22

Principles of Magnetics

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22.1 Introduction

Although magnetism has been known since ancient times, the connection between electricity and magnetism was not discovered until the early 19th century. Electromagnetics is the study of electric and magnetic field behavior. These fields arise from charged particles both at rest and in motion, and they may exert forces on other charged particles and materials.

Hans Christian Oersted (a Danish scientist) demonstrated the relation between electricity and magnetism. In 1819, he showed that a compass needle could be deflected by a current-carrying conductor. Andrew Ampere (1775–1836) experimented with two current-carrying conductors and found that they repel or attract each other. He developed a concept to understand the electromagnetism that led to the development of transformers and electric generators.

The theory of electromagnetic fields was developed by James Clerk Maxwell (Scottish scientist) and published in 1865. His work was the culmination of a long series of experimental and theoretical research performed by a number of other scientists over the centuries. Maxwell published a set of equations that completely describe the electromagnetic field. He developed a unified theory of electromagnetism, and he also predicted the existence of radio waves. Heinrich Hertz (a German physicist) proved the existence of such waves early in the 20th century.

The electromagnetic force (emf) is one of the four known fundamental forces of nature. The emf is responsible for the functioning of a large number of devices that are important to modern civilization including radio, television, cellular telephones, computers, and electric machinery. The emf is caused by an electromagnetic field that is described by two quantities, the electric field and the magnetic field, both of which can vary in space and time.

22.2 Nature of a Magnetic Field

Magnetism can create a force between magnetic materials depending on their magnetic fields. Magnetic fields can be produced by moving charged particles in electromagnets (e.g., electrons flowing through a coil of wire connected to a battery) or in permanent magnets (spinning electrons within the atoms generate the field). Figure 22.1 shows Faraday's concept of the magnetic flux lines or lines of force on a

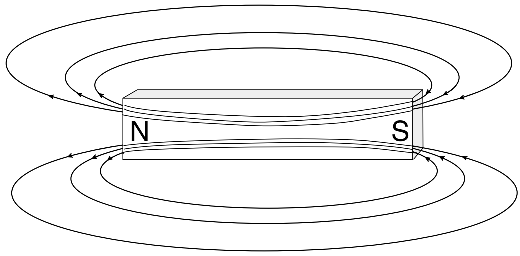

FIGURE 22.1 Magnetic field (Φ) of a bar magnet.

permanent bar magnet. The magnetic field is much stronger at the poles than anywhere else. The direction of the field lines is from the North Pole to the South Pole, and the external magnetic field lines never cross.

According to the molecular theory of magnetism, within permanent magnets there are tiny molecules or domains that can be considered micromagnets. When they line up in a row, they combine to increase the magnetic field strength. For example, in a normal piece of steel, the domains are arranged in random order having positive and negative poles scattered in all directions. When the steel is magnetized, the domains line up, allowing the whole piece of steel to act like one large magnet. By placing a magnet beneath a piece of paper and placing iron filings on top of the piece of paper, the iron filings will arrange themselves to look like the invisible magnetic force that surrounds the magnet. This invisible magnetic force, which exists in the air or space around the magnet, is known as a magnetic field and the lines are called magnetic lines of force, as shown in Fig. 22.1.

Ferromagnetic materials (e.g., iron, nickel, and cobalt) are those materials whose domains are capable of aligning to create a magnetic field. Because of this ability, they provide an easy path for external magnetic field lines. Elements and alloy substances differ in their ability to become magnetized by an external field (susceptibility). Materials can be strongly magnetized by the formation domains in which individual atoms that are weakly magnetic because of their spinning electrons align to form areas of strong magnetism. Magnetic materials lose their magnetism if heated to or above the Curie temperature. Other materials are mostly paramagnetic, that is, only weakly pulled toward a strong magnet. This is because their atoms have a low level of magnetism and do not form domains. Diamagnetic materials are the opposite of ferromagnetic materials; they are weakly repelled by a magnet since electrons within their atoms act as electromagnets and oppose the applied magnetic force. Antiferromagnetic materials have a very low susceptibility, which increases with temperature.

22.3 Electromagnetism

Electromagnetism is a magnetic effect due to electric currents. When a compass is placed in close proximity to a wire carrying an electrical current, the compass needle will turn until it is at a right angle to the conductor. The compass needle lines up in the direction of a magnetic field around the wire. It has been found that wires carrying current have the same type of magnetic field that exists around a magnet, as shown in Fig. 22.2. One can say that an electric current induces a magnetic field and the field is proportional to the current, I.

In Fig. 22.2, the "rings" represent the magnetic lines of force existing around a wire that carries an electric current, I. The magnetic field is strongest directly around the wire, and extends outward from the wire, gradually decreasing in intensity.

The direction of a magnetic field can be predicted by use of the right-hand rule. According to the right-hand rule, the right hand is placed around the wire that is carrying the current and the thumb follows the direction of current flow. Then the fingers will show the direction of the magnetic field around the conductor.

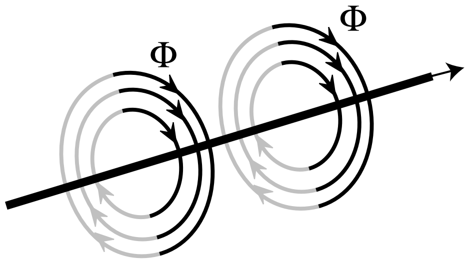

FIGURE 22.2 Magnetic field produced by current, *I*.

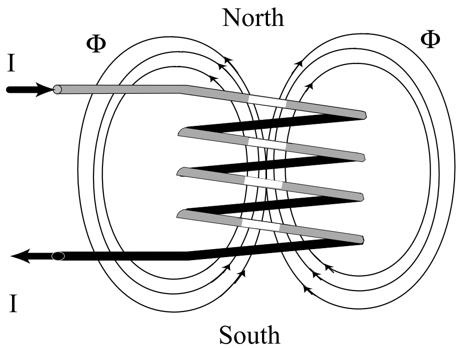

FIGURE 22.3 Magnetic field (Φ) produced by a coil.

Figure 22.3 shows a case where the wire is looped into a coil. A little magnetic field wraps around each wire and, by combining each wire turn, the coil magnetic flux (Φ) is created. It was found by experimentation that if a wire is wound in the form of a coil, the total magnetic field around the coil is magnified. This is because the magnetic fields of the turns add up to make one large flux flow, resulting in a magnetic field (Φ), shown in Fig. 22.3.

22.4 Magnetic Flux Density

Fig. 22.4 shows a ferromagnetic material where the most of flux is combined to the core. Only a small amount of the leakage flux escapes on the sides of the coil. The unit of flux (Φ) is the weber in the SI system. Flux density (B) is the magnetic flux per unit area. If the cross-sectional area (A) in SI units is m^2, then the flux density is in webers per m^2 (Wb/m^2), which is called tesla (T). Flux density (B) is defined by the total flux (Φ) passing perpendicularly through an area (A).

$$B = \frac{\Phi}{A} \qquad (T) \tag{22.1}$$

22.5 Magnetic Circuits

Current (I) flowing through the coil shown in Figs. 22.3 and 22.4 creates the magnetomotive force ($\Im$). The greater number of turns, the greater will be the flux. The magnetomotive force, or mmf, is defined as

$$\Im = N \cdot I \qquad \text{(ampere—turns, At)} \tag{22.2}$$

where N is the number of coil turns and I is the current passing through the wire. For example, a coil with 200 turns and 2 A will have an mmf of 400 At.

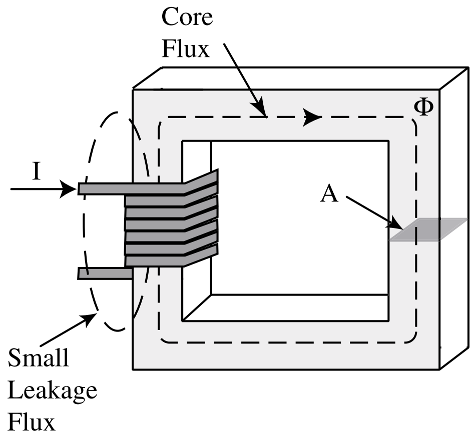

FIGURE 22.4 Magnetic flux density in a ferromagnetic material.

The magnitude of magnetic flux depends upon the opposition presented by the magnetic circuit. The opposition to the flux is called reluctance, which is similar to resistance in an electric circuit. The reluctance is defined as

$$\Re = \frac{\ell}{\mu A} \qquad (\text{At/Wb}) \tag{22.3}$$

where ℓ is the length of the magnetic core and A is a cross-sectional area. The property of the material is characterized by its permeability, μ. Materials with high μ are called ferromagnetic materials, and the reluctance of those materials is low.

22.6 Magnetic Field Intensity

The magnetizing force, H, also known as magnetic field intensity, is the mmf per unit length. The magnetic field intensity is written as

$$H = \frac{\Im}{\ell} = \frac{NI}{\ell} \qquad (\text{At/m}) \tag{22.4}$$

Equation (22.4) describes an ability of a coil to produce magnetic flux. If, for example, in Fig. 22.4, the coil has 1000 turns, the length of the magnetic path is 0.6 m and current through the conductor is 1 A, then the magnetic field intensity is 600 At/m.

The field intensity and the resulting flux density are related through the permeability. The flux density is

$$B = \mu H \qquad (\text{T}) \tag{22.5}$$

where μ is core permeability. The core permeability is a material constant describing the level of the flux in a material. When the material constant (μ) is high, the flux density will increase. The permeability has units of webers per ampere-turn-meter in the SI system. The permeability of vacuum in free space is $\mu_o = 4\pi \times 10^{-7}$ (Wb/At-m). When magnetic flux propagates through magnetic media, other than vacuum, the flux density is

$$B = \mu_r \mu_o H \qquad (\text{T}) \tag{22.6}$$

where μ_r is the relative permeability. The relative permeability is 1 for a vacuum and can reach 10,000 for ferromagnetic materials. Ferromagnetic materials have regions called domains of microscopic size.

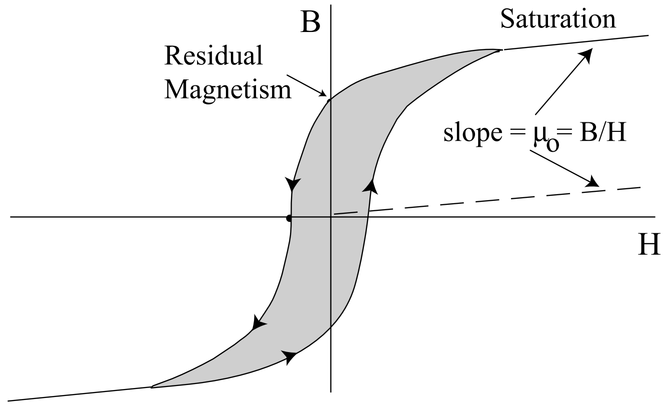

FIGURE 22.5 Hysteresis loop.

When they line up, the material is magnetized. Thus, one can increase the magnetic field until all domains are aligned, at which point the ferromagnetic material is incapable of contributing any more magnetic flux. At that point the material is saturated, as shown on the hysteresis curve in Fig. 22.5.

22.7 Maxwell's Equations

Maxwell's equations are the fundamental concept of electromagnetic (E-M) field theory. Using E-M field theory, one can calculate important quantities such as impedance, inductance, capacitance, etc. Maxwell's equations in differential form are as follows:

$$\nabla \times \bar{H} = J + \frac{\partial \bar{D}}{\partial t} \tag{22.7}$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \tag{22.8}$$

$$\nabla \cdot \bar{D} = \rho \tag{22.9}$$

$$\nabla \cdot \bar{B} = 0 \tag{22.10}$$

where H is the magnetic field intensity (A/m), D is the electric flux density (C/m^2), B is the magnetic flux density (T), J is the current density (A/m^2), ρ is the charge density (C/m^3), and E is the electric field intensity (V/m). The other relations to Maxwell's equations are

$$\bar{D} = \varepsilon\bar{E} = \varepsilon_r \varepsilon_o \bar{E} \tag{22.11}$$

$$\bar{B} = \mu\bar{H} = \mu_r \mu_o \bar{H} \tag{22.12}$$

$$\bar{J} = \sigma\bar{E} \tag{22.13}$$

where ε_o is the permittivity of free space (8.854×10^{-12} F/m) and ε_r is the relative dielectric constant for a given material. In the second equation, μ_o is the permeability of free space ($4\pi \times 10^{-7}$) and μ_r is the relative permeability for a given material. In the third equation, σ is the electric conductivity (Siemens).

Maxwell's equations can be rewritten into integral form using mathematical tools, such as Stokes' theorem and the divergence theorem, and then they look as follows:

$$\text{Faraday's law:} \quad \oint \bar{H} \cdot d\bar{\ell} = I + \int_s \frac{\partial \bar{D}}{\partial t} \cdot d\bar{s} \tag{22.14}$$

$$\text{Ampere's law:} \quad \oint \bar{E} \cdot d\bar{\ell} = -\int_s \frac{\partial \bar{B}}{\partial t} \cdot d\bar{s} \tag{22.15}$$

$$\text{Gauss' law:} \quad \oint_s \bar{D} \cdot d\bar{s} = q_{\text{encl.}} = \int_{\text{vol}} \rho \, dv \tag{22.16}$$

$$\oint_s \bar{B} \cdot d\bar{s} = q_{\text{encl.}} = 0 \tag{22.17}$$

Michael Faraday (1791–1867) experimented with magnetic fields. He wound two coils on an iron ring. When one coil was powered from a battery, he noticed that a transient voltage developed on the second coil and, later, this led him to develop a transformer. Faraday concluded from his observations that voltage is induced in a circuit whenever the linking flux in the magnetic circuit changes. He also discovered a formula describing the change of a magnetic flux, which is proportional to the voltage change across the coil. Equation (22.14) shows the Faraday law in the integral form derived from Maxwell's equations. The first right-hand term of this equation is regular current flowing in a wire, and the second term is due to capacitive coupling called the "displacement current." In most cases the displacement current is neglected.

An example of a magnetic field density at a distance r of a long straight wire is shown in Fig. 22.6. One can assume $I = 100$ A, $r = 1$ m, and $\mu = \mu_o$. Using Eq. (22.14) one can write

$$\oint \bar{H} \cdot d\bar{\ell} = I$$

and take the integral around the wire at a constant distance r.

Integrating over a circular path,

$$\oint \bar{H} \cdot d\bar{\ell} = 2\pi r H_\Phi = I$$

and then,

$$B_\Phi = \frac{\mu I}{2\pi r} = \frac{100 \times 4\pi \times 10^{-7}}{2\pi \times 1} = 2 \times 10^{-5} \quad \text{(T)}$$

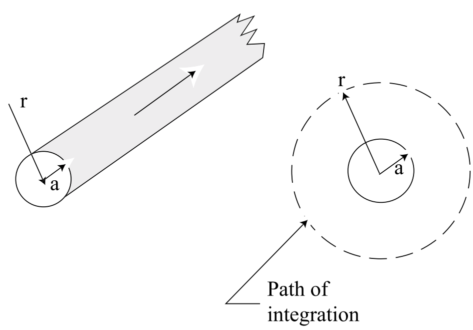

FIGURE 22.6 Long straight wire carrying a current, I.

In this example magnetic field lines form circles around the wire, as shown in Fig. 22.2. The magnetic field intensity decreases with distance from the wire.

By Faraday's law, the induced voltage is proportional to the rate of the magnetic flux change times the number of turns in a coil. In calculus notation, the rate of flux change times the number of turns is

$$e = N\frac{d\Phi}{dt} \quad \text{(V)} \tag{22.18}$$

where e is in volts, Φ is webers, N is the number of turns, and t is in seconds. For example, if the magnetic flux changes at a rate of 1 Wb/s in a single turn coil, the induced voltage is 1 V.

22.8 Inductance

The induced voltage in a coil is proportional to the magnetic flux change that is shown in Eq. (22.18). It is also known that the induced current is proportional to the current. Thus, one can write that the induced voltage is proportional to the current change,

$$e = L\frac{di}{dt} \quad \text{(V)} \tag{22.19}$$

where L is the inductance of the coil. The unit of inductance is the henry in the SI system. In practice, in electrical circuit calculations, the voltage across the inductance is denoted by v_L rather than e. Then, one can rewrite Eq. (22.19) as

$$v_L = L\frac{di}{dt} \quad \text{(V)} \tag{22.20}$$

22.9 Practical Considerations

Faraday's law states that a time-varying magnetic field through a surface bounded by a closed path induces a voltage inside a conductor loop. This fundamental principle has important consequences for parasitic coupling in electronic hardware, such as a noisy circuit on a printed circuit board of a computer. The problem is a significant time-varying magnetic field as a result of current levels in different conductive traces. Some of the traces can make current loops. The magnetic field generated by the loop area "looks" for other loops—the circuits where it can induce a voltage across the load. We consider the target loop area when looking at its mutual inductance, and the target loop area is determined by the closed current path in the victim circuit. The magnitude of induced voltage in the victim circuit depends on various factors:

- Current magnitude in the first circuit
- Source and load circuit impedances
- Size of the loop area in the victim circuit
- Distance between the victim and source circuits
- Orientation of the loops

This coupling can cause faulty operation of the victim circuit.