hand are placed around the windings in the direction of electron current flow, the thumb will point

1 gauss	=	6.4516 lines/sq. in.
1 gauss	=	0.0001 tesla
1 tesla	=	10,000 gauss
1 tesla	=	64,516 lines/sq. in.
1 tesla	=	1 weber/sq. meter
1 weber	=	100,000,000 lines of flux
1 line/sq. in.	=	0.155 gauss
1 line/sq. in.	=	0.0000155 tesla
1 gilbert	=	0.7959949 ampere turns
1 ampere turn	=	1.256637 gilberts

Table 1-1 Conversion factors for magnetic units of measure.

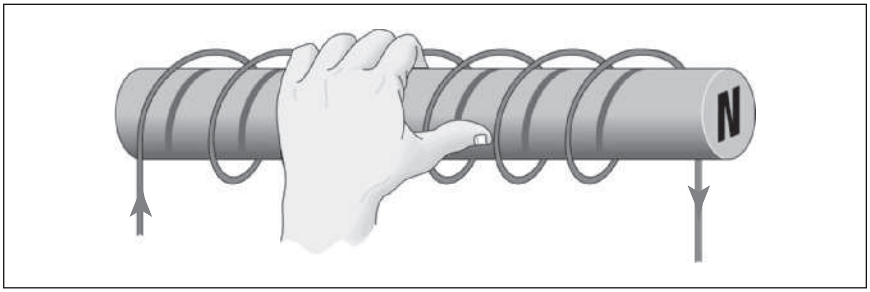


Figure 1-18 The "left-hand rule" can be used to determine the polarity of an electromagnet.

to the north magnetic pole *(Figure 1-18)*. If the direction of current flow is reversed, the polarity of the magnetic field will reverse also.

DEMAGNETIZING

When an object is to be **demagnetized**, its molecules must be disarranged as they are in a nonmagnetized material. This can be done by placing the object in the field of a strong electromagnet connected to an alternating current (AC) line. Since the magnet is connected to AC current, the polarity of the magnetic field reverses each time the current changes direction. The molecules of the object to be demagnetized are, therefore, aligned first in one direction and then in the other. If the object is pulled away from the AC magnetic field, the effect of the field becomes weaker as the object is moved farther away *(Figure 1-19)*. The

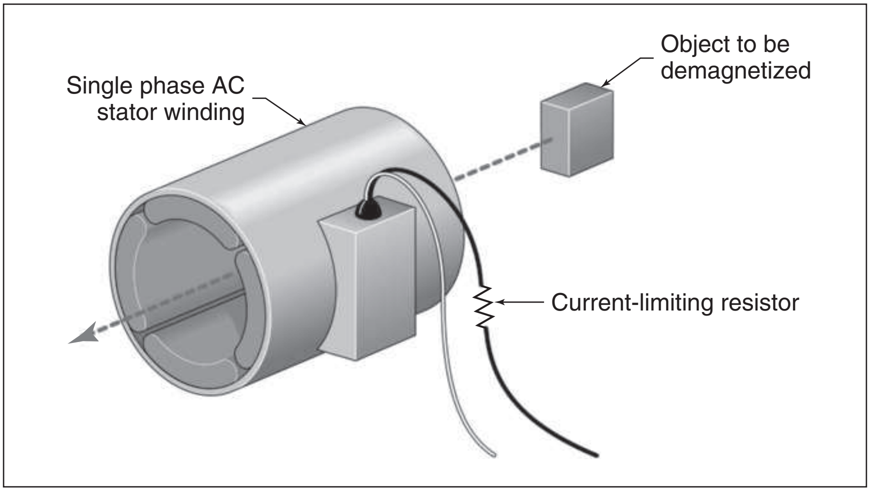


Figure 1-19 Demagnetizing an object.

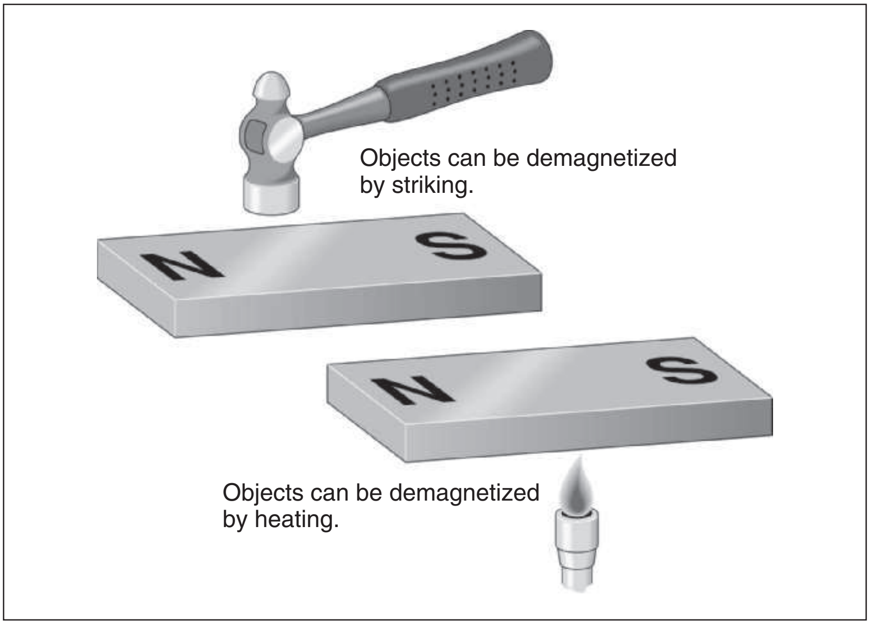


Figure 1-20 Other methods for demagnetizing objects.

weakening of the magnetic field causes the molecules of the object to be left in a state of disarray. The ease or difficulty with which an object can be demagnetized depends on the strength of the AC magnetic field and the coercive force of the object.

An object can be demagnetized in two other ways *(Figure 1-20)*. If a magnetized object is struck, the vibration will often cause the molecules to rearrange themselves in a disordered fashion. It may be necessary to strike the object several times. Heating also will demagnetize an object. When the temperature becomes high enough, the molecules will rearrange themselves in a disordered fashion.

MAGNETIC DEVICES

A list of devices that operate on magnetism would be very long indeed. Some of the more common devices are electromagnets, measuring instruments, inductors, transformers, and motors.

The Speaker

The speaker is a common device that operates on the principle of magnetism *(Figure 1-21)*. The speaker produces sound by moving a cone; the movement causes a displacement of air. The tone is determined by how fast the cone vibrates. Low or bass sounds are produced by vibrations in the range of 20 cycles per second. High sounds are produced when the speaker vibrates in the range of 20,000 cycles per second.

The speaker uses two separate magnets. One is a permanent magnet, and the other is an electromagnet. The permanent magnet is held stationary, and the electromagnet is attached to the speaker cone. When current flows through the coil of the electromagnet, a magnetic field is produced. The polarity of the field is determined by the direction of current flow. When the electromagnet has a north polarity, it is repelled away from the permanent magnet, causing the speaker cone to move outward and displace air. When the current flow reverses through the coil, the electromagnet has a south polarity and is attracted to the

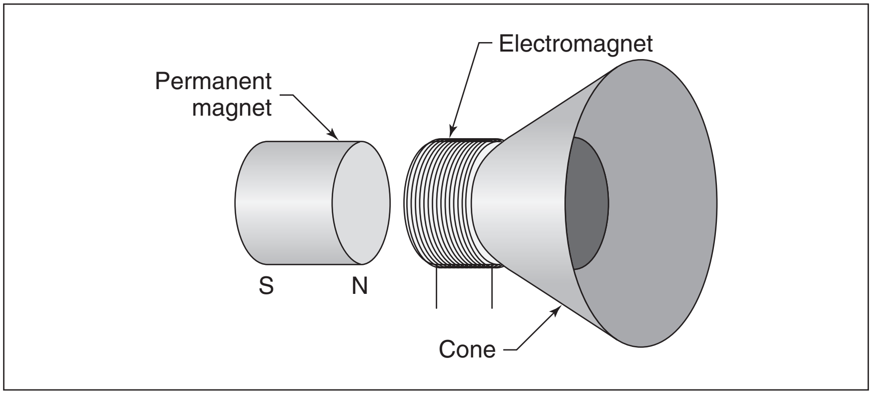


Figure 1-21 A speaker uses both an electromagnet and a permanent magnet.

permanent magnet. The speaker cone then moves inward and again displaces air. The number of times per second that the current through the coil reverses determines the tone of the speaker.

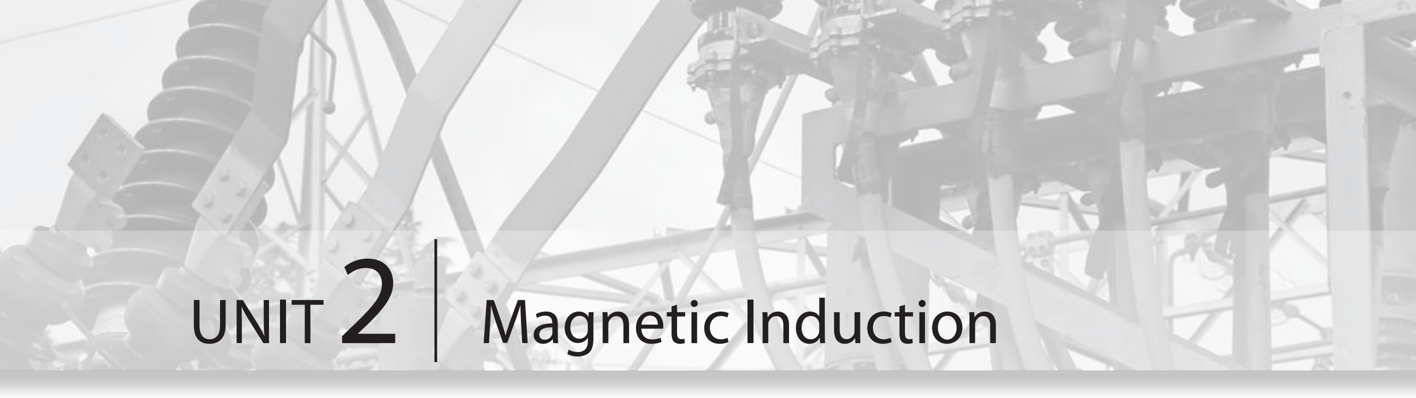
Summary

1. Early natural magnets were known as lodestones.
2. The earth has a north and a south magnetic pole.
3. The magnetic poles of the earth and the axis poles are not the same.
4. Like poles of a magnet repel each other, and unlike poles attract each other.
5. Some materials have the ability to become better magnets than others.
6. Three basic types of magnetic material are:
   A. Ferromagnetic
   B. Paramagnetic
   C. Diamagnetic
7. When current flows through a wire, a magnetic field is created around the wire.
8. The direction of current flow through the wire determines the polarity of the magnetic field.
9. The strength of an electromagnet is determined by the ampere-turns.
10. The type of core material used in an electromagnet can increase its strength.
11. Three different systems are used to measure magnetic values:
    A. The English system
    B. The CGS system
    C. The MKS system
12. An object can be demagnetized by placing it in an AC magnetic field and pulling it away, by striking, and by heating.

Review Questions

1. Is the north magnetic pole of the earth a north polarity or a south polarity?
2. What were early natural magnets known as?
3. The south pole of one magnet is brought close to the south pole of another magnet. Will the magnets repel or attract each other?

4. How can the polarity of an electromagnet be determined if the direction of current flow is known?
5. Define the following terms:
   Flux density
   Permeability
   Reluctance
   Saturation
   Coercive force
   Residual magnetism
6. A force of 1 ounce is equal to how many dynes?



UNIT 2 | Magnetic Induction

Objectives

After studying this unit, you should be able to:

- Discuss magnetic induction.
- List factors that determine the amount and polarity of an induced voltage.
- Discuss Lenz's law.
- Discuss an exponential curve.
- List devices used to help prevent inductive voltage spikes.

Magnetic induction is one of the most important concepts in the electrical field. It is the basic operating principle underlying alternators, transformers, and most alternating-current motors. It is imperative that anyone desiring to work in the electrical field have an understanding of the principles involved.

MAGNETIC INDUCTION

In Unit 1, it was stated that one of the basic laws of electricity is that whenever current flows through a conductor, a magnetic field is created around the conductor *(Figure 2-1)*. The direction of the current flow determines the polarity of the magnetic field, and the amount of current determines the strength of the magnetic field.

That basic law in reverse is the principle of **magnetic induction**, which states that **whenever a conductor cuts through magnetic lines of flux, a voltage is induced into the conductor**. The conductor in *Figure 2-2* is connected to a zero-center microammeter, creating a complete circuit. When the conductor is moved downward through the magnetic lines of flux, the induced voltage will cause electrons to flow in the direction indicated by the arrows. This flow of electrons causes the pointer of the meter to be deflected from the center-zero position.

If the conductor is moved upward, the polarity of induced voltage will be reversed and the current will flow in the opposite direction *(Figure 2-3)*. The pointer will be deflected in the opposite direction.

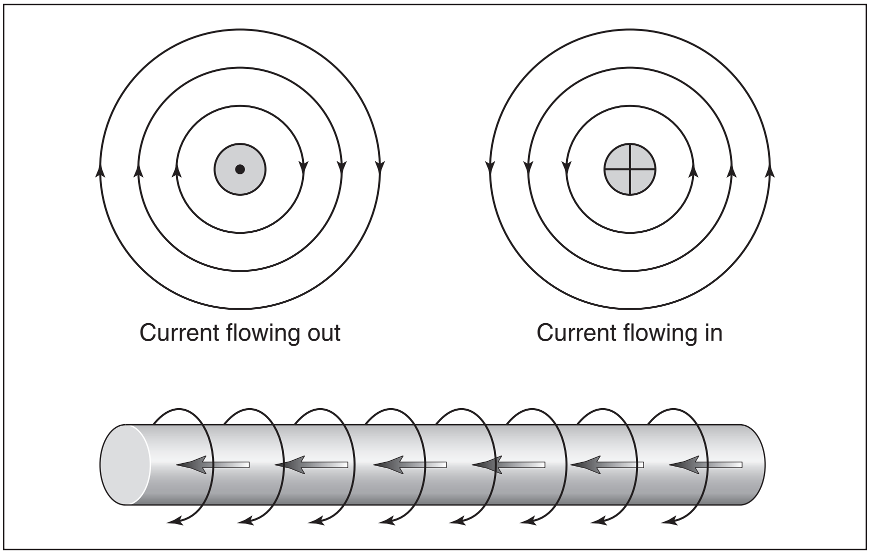


Figure 2-1 Current flowing through a conductor produces a magnetic field around the conductor.

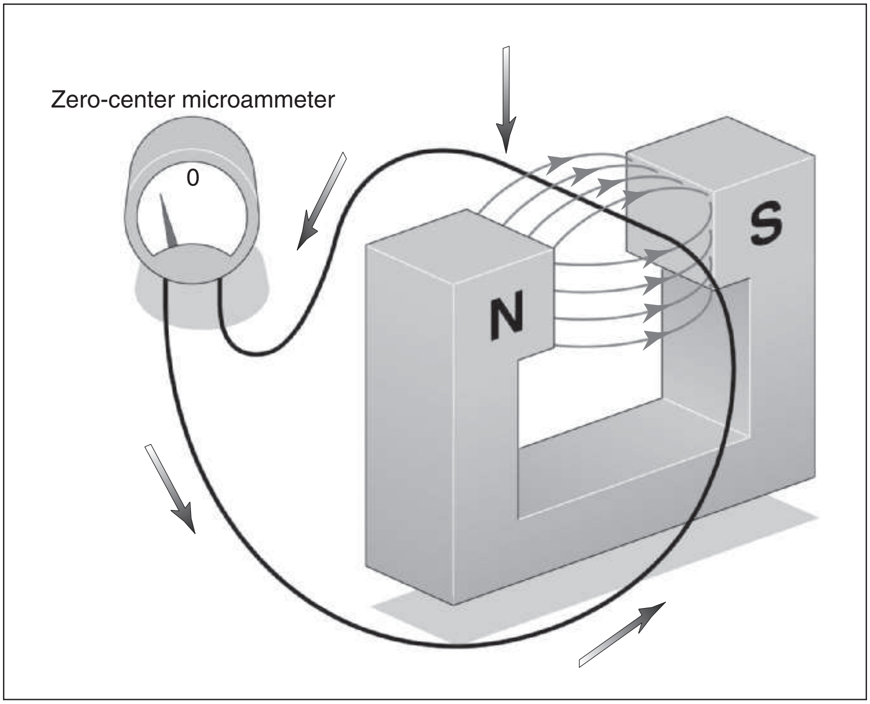


Figure 2-2 A voltage is induced when a conductor cuts magnetic lines of flux.

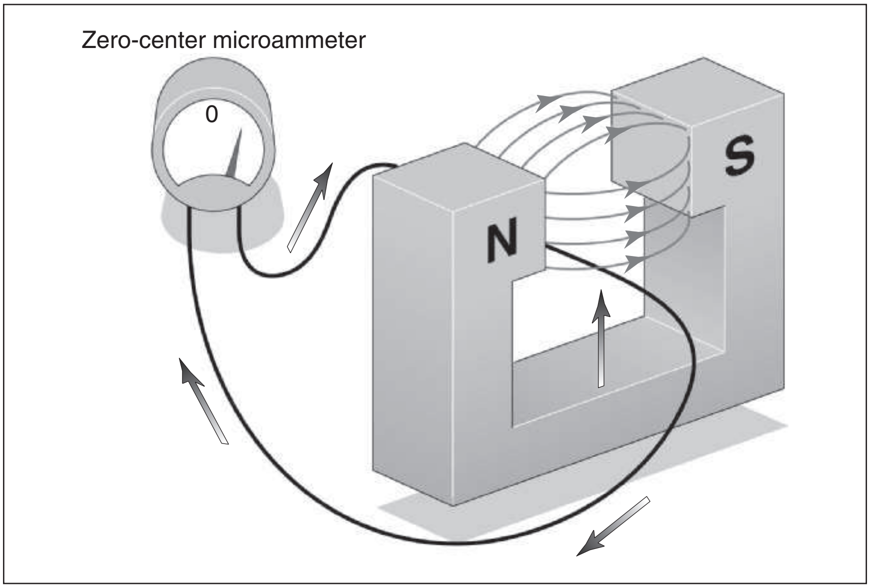


Figure 2-3 Reversing the direction of movement reverses the polarity of the voltage.

The polarity of the induced voltage can also be changed by reversing the polarity of the magnetic field *(Figure 2-4)*. In this example, the conductor is again moved downward through the lines of flux, but the

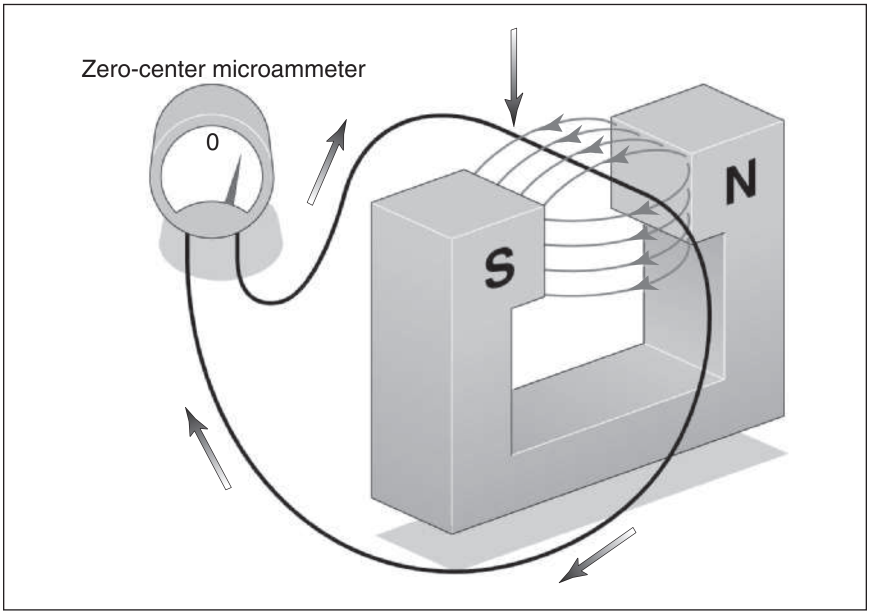


Figure 2-4 Reversing the polarity of the magnetic field reverses the polarity of the voltage.

polarity of the magnetic field has been reversed. Therefore, the polarity of the induced voltage will be the opposite of that in *Figure 2-2*, and the pointer of the meter will be deflected in the opposite direction. It can be concluded that **the polarity of the induced voltage is determined by the polarity of the magnetic field in relation to the direction of movement**.

MOVING MAGNETIC FIELDS

The important factors concerning magnetic induction are a conductor, a magnetic field, and movement. In practice, it is often desirable to move the magnet instead of the conductor. Most alternating current generators or alternators operate on this principle. In *Figure 2-5*, a coil of wire is held stationary while a magnet is moved through the coil. As the magnet is moved, the lines of flux cut through the windings of the coil and induce a voltage into them.

DETERMINING THE AMOUNT OF INDUCED VOLTAGE

Three factors determine the amount of voltage that will be induced in a conductor:

1. **the number of turns of wire, or length of conductor.**
2. **the strength of the magnetic field** (flux density), and
3. **the speed of the cutting action**.

In order to induce 1 V in a conductor, the conductor must cut 100,000,000 lines of magnetic flux in 1 s. In magnetic measurement,

weber (Wb)

100,000,000 lines of flux are equal to one **weber (Wb)**. Therefore, if a conductor cuts magnetic lines of flux at a rate of 1 Wb/s, a voltage of 1 V

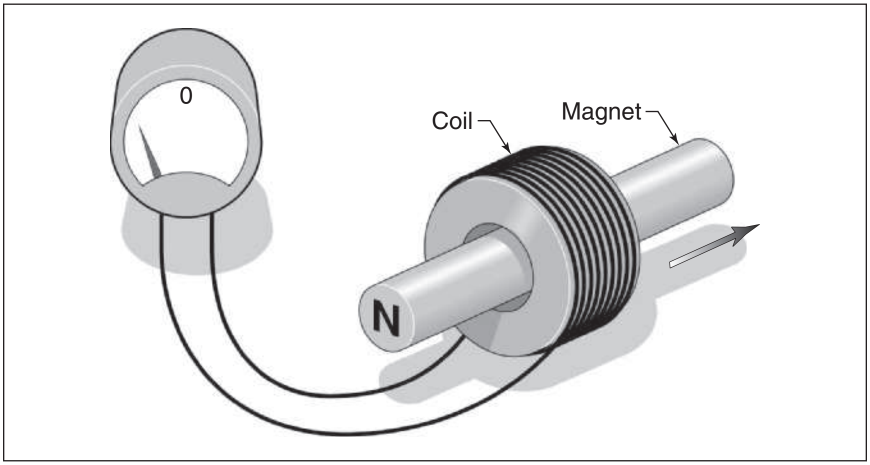


Figure 2-5 Voltage is induced by a moving magnetic field.

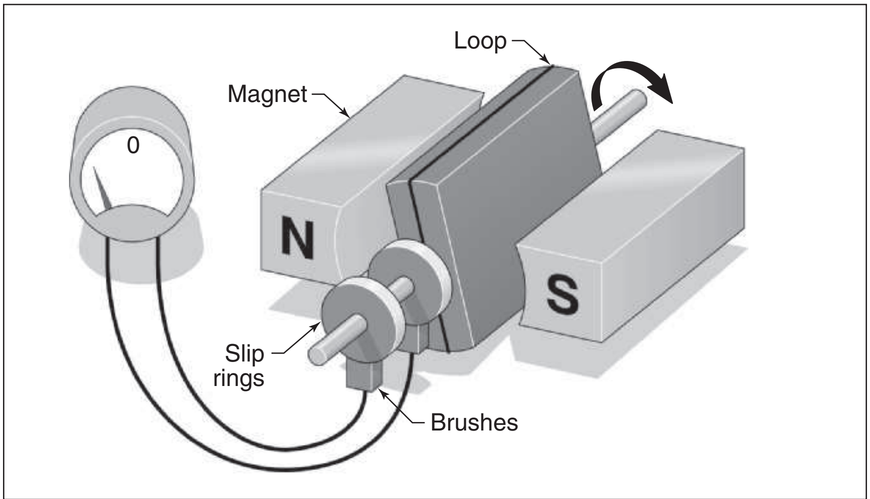


Figure 2-6 A single-loop generator.

will be induced. A simple one-loop generator is shown in *Figure 2-6*. The loop is attached to a rod that is free to rotate. This assembly is suspended between the poles of two stationary magnets. If the loop is turned, the conductor cuts through magnetic lines of flux and a voltage is induced into the conductor.

If the speed of rotation is increased, the conductor cuts more lines of flux per second, and the amount of induced voltage increases. If the speed of rotation remains constant and the strength of the magnetic field is increased, there will be more lines of flux per square inch. When there are more lines of flux, the number of lines cut per second increases and the induced voltage increases. If more turns of wire are added to the loop *(Figure 2-7)*, more flux lines are cut per second and the amount of induced voltage increases again. Adding more turns has the effect of connecting single conductors in series, causing a further increase of induced voltage.

LENZ'S LAW

When a voltage is induced in a coil and there is a complete circuit, current will flow through the coil *(Figure 2-8)*. When current flows through the coil, a magnetic field is created around the coil. This magnetic field develops a polarity opposite that of the moving magnet. The magnetic field developed by the induced current acts to attract the moving magnet and pull it back inside the coil.

If the direction of motion is reversed, the polarity of the induced current is reversed, and the magnetic field created by the induced current again opposes the motion of the magnet. This principle was first noticed

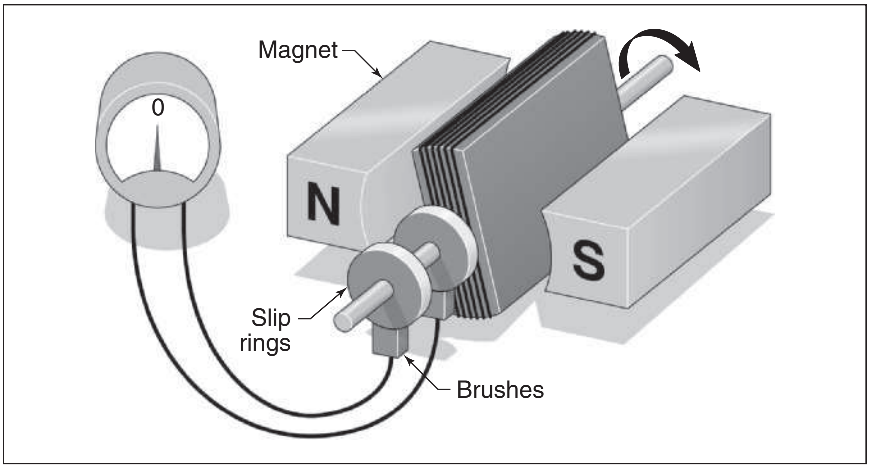


Figure 2-7 Increasing the number of turns increases the induced voltage.

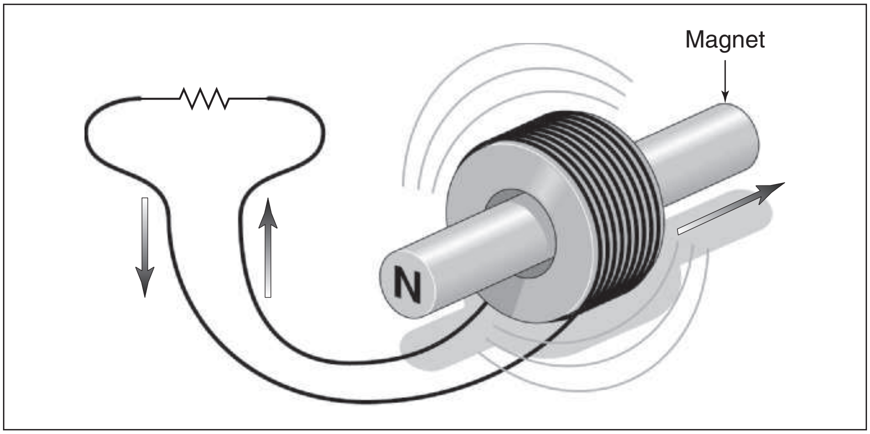


Figure 2-8 An induced current produces a magnetic field around the coil.

by Heinrich Lenz many years ago and is summarized in **Lenz's law**, which states that **an induced voltage or current opposes the motion that causes it**. From this basic principle, other laws concerning inductors have been developed. One is that **inductors always oppose a change of current**. The coil in *Figure 2-9*, for example, has no induced voltage and therefore no induced current. If the magnet is moved toward the coil, however, magnetic lines of flux will begin to cut the conductors of the coil, and a current will be induced in the coil. The induced current causes magnetic lines of flux to expand outward around the coil *(Figure 2-10)*. As this expanding magnetic field cuts through the conductors of the coil,

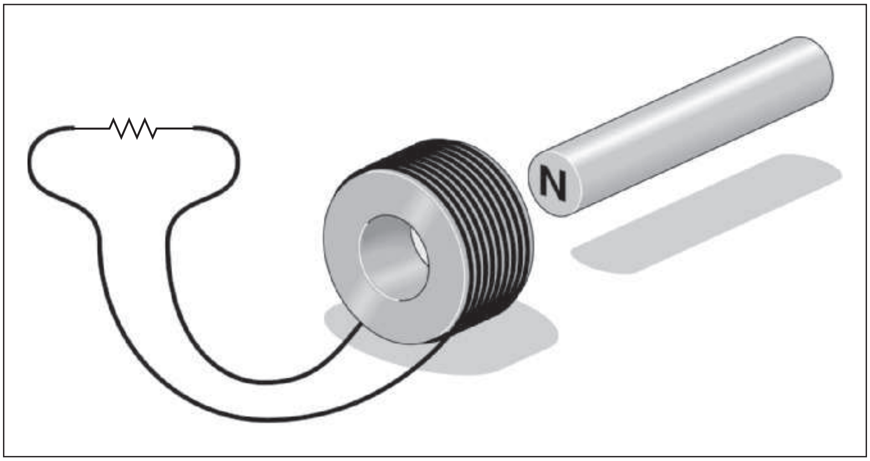


Figure 2-9 There is no current flow through the coils.

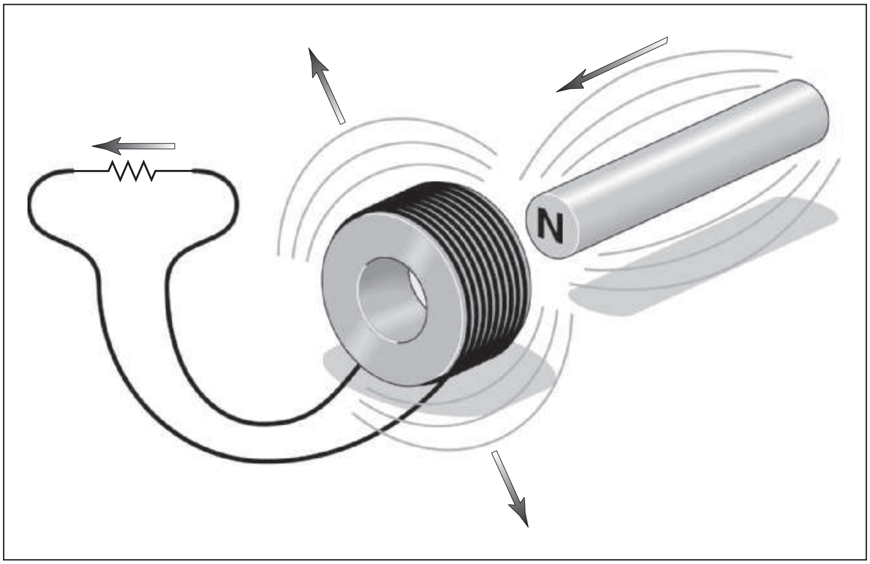


Figure 2-10 Induced current produces a magnetic field around the coil.

a voltage is induced in the coil. The polarity of the voltage is such that it opposes the induced current caused by the moving magnet.

If the magnet is moved away, the magnetic field around the coil will collapse and induce a voltage in the coil *(Figure 2-11)*. Since the direction of movement of the collapsing field has been reversed, the induced voltage will be opposite in polarity, forcing the current to flow in the same direction.

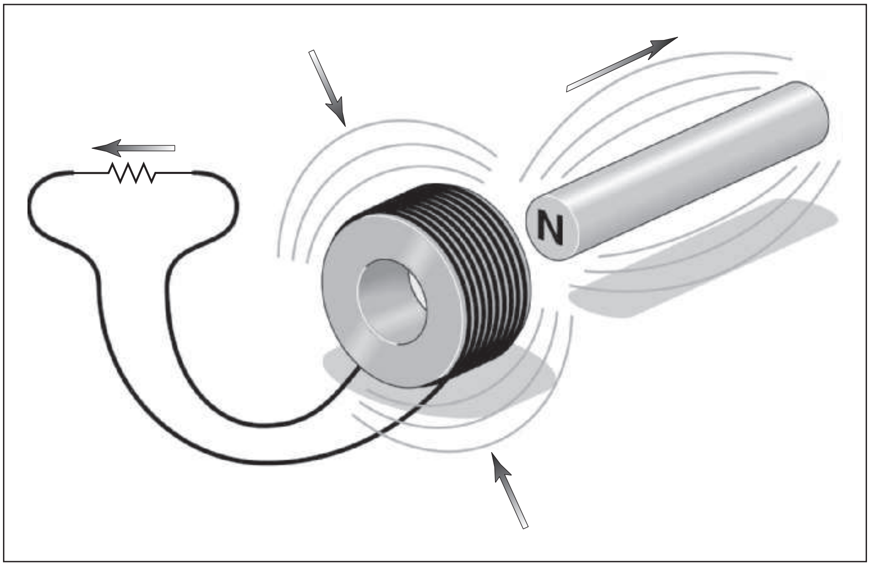


Figure 2-11 The induced voltage forces current to flow in the same direction.

RISE TIME OF CURRENT IN AN INDUCTOR

When a resistive load is suddenly connected to a source of direct current *(Figure 2-12)*, the current will instantly rise to its maximum value. The resistor shown in *Figure 2-12* has a value of 10 Ω and is connected to a 20-V source. When the switch is closed the current will instantly rise to a value of 2 A (20 V/10 Ω = 2 A).

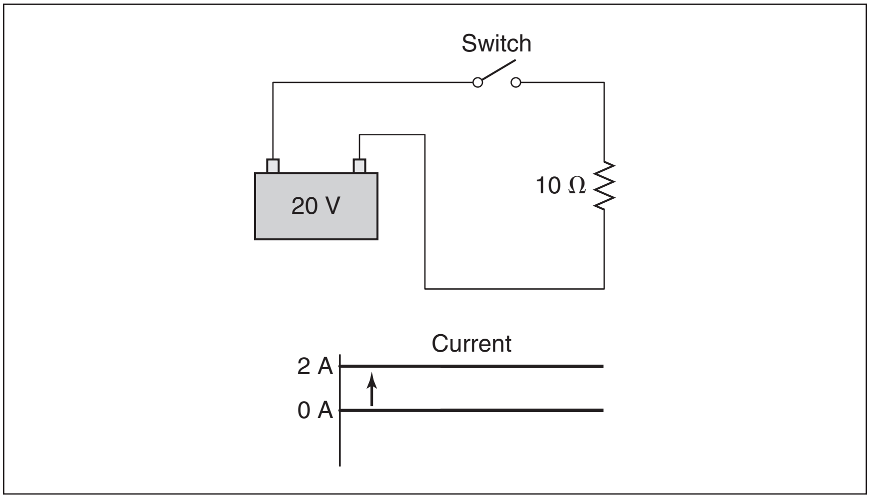


Figure 2-12 The current rises instantly in a resistive circuit.

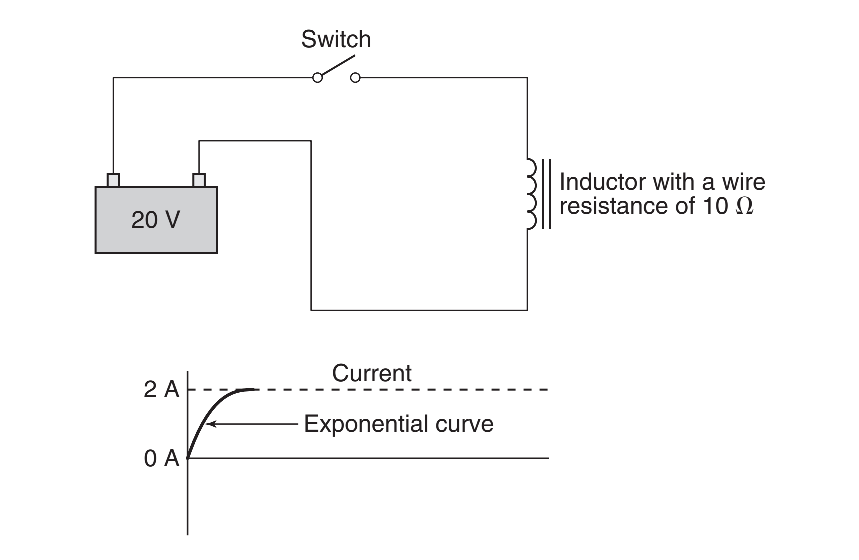


Figure 2-13 Current rises through an indicator at an exponential rate.

If the resistor is replaced with an inductor that has a wire resistance of 10 Ω and the switch is closed, the current cannot instantly rise to its maximum value of 2 A *(Figure 2-13)*. As current begins to flow through an inductor, the expanding magnetic field cuts through the conductors, inducing a voltage into them. In accord with Lenz's law, the induced voltage is opposite in polarity to the applied voltage. The induced voltage, therefore, acts as a resistance to hinder the flow of current through the inductor *(Figure 2-14)*.

The induced voltage is proportional to the rate of change of current (speed of the cutting action). When the switch is first closed,

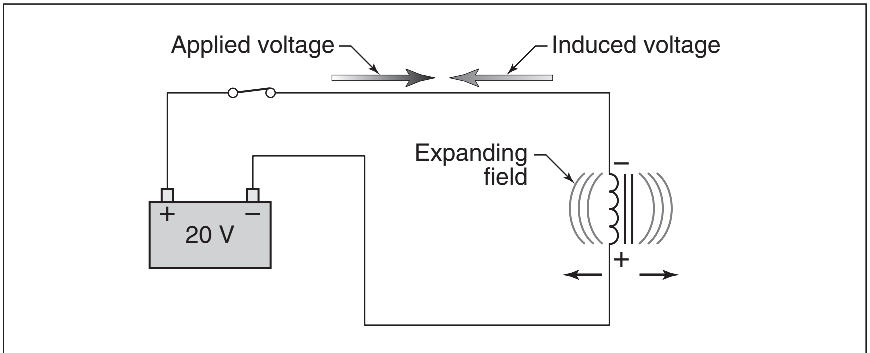


Figure 2-14 The induced voltage is opposite in polarity to the applied voltage.

current flow through the coil tries to rise instantly. This extremely fast rate of current change induces maximum voltage in the coil. As the current flow approaches its maximum Ohm's law value, 2 A in this example, the rate of change becomes less and the amount of induced voltage decreases.

THE EXPONENTIAL CURVE

The **exponential curve** describes a rate of certain occurrences. The curve is divided into five time constants. Each time constant is equal to 63.2% of some value. An exponential curve is shown in *Figure 2-15*. In this example, current must rise from zero to a value of 1.5 A in 100 ms at an exponential rate. Since the current requires a total of 100 ms to rise to its full value, each time constant is 20 ms (100 ms/5 time constants = 20 ms per time constant). During the first time constant, the current will rise from 0 to 63.2% of its total value, or 0.948 A (1.5 × 0.632 = 0.948). During the second time constant, the current rises to a value of 1.297 A. This is an increase of 0.349 A during the second time constant. This increase is 63.2 percent of the remaining current from 0.948 A to 1.5 A (1.5 – 0.948 = 0.552) (0.552 × 0.632 = 0.349). At the end of the third time constant, the current has risen to a value of 1.425 A. This is a current

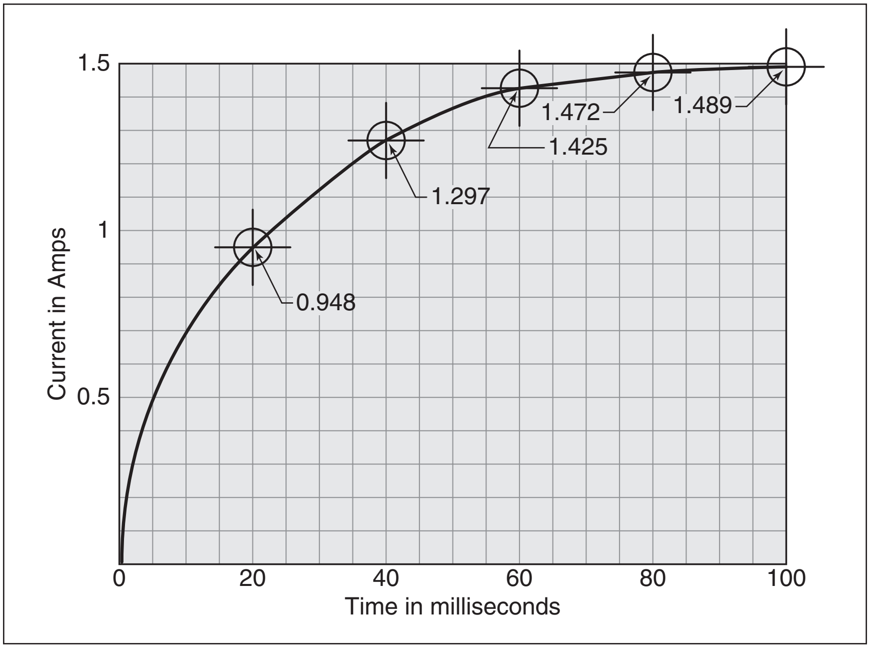


Figure 2-15 Exponential curve.

increase of 0.128 A during the third time constant. This increase is 63.2 percent of the remaining current from 1.297 A to 1.5 A (1.5 – 1.297 = 0.203) (0.203 × 0.632 = 0.128).

It should be noted that when power is applied to an inductor, the current not only increases at an exponential rate to its maximum value, but it also decreases at an exponential rate when power is disconnected. *Table 2-1* gives the decimal fraction of the maximum current value for both the built-up and decay of current through an inductor.

Because the current increases at a rate of 63.2% during each time constant, it is theoretically impossible to reach the total value of 1.5 A. After five time constants, however, the current has reached approximately 99.3% of the maximum value and for all practical purposes is considered to be complete.

The exponential curve can often be found in nature. If clothes are hung on a line to dry, they will dry at an exponential rate. Another example of the exponential curve can be seen in *Figure 2-16*. In this example, a bucket has been filled to a certain mark with water. A hole

Exponential Rate of Current Build-up	
Time Constant	Multiplication Factor
1	$0.632 \times I_{Max}$
2	$0.865 \times I_{Max}$
3	$0.950 \times I_{Max}$
4	$0.992 \times I_{Max}$
5	$0.981 \times I_{Max}$

Exponential Rate of Current Decay	
Time Constant	Multiplication Factor
1	$0.368 \times I_{Max}$
2	$0.135 \times I_{Max}$
3	$0.050 \times I_{Max}$
4	$0.019 \times I_{Max}$
5	$0.008 \times I_{Max}$

Table 2-1

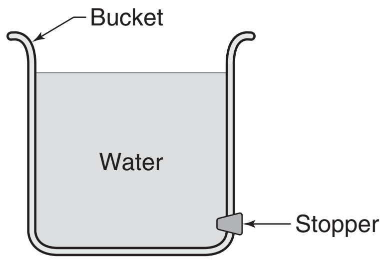


Figure 2-16 Exponential curves can be found in nature.

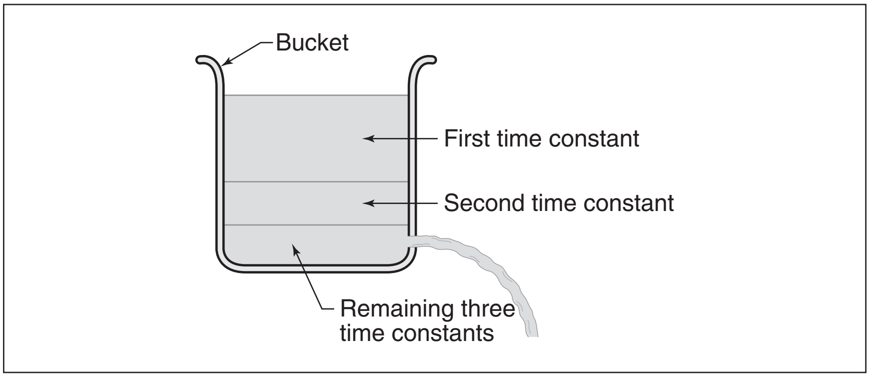


Figure 2-17 Water flows from a bucket at an exponential rate.

has been cut at the bottom of the bucket and a stopper placed in the hole. When the stopper is removed from the bucket, water will flow out at an exponential rate. Assume, for example, it takes 5 min for the water to flow out of the bucket. Exponential curves are always divided into five time constants, so in this case each time constant has a value of 1 min. In *Figure 2-17*, if the stopper is removed and water is permitted to drain from the bucket for a period of 1 min before the stopper is replaced, during that first time constant 63.2% of the water in the bucket will drain out. If the stopper is again removed for a period of 1 min, 63.2% of the water remaining in the bucket will drain out. Each time the stopper is removed for a period of one time constant, the bucket will lose 63.2% of its remaining water.

INDUCTANCE

henry (H)

Inductance is measured in units called the **henry (H)** and is represented by the letter *L*. **A coil has an inductance of one henry when a current change of one ampere per second results in an induced voltage of one volt.**

The amount of inductance a coil will have is determined by its physical properties and construction. A coil wound on a nonmagnetic core material such as wood or plastic is referred to as an **air-core** inductor. If the coil is wound on a core made of magnetic material such as silicon steel or soft iron it is referred to as an **iron-core** inductor. Iron-core inductors produce more inductance with fewer turns than air-core inductors because of the good magnetic path provided by the core material. Iron-core inductors cannot be used for high-frequency applications, however, because of **eddy current** loss and **hysteresis loss** in the core material.

eddy current
hysteresis loss

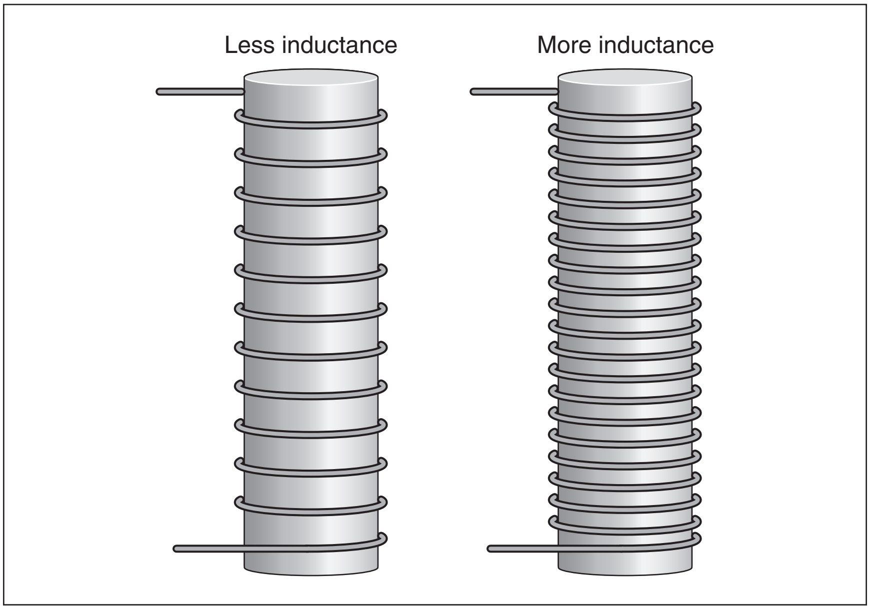


Figure 2-18 Inductance is determined by the physical construction of the coil.

Another factor that determines inductance is how far the windings are separated from each other. If the turns of wire are far apart they will have less inductance than turns wound closer together *(Figure 2-18)*.

R-L Time Constants

The time necessary for current in an inductor to reach its full Ohm's law value, called the **R-L time constant**, can be computed using the formula

$$T = \frac{L}{R}$$

where

T = time in seconds
L = inductance in henrys
R = resistance in ohms

This formula computes the time of one time constant.

Example 1

A coil has an inductance of 1.5 H and a wire resistance of 6 Ω. If the coil is connected to a battery of 3 V, how long will it take the current to reach its full Ohm's law value of 0.5 A (3 V/6 Ω = 0.5 A)?

Solution

To find the time of one time constant, use the formula

$$T = \frac{L}{R}$$

$$T = \frac{1.5}{6}$$

$$T = 0.25 \text{ s}$$

The time for one time constant is 0.25 s. Since five time constants are required for the current to reach its full value of 0.5 A, 0.25 s will be multiplied by 5.

$$0.25 \times 5 = 1.25 \text{ s}$$

INDUCED VOLTAGE SPIKES

A **voltage spike** occurs when the current flow through an inductor stops, and the current decreases at an exponential rate also *(Figure 2-19)*. As long as a complete circuit exists when the power is interrupted, there is little or no problem. In the circuit shown in *Figure 2-20*, a resistor and inductor are connected in parallel. When the switch is closed, the battery will supply current to both. When the switch is opened, the magnetic field surrounding the inductor will collapse and induce a voltage into the inductor. The induced voltage will attempt to keep current flowing in the same direction. Recall that

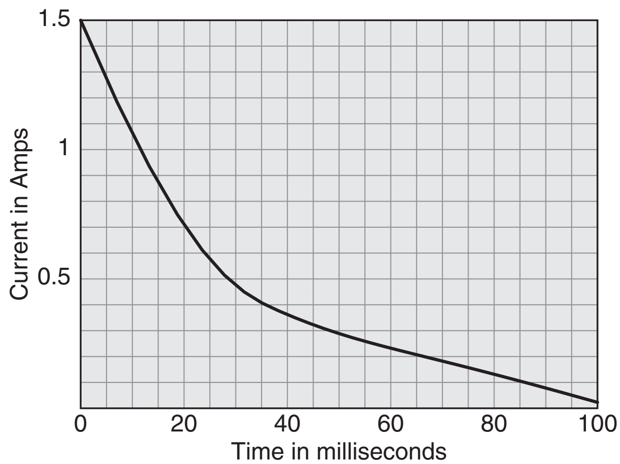


Figure 2-19 Current flow through an inductor decreases at an exponential rate.

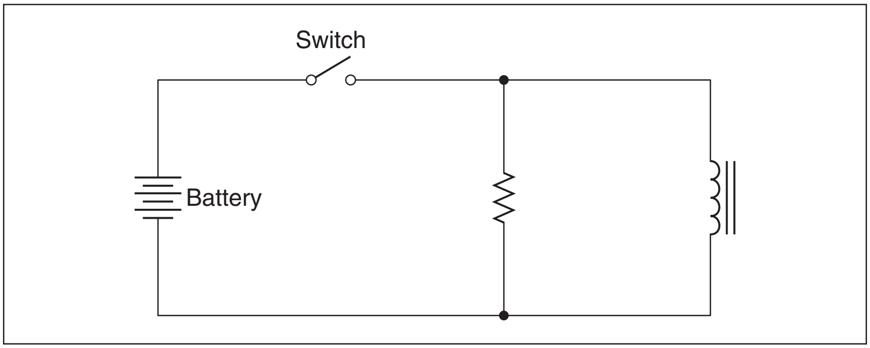


Figure 2-20 The resistor helps prevent voltage spikes caused by the inductor.

inductors oppose a change of current. The amount of current flow and the time necessary for the flow to stop will be determined by the resistor and the properties of the inductor. The amount of voltage produced by the collapsing magnetic field is determined by the maximum current in the circuit and the total resistance in the circuit. In the circuit shown in *Figure 2-20*, assume that the inductor has a wire resistance of 6 Ω, and the resistor has a resistance of 100 Ω. Also assume that when the switch is closed a current of 2 A will flow through the inductor.

When the switch is opened, a series circuit exists composed of the resistor and inductor *(Figure 2-21)*. The maximum voltage developed in this circuit would be 212 V (2 A × 106 Ω = 212 V). If the circuit resistance were increased, the induced voltage would become greater. If the circuit resistance were decreased, the induced voltage would become less.

Another device often used to prevent induced voltage spikes when the current flow through an inductor is stopped is the diode *(Figure 2-22)*. The diode is an electronic component that operates as an electrical

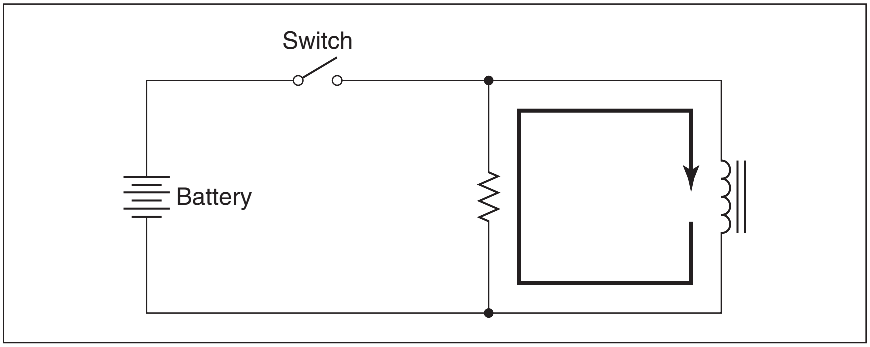


Figure 2-21 When the switch is opened, a series path is formed by the resistor and inductor.

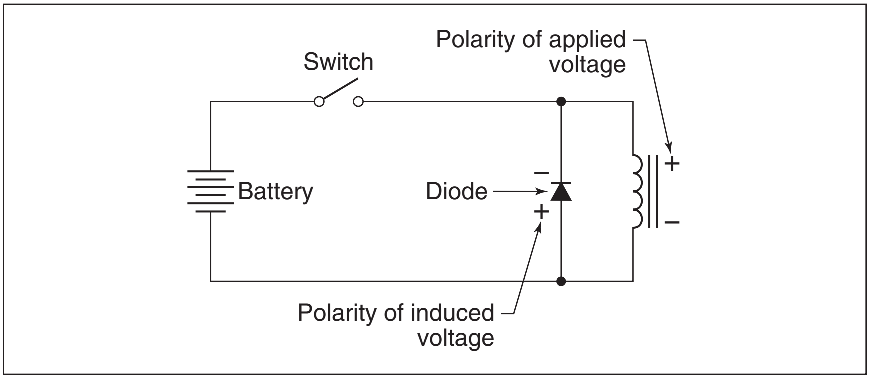


Figure 2-22 The diode is used to prevent induced voltage spikes.

check valve. The diode will permit current to flow through it in only one direction. The diode is connected in parallel with the inductor in such a manner that when voltage is applied to the circuit, the diode is reverse-biased and acts as an open switch. When the diode is reverse-biased no current will flow through it.

When the switch is opened, the induced voltage produced by the collapsing magnetic field will be opposite in polarity to the applied voltage. The diode then becomes forward-biased and acts as a closed switch. Current can now flow through the diode and complete a circuit back to the inductor. A silicon diode has a forward voltage drop of approximately 0.7 V regardless of the current flowing through it. Since the diode is connected in parallel with the inductor, and voltage drops of devices connected in parallel must be the same, the induced voltage is limited to approximately 0.7 V. The diode can be used to eliminate inductive voltage spikes in direct-current circuits only; it cannot be used for this purpose in alternating-current circuits.

A device that can be used for spike suppression in either direct- or alternating-current circuits is the **metal oxide varistor (MOV)**. The MOV is a bidirectional device, which means that it will conduct current in either direction, and can therefore be used in alternating-current circuits. The metal oxide varistor is an extremely fast-acting solid-state component that will exhibit a change of resistance when the voltage reaches a certain point. Assume that the MOV shown in *Figure 2-23* has a voltage rating of 140 V, and that the voltage applied to the circuit is 120 V. When the switch is closed and current flows through the circuit, a magnetic field will be established around the inductor *(Figure 2-24)*. As long as the voltage applied to the MOV is less than 140 V, it will exhibit an extremely high resistance, in the range of several hundred thousand ohms.

When the switch is opened, current flow through the coil suddenly stops, and the magnetic field collapses. This sudden collapse of the

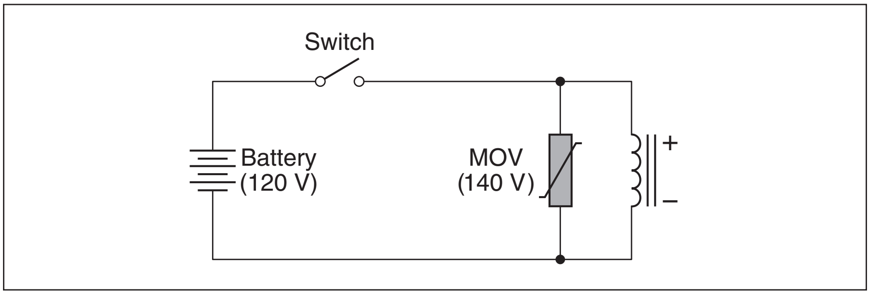


Figure 2-23 Metal oxide varistor used to suppress a voltage spike.

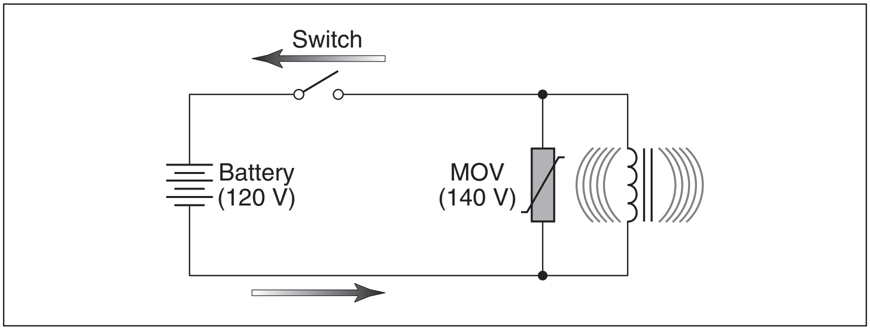


Figure 2-24 When the switch is closed, a magnetic field is established around the inductor.

magnetic field will cause an extremely high voltage to be induced in the coil. When this induced voltage reaches 140 V, however, the MOV will suddenly change from a high resistance to a low resistance, preventing the voltage from becoming greater than 140 V *(Figure 2-25)*.

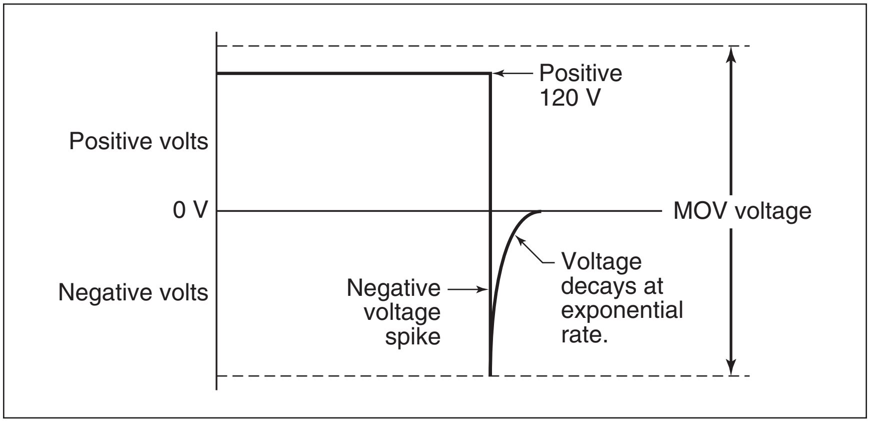


Figure 2-25 The MOV prevents the spike from becoming too high.

Metal oxide varistors are extremely fast-acting. They can typically change resistance values in less than 20 ns (nanoseconds). They are often found connected across the coils of relays and motor starters in control systems to prevent voltage spikes from being induced back into the line. They are also found in the surge protectors used to protect many home appliances such as televisions, stereos, and computers.

If nothing is connected in the circuit with the inductor when the switch opens, the induced voltage can become extremely high. In this instance, the resistance of the circuit is the air gap of the switch contacts, which is practically infinite. The inductor will attempt to produce any voltage necessary to prevent a change of current. Inductive voltage spikes can reach thousands of volts. This is the principle of operation of many high-voltage devices such as the ignition systems of many automobiles.

Another device that uses the collapsing magnetic field of an inductor to produce a high voltage is the electric-fence charger, shown in *Figure 2-26*. The switch is constructed in such a manner that it will pulse on and off. When the switch closes, current flows through the inductor, and a magnetic field is produced around the inductor. When the switch opens, the magnetic field collapses and induces a high voltage across the inductor. If anything or anyone standing on the ground touches the fence, a circuit is completed through the object or person and the ground. The coil is generally constructed of many turns of very small wire. This construction provides the coil with a high resistance and limits current flow when the field collapses.

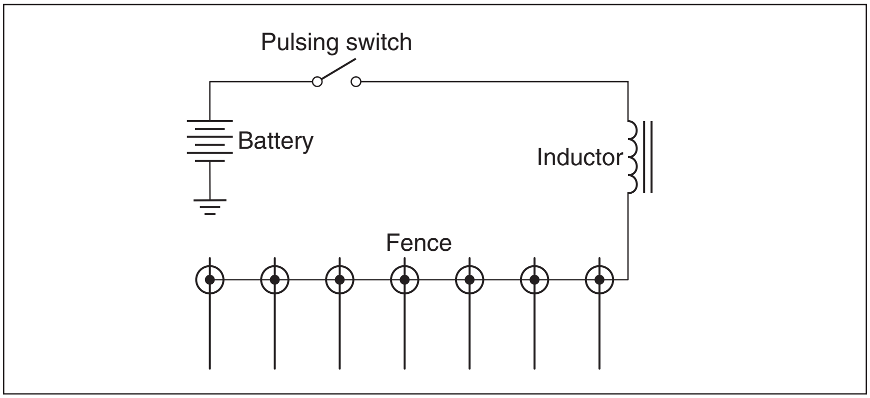


Figure 2-26 An inductor is used to produce a high voltage for an electric fence.

Summary

1. When current flows through a conductor, a magnetic field is created around the conductor.
2. When a conductor is cut by a magnetic field, a voltage is induced in the conductor.
3. The polarity of the induced voltage is determined by the polarity of the magnetic field in relation to the direction of motion.
4. Three factors that determine the amount of induced voltage are:
   a. The number of turns of wire,
   b. The strength of the magnetic field, and
   c. The speed of the cutting action.
5. One volt is induced in a conductor when magnetic lines of flux are cut at a rate of one weber per second.
6. Induced voltage is always opposite in polarity to the applied voltage.
7. Inductors oppose a change of current.
8. Current rises in an inductor at an exponential rate.
9. An exponential curve is divided into five time constants.
10. Each time constant is equal to 63.2% of some value.
11. Inductance is measured in units called henrys (H).
12. A coil has an inductance of 1 H when a current change of 1 A per second results in an induced voltage of 1 V.
13. Air-core inductors are inductors wound on cores of nonmagnetic material.
14. Iron-core inductors are wound on cores of magnetic material.
15. The amount of inductance an inductor will have is determined by the number of turns of wire and the physical construction of the coil.
16. Inductors can produce extremely high voltages when the current flowing through them is stopped.
17. Two devices used to help prevent large spike voltages are the resistor and diode.

Review Questions

1. What determines the polarity of magnetism when current flows through a conductor?
2. What determines the strength of the magnetic field when current flows through a conductor?

3. Name three factors that determine the amount of induced voltage in a coil.
4. How many lines of magnetic flux must be cut in 1 s to induce a voltage of 1 V?
5. What is the effect on induced voltage of adding more turns of wire to a coil?
6. Into how many time constants is an exponential curve divided?
7. Each time constant of an exponential curve is equal to what percentage of the whole?
8. An inductor has an inductance of 0.025 H and a wire resistance of 3 Ω. How long will it take the current to reach its full Ohm's law value?
9. Refer to the circuit shown in *Figure 2-20*. Assume that the inductor has a wire resistance of 0.2 Ω and the resistor has a value of 250 Ω. If a current of 3 A is flowing through the inductor, what will be the maximum induced voltage when the switch is opened?
10. What electronic component is often used to prevent large voltage spikes from being produced when the current flow through an inductor is suddenly terminated?

UNIT 3 | Inductance in Alternating-Current Circuits

Objectives

After studying this unit, you should be able to:

- Discuss the properties of inductance in an alternating-current circuit.
- Discuss inductive reactance.
- Compute values of inductive reactance and inductance.
- Discuss the relationship of voltage and current in a pure inductive circuit.
- Be able to compute values for inductors connected in series or parallel.
- Discuss reactive power (VARs).
- Determine the Q of a coil.

This unit discusses the effects of inductance on alternating-current circuits. The unit explains how current is limited in an inductive circuit as well as the effect inductance has on the relationship of voltage and current.

INDUCTANCE

Inductance (L) is one of the primary types of loads in alternating-current circuits. Some amount of inductance is present in all alternating-current circuits because of the continually changing magnetic field *(Figure 3-1)*. The amount of inductance of a single conductor is extremely small, and in most instances it is not considered in circuit calculations. Circuits are generally considered to contain inductance when any type of load that contains a coil is used. For circuits that contain a coil, inductance *is* considered in circuit calculations. Loads such as motors, transformers, lighting ballasts, and chokes all contain coils of wire.

In Unit 2, it was discussed that whenever current flows through a coil of wire a magnetic field is created around the wire *(Figure 3-2)*.

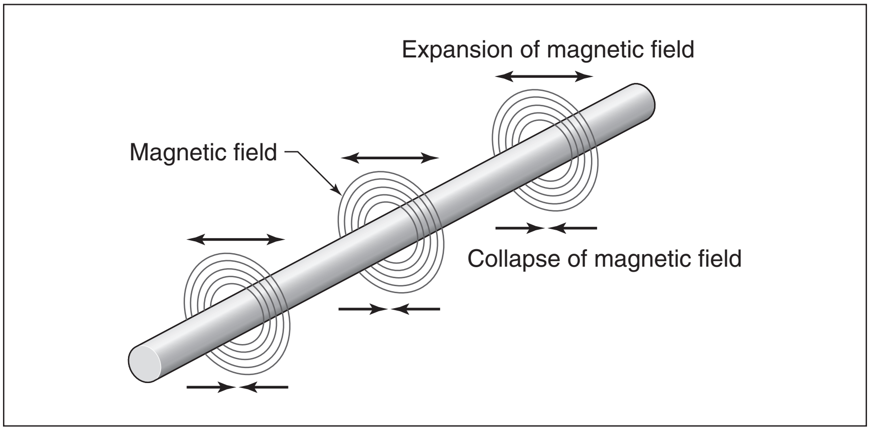


Figure 3-1 A continually changing magnetic field induces a voltage into any conductor.

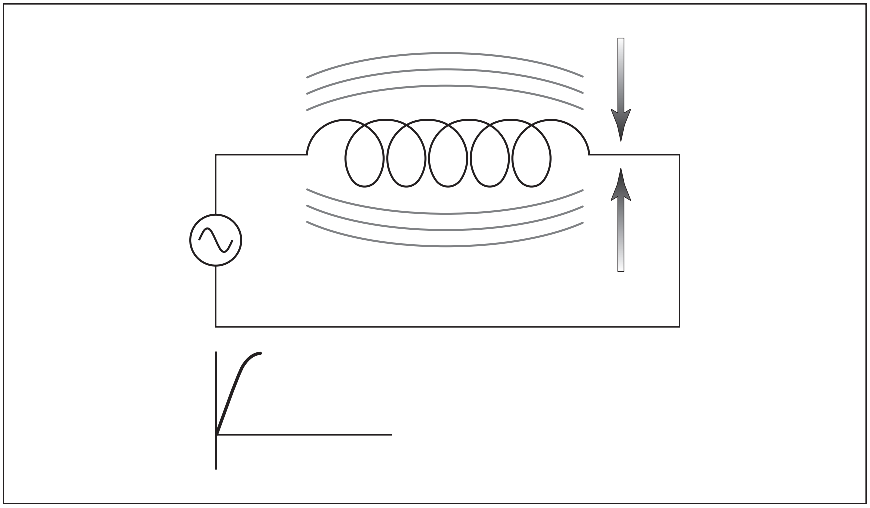


Figure 3-2 As current flows through a coil, a magnetic field is created around the coil.

If the amount of current decreases, the magnetic field will collapse *(Figure 3-3)*. Recall from Unit 2 several facts concerning inductance:

1. When magnetic lines of flux cut through a coil, a voltage is induced in the coil.
2. The polarity of an induced voltage will always be the polarity that opposes a change of current. The polarity may sometimes be the opposite of the applied voltage and sometimes the same

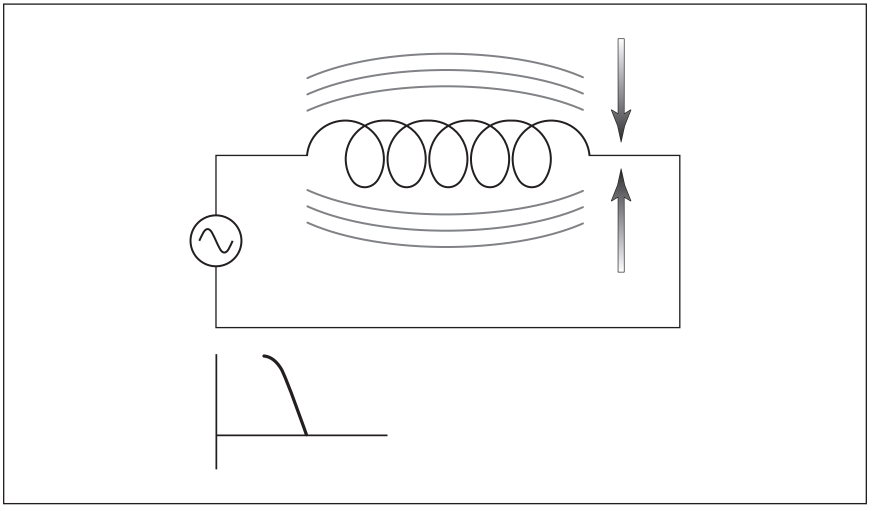


Figure 3-3 As current flow decreases, the magnetic field collapses.

as the applied voltage. If the applied voltage is causing current to increase through the inductor, the polarity of the induced voltage will be opposite the applied voltage to oppose the change in current. When the current reaches its peak value, there is no induced voltage because there is no change of current. When the current starts to decrease back toward zero, the polarity of the induced voltage will be the same as the applied voltage to again oppose a change of current by maintaining current flow.

3. The amount of induced voltage is proportional to the rate of change of current.
4. An inductor opposes a change of current.

The inductors in *Figure 3-2* and *Figure 3-3* are connected to an AC voltage. Therefore, the magnetic field continually increases, decreases, and reverses polarity. Since the magnetic field continually changes magnitude and direction, a voltage is continually being induced in the coil. This **induced voltage** is 180° out of phase with the applied voltage and is always in opposition to a change of current *(Figure 3-4)*. Since the induced voltage always opposes a change of current, the applied voltage must overcome the induced voltage before current can flow through the circuit. For example, assume an inductor is connected to a 120-V AC line. Now assume that the inductor has an induced voltage of 116 V. Since an equal amount of applied voltage must be used to overcome the induced voltage, there will be only 4 V to push current through the wire resistance of the coil (120 – 116 = 4).

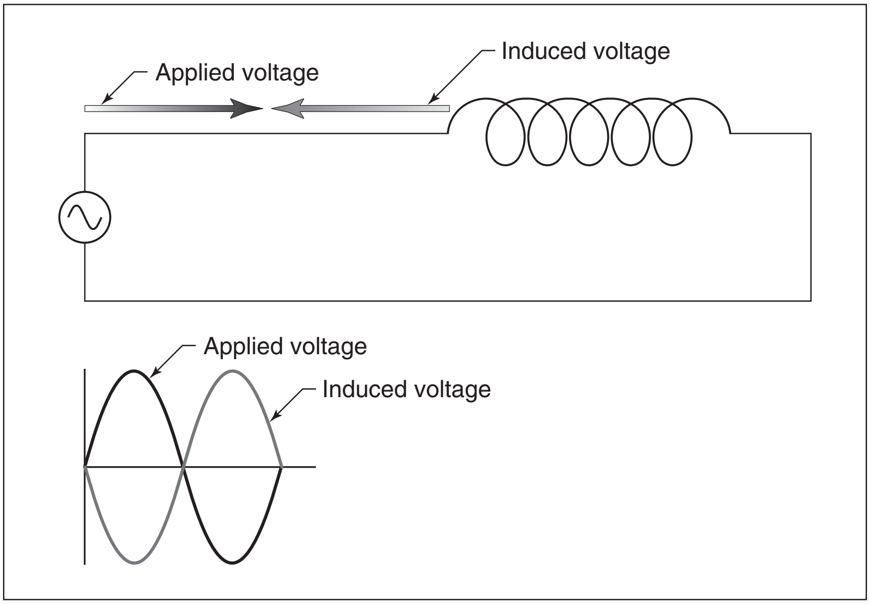


Figure 3-4 The applied voltage and induced voltage are 180° out of phase with each other.

Computing the Induced Voltage

The amount of induced voltage in an inductor can be computed if the resistance of the wire in the coil and the amount of circuit current are known. For example, assume that an ohmmeter is used to measure the actual amount of resistance in a coil, and the coil is found to contain 6 Ω of wire resistance *(Figure 3-5)*. Now assume that the coil is connected to a 120-V AC circuit and an ammeter measures a current flow of 0.8 A *(Figure 3-6)*. Ohm's law can now be used to determine the amount of voltage necessary to push 0.8 A of current through 6 Ω of resistance.

$$E = I \times R$$

$$E = 0.8 \times 6$$

$$E = 4.8 \text{ V}$$

Since only 4.8 V is needed to push the current through the wire resistance of the inductor, the remainder of the 120 V is used to overcome the coil's induced voltage of 115.2 V (120 – 4.8 = 115.2).

INDUCTIVE REACTANCE

Notice that the induced voltage is able to limit the flow of current through the circuit in a manner similar to resistance. This induced

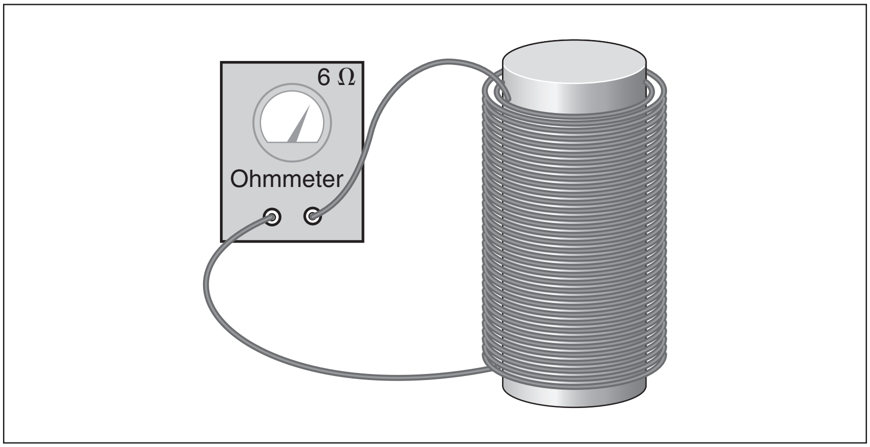


Figure 3-5 Measuring the resistance of a coil.

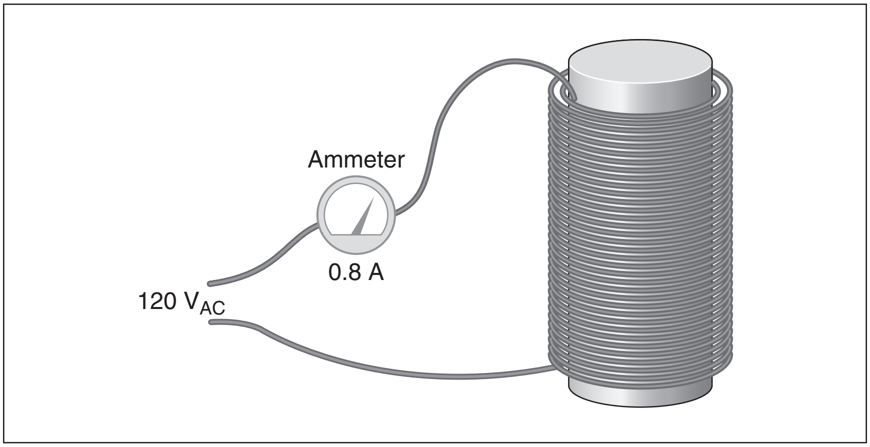


Figure 3-6 Measuring circuit current with an ammeter.

voltage is *not* resistance, but it can limit the flow of current just as resistance does. This current-limiting property of the inductor is called **reactance** and is symbolized by the letter *X*. This reactance is caused by inductance, so it is called **inductive reactance** and is symbolized by $\mathbf{X_L}$, pronounced "X sub L." Inductive reactance is measured in ohms just as resistance is and can be computed when the values of inductance and frequency are known. The following formula can be used to find inductive reactance:

reactance

inductive reactance (X_L)

$$X_L = 2\pi fL$$