Magnetism

I. INTRODUCTION

Magnetism, an aspect of electromagnetism, one of the fundamental forces of nature. Magnetic forces are produced by the motion of charged particles such as electrons, indicating the close relationship between electricity and magnetism. The unifying frame for these two forces is called electromagnetic theory (*see* Electromagnetic Radiation). The most familiar evidence of magnetism is the attractive or repulsive force observed to act between magnetic materials such as iron. More subtle effects of magnetism, however, are found in all matter. In recent times these effects have provided important clues to the atomic structure of matter.

II. HISTORY OF STUDY

The phenomenon of magnetism has been known of since ancient times. The mineral lodestone (*see* Magnetite), an oxide of iron that has the property of attracting iron objects, was known to the Greeks, Romans, and Chinese. When a piece of iron is stroked with lodestone, the iron itself acquires the same ability to attract other pieces of iron. The magnets thus produced are *polarized*—that is, each has two sides or ends called north-seeking and south-seeking poles. Like poles repel one another, and unlike poles attract. The compass was first used for navigation in the West some time after AD1200. In the 13th century, important investigations of magnets were made by the French scholar Petrus Peregrinus. His discoveries stood for nearly 300 years, until the English physicist and physician William Gilbert published his book *Of Magnets, Magnetic Bodies, and the Great Magnet of the Earth* in 1600. Gilbert applied scientific methods to the study of electricity and magnetism. He pointed out that the earth itself behaves like a giant magnet, and through a series of experiments, he investigated and disproved several incorrect notions about magnetism that were accepted as being true at the time. Subsequently, in 1750, the English geologist John Michell invented a balance that he used in the study of magnetic forces. He showed that the attraction and repulsion of magnets decrease as the squares of the distance from the respective poles increase. The French physicist Charles Augustin de Coulomb, who had measured the forces between electric charges, later verified Michell's observation with high precision.

III. ELECTROMAGNETIC THEORY

In the late 18th and early 19th centuries, the theories of electricity and magnetism were investigated simultaneously. In 1819 an important discovery was made by the Danish physicist Hans Christian Oersted, who found that a magnetic needle could be deflected by an electric current flowing through a wire. This discovery, which showed a connection between electricity and magnetism, was followed up by the French scientist André Marie Ampère, who studied the forces between wires carrying electric currents, and by the French physicist Dominique François Jean Arago, who magnetized a piece of iron by placing it near a current-carrying wire. In 1831 the English scientist Michael Faraday discovered that moving a magnet near a wire induces an electric current in that wire, the inverse effect to that found by Oersted: Oersted showed that an electric current creates a magnetic field, while Faraday showed that a magnetic field can be used to create an electric current. The full unification of the theories of electricity and magnetism was achieved by the English physicist James Clerk Maxwell, who predicted the existence of electromagnetic waves and identified light as an electromagnetic phenomenon.

Subsequent studies of magnetism were increasingly concerned with an understanding of the atomic and molecular origins of the magnetic properties of matter. In 1905 the French physicist Paul Langevin produced a theory regarding the temperature dependence of the magnetic properties of paramagnets (discussed below), which was based on the atomic structure of matter. This theory is an early example of the description of large-scale properties in terms of the properties of electrons and atoms. Langevin's theory was subsequently expanded by the French physicist Pierre Ernst Weiss, who postulated the existence of an internal, "molecular" magnetic field in materials such as iron. This concept, when combined with Langevin's theory, served to explain the properties of strongly magnetic materials such as lodestone.

After Weiss's theory, magnetic properties were explored in greater and greater detail. The theory of atomic structure of Danish physicist Niels Bohr, for example, provided an understanding of the periodic table and showed why magnetism occurs in transition elements such as iron and the rare earth elements, or in compounds containing these elements. The American physicists Samuel Abraham Goudsmit and George Eugene Uhlenbeck showed in 1925 that the electron itself has spin and behaves like a small bar magnet. (At the atomic level, magnetism is measured in terms of *magnetic moments*—a magnetic moment is a vector quantity that depends on the strength and orientation of the magnetic field, and the configuration of the object that produces the magnetic field.) The German physicist Werner Heisenberg gave a detailed explanation for Weiss's molecular field in 1927, on the basis of the newly-developed quantum mechanics (*see* Quantum Theory). Other scientists then predicted many more complex atomic arrangements of magnetic moments, with diverse magnetic properties.

IV. THE MAGNETIC FIELD

Objects such as a bar magnet or a current-carrying wire can influence other magnetic materials without physically contacting them, because magnetic objects produce a *magnetic field*. Magnetic fields are usually represented by *magnetic flux lines*. At any point, the direction of the magnetic field is the same as the direction of the flux lines, and the strength of the magnetic field is proportional to the space between the flux lines. For example, in a bar magnet, the flux lines emerge at one end of the magnet, then curve around the other end; the flux lines can be thought of as being closed loops, with part of the loop inside the magnet, and part of the loop outside. At the ends of the magnet, where the flux lines are closest together, the magnetic field is strongest; toward the side of the magnet, where the flux lines are farther apart, the magnetic field is weaker. Depending on their shapes and magnetic strengths, different kinds of magnets produce different patterns of flux lines. The pattern of flux lines created by magnets or any other object that creates a magnetic field can be mapped by using a compass or small iron filings. Magnets tend to align themselves along magnetic flux lines. Thus a compass, which is a small magnet that is free to rotate, will tend to orient itself in the direction of the magnetic flux lines. By noting the direction of the compass needle when the compass is placed at many locations around the source of the magnetic field, the pattern of flux lines can be inferred. Alternatively, when iron filings are placed around an object that creates a magnetic field, the filings will line up along the flux lines, revealing the flux line pattern.

Magnetic fields influence magnetic materials, and also influence charged particles that move through the magnetic field. Generally, when a charged particle moves through a magnetic field, it feels a force that is at right angles both to the velocity of the charged particle and the magnetic field. Since the force is always perpendicular to the velocity of the charged particle, a charged particle in a magnetic field moves in a curved path. Magnetic fields are used to change the paths of charged particles in devices such as particle accelerators and mass spectrometers.

V. KINDS OF MAGNETIC MATERIALS

The magnetic properties of materials are classified in a number of different ways.

One classification of magnetic materials—into *diamagnetic, paramagnetic,* and *ferromagnetic*—is based on how the material reacts to a magnetic field. Diamagnetic materials, when placed in a magnetic field, have a magnetic moment induced in them that opposes the direction of the magnetic field. This property is now understood to be a result of electric currents that are induced in individual atoms and molecules. These currents, according to Ampere's law, produce magnetic moments in opposition to the applied field. Many materials are diamagnetic; the strongest ones are metallic bismuth and organic molecules, such as benzene, that have a cyclic structure, enabling the easy establishment of electric currents.

Paramagnetic behavior results when the applied magnetic field lines up all the existing magnetic moments of the individual atoms or molecules that make up the material. This results in an overall magnetic moment that adds to the magnetic field. Paramagnetic materials usually contain transition metals or rare earth elements that possess unpaired electrons. Paramagnetism in nonmetallic substances is usually characterized by temperature dependence; that is, the size of an induced magnetic moment varies inversely to the temperature. This is a result of the increasing difficulty of ordering the magnetic moments of the individual atoms along the direction of the magnetic field as the temperature is raised.

A ferromagnetic substance is one that, like iron, retains a magnetic moment even when the external magnetic field is reduced to zero. This effect is a result of a strong interaction between the magnetic moments of the individual atoms or electrons in the magnetic substance that causes them to line up parallel to one another. In ordinary circumstances these ferromagnetic materials are divided into regions called *domains;* in each domain, the atomic moments are aligned parallel to one another. Separate domains have total moments that do not necessarily point in the same direction. Thus, although an ordinary piece of iron might not have an overall magnetic moment, magnetization can be induced in it by placing the iron in a magnetic field, thereby aligning the moments of all the individual domains. The energy expended in reorienting the domains from the magnetized back to the demagnetized state manifests itself in a lag in response, known as *hysteresis.*

Ferromagnetic materials, when heated, eventually lose their magnetic properties. This loss becomes complete above the *Curie temperature,* named after the French physicist Pierre Curie, who discovered it in 1895. (The Curie temperature of metallic iron is about 770° C/1300° F.)

VII. APPLICATIONS

Numerous applications of magnetism and of magnetic materials have arisen in the past 100 years. The electromagnet, for example, is the basis of the electric motor and the transformer. In more recent times, the development of new magnetic materials has also been important in the computer revolution. Computer memories can be fabricated using *bubble domains*. These domains are actually smaller regions of magnetization that are either parallel or antiparallel to the overall magnetization of the material. Depending on this direction, the bubble indicates either a one or a zero, thus serving as the units of the binary number system used in computers. Magnetic materials are also important constituents of tapes and disks on which data are stored.

In addition to the atomic-sized magnetic units used in computers, large, powerful magnets are crucial to a variety of modern technologies. Magnetic levitation trains use strong magnets to enable the train to float above the track so that there is no friction between the vehicle and the tracks to slow the train down. Powerful magnetic fields are used in nuclear magnetic resonance imaging, an important diagnostic tool used by doctors. Superconducting magnets are used in today's most powerful particle accelerators to keep the accelerated particles focused and moving in a curved path.

Contributed By: Martin Blume, M.A., Ph.D.
Deputy Director, Brookhaven National Laboratory.

"Magnetism". Microsoft® Encarta® Online Encyclopedia 2001
http://encarta.msn.com (15 Oct. 2001)

Induction (electricity)

I. INTRODUCTION

Induction (electricity), in electricity, the creation of an electric current in a conductor moving across a magnetic field (hence the full name, electromagnetic induction). The effect was discovered by the British physicist Michael Faraday and led directly to the development of the rotary electric generator, which converts mechanical motion into electric energy.

II. ELECTRIC GENERATOR

When a conductor, such as a wire, moves through the gap between the poles of a magnet, the negatively charged electrons in the wire will experience a force along the length of the wire and will accumulate at one end of it, leaving positively charged atomic nuclei, partially stripped of electrons, at the other end. This creates a potential difference, or voltage, between the ends of the wire. If the ends of the wire are connected by a conductor, a current will flow around the circuit. This is the principle behind the rotary electric power generator, in which a loop of wire is spun through a magnetic field so as to produce a voltage and generate a current in a closed circuit.

III. ELECTRIC TRANSFORMER

Induction occurs only if the wire moves at right angles to the direction of the magnetic field. This motion is necessary for induction to occur, but it is a relative motion between the wire and the magnetic field. Thus, an expanding or collapsing magnetic field can induce a current in a stationary wire. Such a moving magnetic field can be created by a surge of current through a wire or electromagnet. As the current in the electromagnet rises and falls, its magnetic field grows and collapses (the lines of force move outward, then inward). The moving field can induce a current in a nearby stationary wire. Such induction without mechanical motion is the basis of the electric transformer.

A transformer usually consists of two adjacent coils of wire wound around a single core of magnetic material. It is used to couple two or more a-c circuits by employing the induction between the coils. *See* Electric Power Systems.

IV. SELF-INDUCTION

When the current in a conductor varies, the resulting changing magnetic field cuts across the conductor itself and induces a voltage in it. This selfinduced voltage is opposite to the applied voltage and tends to limit or reverse the original current. Electric self-induction is thus analogous to mechanical inertia. An inductance coil, or choke, tends to smooth out a varying current, as a flywheel smooths out the rotation of an engine. The amount of self-induction of a coil, its inductance, is measured by the electrical unit called the henry, named after the American physicist Joseph Henry, who discovered the effect. The inductance is independent of current or voltage; it is determined only by the geometry of the coil and the magnetic properties of its core.

"Induction (electricity)". Microsoft® Encarta® Online Encyclopedia 2001
http://encarta.msn.com (15 Oct. 2001)

Electric Motors and Generators

I. INTRODUCTION

Electric Motors and Generators, group of devices used to convert mechanical energy into electrical energy, or electrical energy into mechanical energy, by electromagnetic means (*see* Energy). A machine that converts mechanical energy into electrical energy is called a generator, alternator, or dynamo, and a machine that converts electrical energy into mechanical energy is called a motor.

Two related physical principles underlie the operation of generators and motors. The first is the principle of electromagnetic induction discovered by the British scientist Michael Faraday in 1831. If a conductor is moved through a magnetic field, or if the strength of a stationary conducting loop is made to vary, a current is set up or induced in the conductor (*see* Induction). The converse of this principle is that of electromagnetic reaction, first observed by the French physicist André Marie Ampère in 1820. If a current is passed through a conductor located in a magnetic field, the field exerts a mechanical force on it. *See* Magnetism.

The simplest of all dynamoelectric machines is the disk dynamo developed by Faraday. It consists of a copper disk mounted so that part of the disk, from the center to the edge, is between the poles of a horseshoe magnet. When the disk is rotated, a current is induced between the center of the disk and its edge by the action of the field of the magnet. The disk can be made to operate as a motor by applying a voltage between the edge of the disk and its center, causing the disk to rotate because of the force produced by magnetic reaction.

The magnetic field of a permanent magnet is strong enough to operate only a small practical dynamo or motor. As a result, for large machines, electromagnets are employed. Both motors and generators consist of two basic units, the field, which is the electromagnet with its coils, and the armature, the structure that supports the conductors which cut the magnetic field and carry the induced current in a generator or the exciting current in a motor. The armature is usually a laminated soft-iron core around which conducting wires are wound in coils.

II. DIRECT-CURRENT (DC) GENERATORS

If an armature revolves between two stationary field poles, the current in the armature moves in one direction during half of each revolution and in the other direction during the other half. To produce a steady flow of unidirectional, or direct, current from such a device, it is necessary to provide a means of reversing the current flow outside the generator once during each revolution. In older machines this reversal is accomplished by means of a commutator, a split metal ring mounted on the shaft of the armature. The two halves of the ring are insulated from each other and serve as the terminals of the armature coil. Fixed brushes of metal or carbon are held against the commutator as it revolves, connecting the coil electrically to external wires. As the armature turns, each brush is in contact alternately with the halves of the commutator, changing position at the moment when the current in the armature coil reverses its direction. Thus there is a flow of unidirectional current in the outside circuit to which the generator is connected. DC generators are usually operated at fairly low voltages to avoid the sparking between brushes and commutator that occurs at high voltage. The highest potential commonly developed by such generators is 1500 V. In some newer machines this reversal is accomplished using power electronic devices, for example, diode rectifiers.

Modern DC generators use drum armatures that usually consist of a large number of windings set in longitudinal slits in the armature core and connected to appropriate segments of a multiple commutator. In an armature having only one loop of wire, the current produced will rise and fall depending on the part of the magnetic field through which the loop is moving. A commutator of many segments used with a drum armature always connects the external circuit to one loop of wire moving through the high-intensity area of the field, and as a result the current delivered by the armature windings is virtually constant. Fields of modern generators are usually equipped with four or more electromagnetic poles to increase the size and strength of the magnetic field. Sometimes smaller interpoles are added to compensate for distortions in the magnetic flux of the field caused by the magnetic effect of the armature.

DC generators are commonly classified according to the method used to provide field current for energizing the field magnets. A series-wound generator has its field in series with the armature, and a shunt-wound generator has the field connected in parallel with the armature. Compound-wound generators have part of their fields in series and part in parallel. Both shunt-wound and compound-wound generators have the advantage of delivering comparatively constant voltage under varying electrical loads. The series-wound generator is used principally to supply a constant current at variable voltage. A magneto is a small DC generator with a permanent-magnet field.

III. DC MOTORS

In general, DC motors are similar to DC generators in construction. They may, in fact, be described as generators "run backwards." When current is passed through the armature of a DC motor, a torque is generated by magnetic reaction, and the armature revolves. The action of the commutator and the connections of the field coils of motors are precisely the same as those used for generators. The revolution of the armature induces a voltage in the armature windings. This induced voltage is opposite in direction to the outside voltage applied to the armature, and hence is called back voltage or counter electromotive force (emf). As the motor rotates more rapidly, the back voltage rises until it is almost equal to the applied voltage. The current is then small, and the speed of the motor will remain constant as long as the motor is not under load and is performing no mechanical work except that required to turn the armature. Under load the armature turns more slowly, reducing the back voltage and permitting a larger current to flow in the armature. The motor is thus able to receive more electric power from the source supplying it and to do more mechanical work.

Because the speed of rotation controls the flow of current in the armature, special devices must be used for starting DC motors. When the armature is at rest, it has virtually no resistance, and if the normal working voltage is applied, a large current will flow, which may damage the commutator or the armature windings. The usual means of preventing such damage is the use of a starting resistance in series with the armature to lower the current until the motor begins to develop an adequate back voltage. As the motor picks up speed, the resistance is gradually reduced, either manually or automatically.

The speed at which a DC motor operates depends on the strength of the magnetic field acting on the armature, as well as on the armature current. The stronger the field, the slower is the rate of rotation needed to generate a back voltage large enough to counteract the applied voltage. For this reason the speed of DC motors can be controlled by varying the field current.

IV. ALTERNATING-CURRENT (AC) GENERATORS (ALTERNATORS)

As stated above, a simple generator without a commutator will produce an electric current that alternates in direction as the armature revolves. Such alternating current is advantageous for electric power transmission , and hence most large electric generators are of the AC type. In its simplest form, an AC generator differs from a DC generator in only two particulars: the ends of its armature winding are brought out to solid unsegmented slip rings on the generator shaft instead of to commutators, and the field coils are energized by an external DC source rather than by the generator itself. Low-speed AC generators are built with as many as 100 poles, both to improve their efficiency and to attain more easily the frequency desired. Alternators driven by high-speed turbines, however, are often two-pole machines. The frequency of the current delivered by an AC generator is equal to half the product of the number of poles and the number of revolutions per second of the armature.

It is often desirable to generate as high a voltage as possible, and rotating armatures are not practical in such applications because of the possibility of sparking between brushes and slip rings and the danger of mechanical failures that might cause short circuits. Alternators are therefore constructed with a stationary armature within which revolves a rotor composed of a number of field magnets. The principle of operation is exactly the same as that of the AC generator described, except that the magnetic field (rather than the conductors of the armature) is in motion.

The current generated by the alternators described above rises to a peak, sinks to zero, drops to a negative peak, and rises again to zero a number of times each second, depending on the frequency for which the machine is designed. Such current is known as single-phase alternating current. If, however, the armature is composed of two windings, mounted at right angles to each other, and provided with separate external connections, two current waves will be produced, each of which will be at its maximum when the other is at zero. Such current is called two-phase alternating current. If three armature windings are set at 120° to each other, current will be produced in the form of a triple wave, known as three-phase alternating current. A larger number of phases may be obtained by increasing the number of windings in the armature, but in modern electrical-engineering practice three-phase alternating current is most commonly used, and the three-phase alternator is the dynamoelectric machine typically employed for the generation of electric power. Voltages as high as 13,200 are common in alternators.

V. AC MOTORS

Two basic types of motors are designed to operate on polyphase alternating current, synchronous motors and induction motors. The synchronous motor is essentially a three-phase alternator operated in reverse. The field magnets are mounted on the rotor and are excited by direct current, and the armature winding is divided into three parts and fed with three-phase alternating current. The variation of the three waves of current in the armature causes a varying magnetic reaction with the poles of the field magnets, and makes the field rotate at a constant speed that is determined by the frequency of the current in the AC power line. The constant speed of a synchronous motor is advantageous in certain devices; however, in applications where the mechanical load on the motor becomes very great, synchronous motors cannot be used, because if the motor slows down under load it will "fall out of step" with the frequency of the current and come to a stop. Synchronous motors can be made to operate from a single-phase power source by the inclusion of suitable circuit elements that cause a rotating magnetic field. The simplest of all electric motors is the squirrel-cage type of induction motor used with a three-phase supply. The armature of the squirrel-cage motor consists of three fixed coils similar to the armature of the synchronous motor. The rotating member consists of a core in which are imbedded a series of heavy conductors arranged in a circle around the shaft and parallel to it. With the core removed, the rotor conductors resemble in form the cylindrical cages once used to exercise pet squirrels. The three-phase current flowing in the stationary armature windings generates a rotating magnetic field, and this field induces a current in the conductors of the cage. The magnetic reaction between the rotating field and the current-carrying conductors of the rotor makes the rotor turn. If the rotor is revolving at exactly the same speed as the magnetic field, no currents will be induced in it, and hence the rotor should not turn at a synchronous speed. In operation the speeds of rotation of the rotor and the field differ by about 2 to 5 percent. This speed difference is known as slip. Motors with squirrel-cage rotors can be used on single-phase alternating current by means of various arrangements of inductance and capacitance that alter the characteristics of the single-phase voltage and make it resemble a two-phase voltage. Such motors are called split-phase motors or condenser motors (or capacitor motors), depending on the arrangement used. Single-phase squirrel-cage motors do not have a large starting torque, and for applications where such torque is required, repulsion-induction motors are used. A repulsion-induction motor may be of the split-phase or condenser type, but has a manual or automatic switch that allows current to flow between brushes on the commutator when the motor is starting, and short-circuits all commutator segments after the motor reaches a critical speed. Repulsion-induction motors are so named because their starting torque depends on the repulsion between the rotor and the stator, and their torque while running depends on induction. Series-wound motors with commutators, which will operate on direct or alternating current, are called universal motors. They are usually made only in small sizes and are commonly used in household appliances.

VI. MISCELLANEOUS MACHINES

For special applications several combined types of dynamoelectric machines are employed. It is frequently desirable to change from direct to alternating current or vice versa, or to change the voltage of a DC supply, or the frequency or phase of an AC supply. One means of accomplishing such changes is to use a motor operating from the available type of electric supply to drive a generator delivering the current and voltage wanted. Motor generators, consisting of an appropriate motor mechanically coupled to an appropriate generator, can accomplish most of the indicated conversions. A rotary converter is a machine for converting alternating to direct current, using separate windings on a common rotating armature. The AC supply voltage is applied to the armature through slip rings, and the DC voltage is led out of the machine through a separate commutator. A dynamotor, which is usually used to convert low-voltage direct current to high-voltage direct current, is a similar machine that has separate armature windings.

Pairs of machines known as synchros, selsyns, or autosyns are used to transmit torque or mechanical movement from one place to another by electrical means. They consist of pairs of motors with stationary fields and armatures wound with three sets of coils similar to those of a three-phase alternator. In use, the armatures of selsyns are connected electrically in parallel to each other but not to any external source. The field coils are connected in parallel to an external AC source. When the armatures of both selsyns are in the same position relative to the magnetic fields of their respective machines, the currents induced in the armature coils will be equal and will cancel each other out. When one of the armatures is moved, however, an imbalance is created that will cause a current to be induced in the other armature. The magnetic reaction to this current will move the second armature until it is in the same relative position as the first. Selsyns are widely used for remote-control and remote-indicating instruments where it is inconvenient or impossible to make a mechanical connection.

DC machines known as amplidynes or rotortrols, which have several field windings, may be used as power amplifiers. A small change in the power supplied to one field winding produces a much larger corresponding change in the power output of the machine. These electrodynamic amplifiers are frequently employed in servomechanism and other control systems.

See Automation; Electricity.

"Electric Motors and Generators," Microsoft® Encarta® Online Encyclopedia 2001