5

Electromagnetism and Magnetic Circuits

TOPICS DISCUSSED

- Magnetic fields
- Types of magnets
- Concept of magnetization
- Magnetization curve
- Magnetic saturation
- Hysteresis loss and Eddy current loss
- Series and parallel magnetic circuits
- Analogy of magnetic and electric circuits
- Magnetic leakage and fringing
- Lifting power of an electromagnet

5.1 MAGNETS AND MAGNETIC FIELDS

Magnetism plays an important role in the field of electrical engineering. Construction of almost all electrical gadgets, equipment, and machines are done using the properties of magnetism, like in transformers, electrical rotating machines, i.e., Magnets show the property of magnetism. Magnets are of two types, viz permanent magnets and electromagnets. Magnets attract all ferromagnetic material which contain iron, nickel, and cobalt.

Permanent magnets are made of material like alnico (alloy of aluminium, nickel, and cobalt) in which the magnetism once created is retained for a very long time, i.e., the magnetic property is permanently set. Electromagnets are made by placing a coil around a magnetic material which forms the core. They demonstrate magnetic properties as long as current flows through the coil.

Magnetic field is the area around a magnet in which there is influence of the magnet. This can be tested by bringing a magnetic needle near a magnet and observing the deflection of the needle. The magnetic field around a magnet is shown through lines of force. There are very large number of lines of force around a magnet. Lines of force are closed curves. The lines of force come out of the magnet body from the North pole and enter the South pole and close their path through the magnet body. The pattern of lines of force is the same for a permanent magnet and for an electromagnet. Fig. 5.1 shows magnets and magnetic fields of permanent magnets and electromagnets of different shapes.

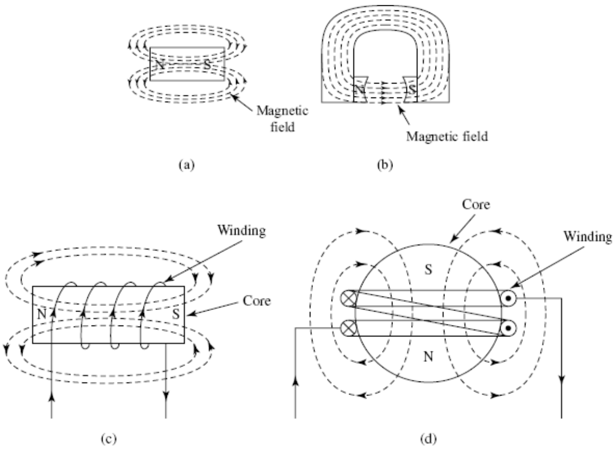

Figure 5.1 (a) and (b) permanent magnets; (c) and (d) electromagnets

Fig. 5.1 (a) shows a bar-type permanent magnet, while Fig. 5.1 (b) shows a horse-shoe-type permanent magnet. Fig. 5.1 (c) and (d) are electromagnets. It should be noticed that the North pole is the one wherefrom the magnetic lines of force come out of the magnet body and the South pole is the one where the lines of force enter the magnet body. In Fig. 5.1 (d) has been shown a solid cylindrical core around which a coil of two turns have been wound. The direction of currents at the two sides of a coil have been shown by crosses and dots. A cross indicates current entering and a dot indicates current coming out. The direction of flux around the coil sides have been determined by applying the cork screw rule. After showing the lines of

To understand further how the magnetic field around a coil is established, we will first draw the field around a current-carrying conductor and then show the magnetic field around a coil.

The direction of the lines of force around a current-carrying conductor has been shown. If the advancement of the screw when it is turned indicates the direction of the current through the conductor, the direction of the rotation of the screw will indicate the direction of the flux produced around the conductor as has been shown in Fig. 5.2 (a). In Fig. 5.2 (b) the cross-sectional view of the conductors and the direction of the current through them have been shown by cross and dot. Flux around the conductor have been shown and their direction is determined by applying the cork-screw rule. When two conductors or coil sides appear side by side carrying current in the same direction, a resultant magnetic field gets established as has been shown in Fig. 5.2 (c).

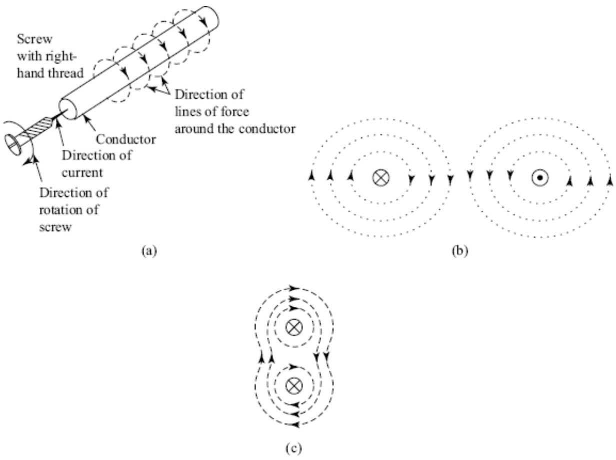

Figure 5.2 (a) Magnetic field around a current-carrying conductor; (b) two conductors placed side by side carrying current in opposite directions; (c) two conductors placed side by side carrying current in the same direction

When a conductor is wound in the form of a coil, a resultant magnetic field is established around it. After passing a direct current, if a magnetic needle is brought near the coil, it will be observed that the coil has a North pole and a South pole. The magnetic field produced by a current-carrying coil, the magnetic field around it, and the positions of the North and South poles have been shown in Fig. 5.3.

The strength of a magnetic field is expressed in terms of the number of flux lines, f and is measured in Webers, where 1 Wb = 10^8 lines.

5.1.2 Magnetic Flux Density

Magnetic flux density, i.e., flux per unit area is denoted by B. If A is the area through which the flux lines emanate, i.e., come out, the flux density is given as

A magnetic potential or magneto motive force (MMF) is expressed as the product of the number turns of the coil and the current passing through it, i.e.,

$$\text{MMF} = \text{N I} \tag{5.2}$$

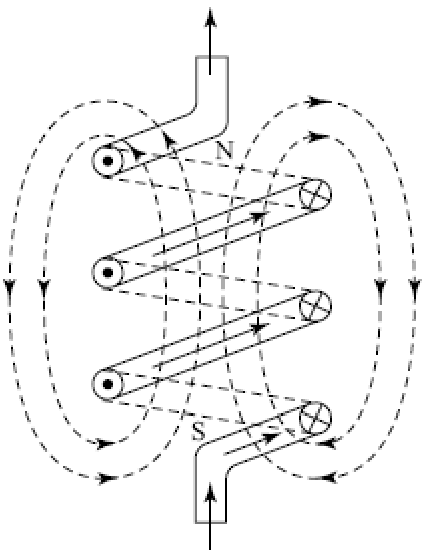

Figure 5.3 Magnetic field around a current-carrying coil

The unit of I is Amperes, and number of turns has no unit. Thus, logically the unit of MMF should be Amperes only. However, to differentiate the unit of MMF from the unit of current, the unit of MMF is expressed as ampere turns (AT).

The magnetic potential or MMF determines the magnetic flux around a coil. To produce a particular amount of flux or flux density, the number of turns or the current flowing, can be varied.

5.1.3 Magnetic Field Strength

The length of the field lines corresponds to the mean length of a coil. Fig. 5.4 shows two electromagnets having the same number of turns wound on two cores of different diameters. If the same amount of current is passed through both the coils, the MMF, i.e., N × I will be the same.

Magnetic field strength

It can be seen from Fig. 5.4 (a) and (b) that the mean length of the flux path is different. In the case of Fig. 5.4 (b) the length is higher. The MMF which is a product of N and I is the same.

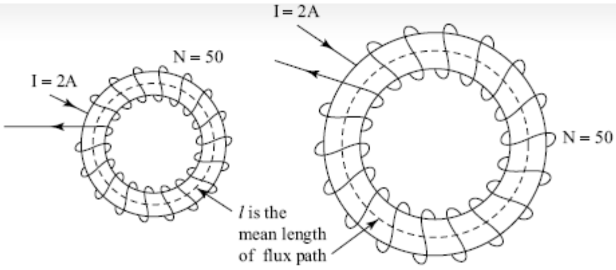

Figure 5.4 Mean length of the flux path in toroidal cores. The mean length of the flux path is more in (b) as compared to that in (a)

For the same MMF, the magnetic flux, f or the magnetic flux density, B will be dependent upon the length of the field lines. The longer is the length, the weaker will be the flux density. Magnetic field strength, H is expressed as

$$H = \frac{NI}{l} \text{ AT/m} \tag{5.3}$$

The longer is the flux line length, the weaker will be the magnetic field strength for the same amount of MMF. Since the magnetic field strength, H depends upon the number of turns of the magnetizing coil, the current flowing through the coil, and the flux line length, there would exist a relationship between the magnetic field strength H and the magnetic flux density B, when a magnetic material is magnetized by applyingMMF. If we plot the flux density, B against the magnetizing force applied, H, we will get a linear relationship as shown so in Fig. 5.5 so that

B α H

or, B = K H

This constant K is called the **permeability** of the core material and is denoted by μ. Thus, we can write

$$B = \mu H \tag{5.4}$$

Since this equation is similar to the equation of a straight line passing through the origin (y = mx), the slope will depend on the value of **permeability**, **μ**. Permeability is the magnetic property of the core material. The core may be, e.g. air, cardboard, bakelite former, or iron.

5.1.4 Permeability

The graphic representation of the relationship between B and H is called the magnetization curve. In the case of air core coil, the magnetization curve is a straight line with a small slope with the H-axis showing that a large value of H is required to produce a small amount of flux or flux density. If iron is used as the core material the slope will greatly increase indicating that a small magnetizing force produces a large amount of flux and a high value of flux density.

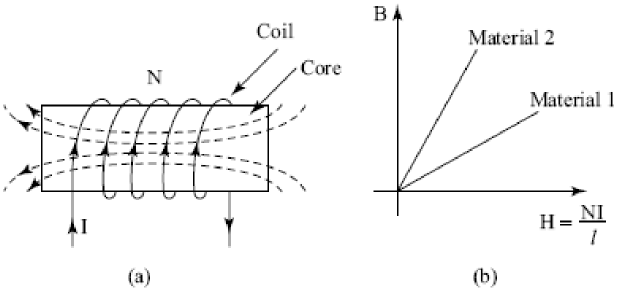

Figure 5.5 (a) Magnetizing force applied to a magnetic material; (b) incomplete B–H curve of two magnetic materials

5.1.5 Relative Permeability

The permeability of a magnetic material is compared with that of free space and is called relative permeability. The relative permeability indicates how many times the material is more permeable than air. Permeability, μ is expressed as

$$\mu = \mu_o \mu_r \tag{5.5}$$

where μ_0 is the permeability of free space and μ_r is the relative permeability, and B is the magnetic flux density.

Magneto motive force (MMF) and magnetic field strength, H

When a current, I flows through a coil of N turns, the MMF, F is the total current linked with the magnetic circuit, i.e., NI amperes. If the magnetic circuit is of uniform cross-sectional area, the MMF per unit length of the magnetic circuit is called magnetic field strength, H.

Thus, $$H = \frac{NI}{l} \text{ AT/m}$$

Relation between flux density, B and field intensity, H

The ratio of B and H is called the permeability of free space and is represented by μ_0

$$\mu_0 = \frac{B}{H} \text{ henry per meter}$$

This value is for free space or air or for any non-magnetic material like paper, wood, oil, etc.

The relation, B = m_0H is true when the medium is free space or air. When the medium through which flux or flux density is established is changed, the value of flux, f or flux density, B increases. It has been observed that when the core of a current-carrying coil is made of iron instead of being an air-core one, the value of the flux density produced increases many times. The ratio of the flux density produced with iron core to the flux density produced with air core by the same magnetic field strength is called the relative permeability, μ_r.

For air, $\mu_r = 1$ and for iron or for some alloys of iron, μ_r can be very high. Relative permeability, as mentioned earlier, indicates how many times the material is more permeable than air (permeability is similar to conductivity in an electrical circuit. Permeability is the ability of the material to allow the establishment of flux through it)

For a non-magnetic material or air or vacuum as the medium, we write

$$B = \mu_0 H \tag{5.6}$$

While for a material of the medium having a relative permeability of m_r we write,

$$\begin{aligned} B &= \mu_0 \mu_r H = \mu H \\ \mu &= \mu_0 \mu_r = 4\pi \times 10^{-7} \times \mu_r \end{aligned} \tag{5.7}$$

5.2 MAGNETIC FIELD DUE TO CURRENT-CARRYING CONDUCTOR LAWS OF ELECTROMAGNETISM

When a conductor carries current, a magnetic field is established around it in a perpendicular plane in the form of concentric circles. The relationship between the current, I and the magnetic field intensity, H is obtained by using Amperes circuital law.

The magnetic field strength at a point due to an incremental length dl of current-carrying conductors is determined by using Biot–Savart law. These two laws are explained below.

5.2.1 Ampere's Circuital Law

This law states that the line integral of magnetic field intensity, H around a closed path is equal to the current enclosed by the path. Consider a current-carrying conductor, I producing a magnetic field an a perpendicular plane as shown in Fig. 5.6. The magnetic field intensity, H at a distance, r from the current-carrying conductor is expressed as the line integral of H multiplied by dl as equal to the total enclosed current. That is

$$\oint H \cdot dl = I \tag{5.8}$$

If there are N number of current-carrying conductors enclosed then, H is expressed as

$$H = \frac{NI}{2\pi r}$$

where $2\pi r$ is the length of the flux path. This expression for H is the same as in eq. (5.3).

5.2.2 Biot-Savart Law

This law is also used to determine the magnetic field intensity, H around a current-carrying conductor. According to Biot-Savart law, the magnetic field intensity at a point P due to current flowing through an extremely small element of length dl is

- directly proportional to the current, I
- directly proportional to the length of the element, dl
- directly proportional to the sine of angle q where q is the angle between the direction of the current and the line joining the element dl with the point P as shown in Fig. 5.7.
- inversely proportional to the square of the distance *r* of the point from the element of length dl.

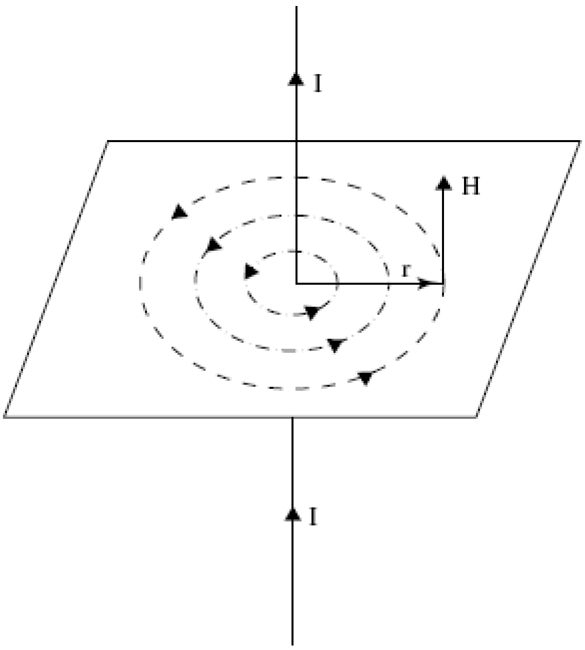

Figure 5.6 Magnetic field around a current-carrying conductor

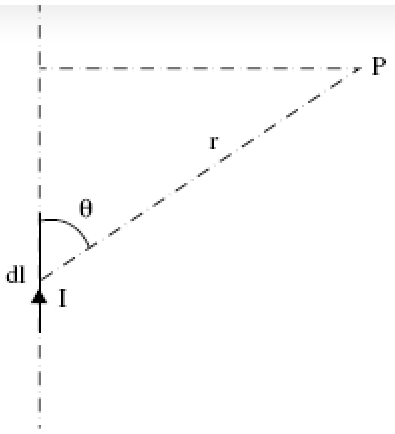

Figure 5.7 Biot-Savart law

The law can be expressed mathematically as

$$dH \propto \frac{I\,dl}{r^2}\sin\theta$$

or, $$dH = \frac{I\,dl\sin\theta}{4\pi r^2} \qquad (5.9)$$

where 1/4π is the constant of proportionality.

By applying Biot-Savart law, we can determine the magnetic field strength around current-carrying conductors arranged in different manner. Some of these are explained as follows.

5.2.3 Application of Biot-Savart Law

a) Magnetic field strength around a long straight current-carrying conductor

Field strength around a long conductor will be calculated by using expression (5.8) from q = 0 to q = p as shown in Fig. 5.8.

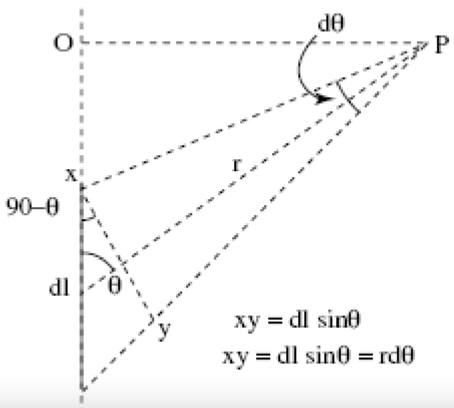

Figure 5.8

Thus,

$$H = \int_0^{\pi} \frac{I\,dl \sin\theta}{4\pi r^2}$$

From Fig (5.8),

$$dl \sin\theta = r\,d\theta$$

Substituting

$$H = \int_0^{\pi} \frac{Ir \sin\theta\, d\theta}{4\pi r^2}$$
$$= \int_0^{\pi} \frac{I \sin\theta\, d\theta}{4\pi r} \backslash$$
$$= \frac{I}{4\pi r} \int_0^{\pi} \sin\theta\, d\theta$$
$$= \frac{I}{4\pi r}[-\cos\theta]_0^{\pi}$$

or, $$H = \frac{I}{2\pi r}\ \text{AT/m}$$

Flux density in a medium of air is

$$B = \mu_0 H = \frac{\mu_0 I}{2\pi r}\ \text{Wb/m}^2$$

b) Field strength around a circular loop

A circular coil of radius r metres carrying a current of I amperes has been shown in Fig. 5.9. The field strength at a point P which is situated at a distance of d metres from the centre of the coil is to be determined. Let dl_1 and dl_2 be the two elements of length diametrically opposite to each other on the circular path. Applying Biot-Savart law, the field strength at P due to current, the elements of length dl_1 and dl_2, respectively are

$$dH_1 = \frac{I\,dl_1}{4\pi x^2} \text{ acting along PQ}$$

$$dH_2 = \frac{I\,dl_2}{4\pi x^2} \text{ acting along PR}$$

and

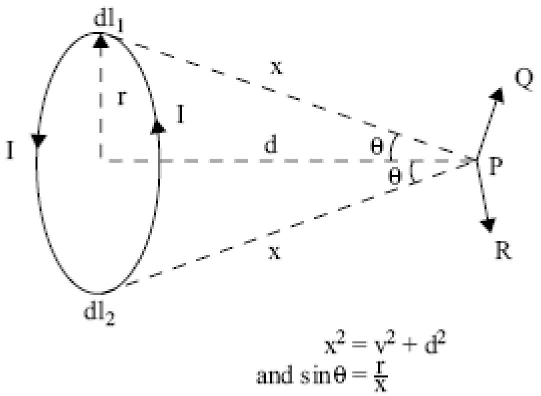

Figure 5.9

The resultant of the two vectors PQ and PR were give the net magnetizing field intensity

$$dH = \frac{2\,I\,dl_1}{4\pi x^2}\sin\phi = \frac{I\,dl_1 \sin\phi}{2\pi x^2}$$

To determine the total H, we have to integrate the above expression as

$$H = \int_0^{\pi r} \frac{I\,dl_1 \sin\phi}{2\pi x^2} = \int_0^{\pi r} \frac{I\,r}{2\pi x^2 \times x}\,dl_1 = \frac{Ir \times \pi r}{2\pi x^3}$$

$$H = \frac{IR^2}{2(r^2+d^2)^{3/2}} \qquad \left[\begin{array}{l} \because x^2 = r^2 + d^2 \\ \text{or } x = (r^2+d^2)^{3/2} \end{array}\right]$$

If the circular coil has N number of turns, then

For determining the field strength at the centre of the current-carrying coil, we put d = 0. Thus, the magnetic field strength, the H_c at the centre of the coil is

$$H_c = \frac{NIr^2}{2r^3}\ \text{AT/m}$$

$$H_c = \frac{NI}{2r}\ \text{AT/m} \tag{5.11}$$

c) Field strength inside a solenoid carrying current

Fig. 5.10 (a) shows a solenoid with N number of turns and having a length *l*. The cross-sectional view has been shown in Fig. 5.10 (b).

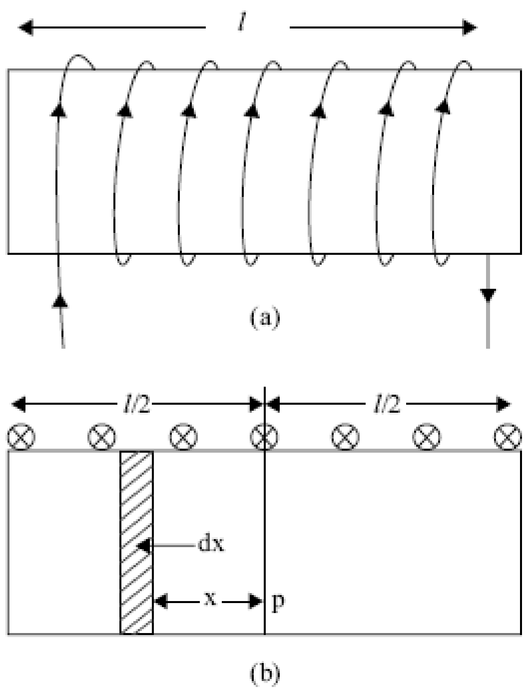

Figure 5.10

We had calculated the field intensity at the centre of a circular coil as

$$H = \frac{Ir^2}{2(r^2 + x^2)^{3/2}}$$

$$\frac{NI}{l}dx$$

Thus, $$dH = \int_{-l/2}^{+l/2} \frac{NI\,dx\,r^2}{l \times 2(r^2 + x^2)^{3/2}}$$

or, $$H = \frac{NIr^2}{2l} \times \frac{l}{r^2(r^2 + l^2/4)^{1/2}}$$

or, $$H = \frac{NI}{(4r^2 + l^2)^{1/2}} \text{ AT/m}$$

If the length of the solenoid is large as compared to its radius, r then, the flux density at the centre of the solenoid is

$$H = \frac{NI}{l} \text{ AT/m}$$

Example 5.1 A single turn coil of radius 10 cm is carrying a current of 100A. Calculate (i) the flux density at the centre of the coil; (ii) the flux density in the perpendicular plane at a distance of 5 cm from the coil.

Solution:

Earlier we had calculated the magnetic field strength at the centre of a current-carrying coil of single turn as

$$H_c = \frac{I}{2r} \text{ AT/m}$$

With air as the medium, the flux density at the centre

$$B_c = \frac{\mu_0 I}{2r}$$

Substituting values

$$B_c = \frac{4\pi \times 10^{-7} \times 100}{2 \times 10 \times 10^{-2}}$$
$$= 628 \times 10^{-6} \text{ Wb/m}^2 \text{ or Tesla}$$

$$B = \frac{\mu_0 I r^2}{2(r^2 + d^2)^{3/2}}$$

Substituting value

$$B = \frac{4\pi \times 10^{-7} \times 100 \times (0.1)^2}{2[0.1^2 + 0.05^2]^{3/2}}$$

$$B = \frac{6.28 \times 10^{-7}}{(0.0125)^{3/2}} \text{ Wb/m}^2$$

$$= \frac{62.8 \times 10^{-6}}{(0.0125)^{-3/2}} \text{ Wb/m}^2$$

or, $$= 268 \times 10^{-6} \text{ Wb/m}^2$$

5.3 MAGNETIZATION CURVE OF A MAGNETIC MATERIAL

Electromagnets are produced by winding a coil around a piece of magnetic material, say iron, and passing current through the coil. When current is increased gradually, the flux will increase. The rate of increase of the flux produced with increase in current will slow down after a sufficient increase of current as shown in Fig. 5.11. The core is said to be saturated when further increase of current through the coil does not cause further increase of flux. The flux per unit area is expressed as flux density B.

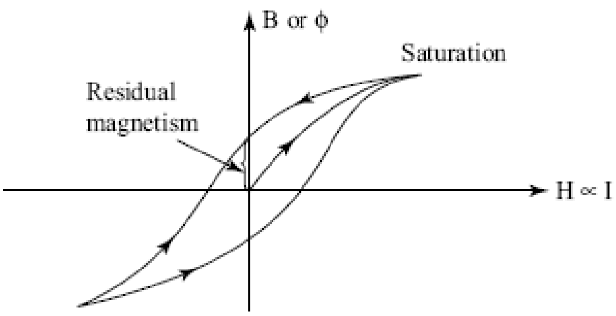

Figure 5.11 B–H characteristic of a magnetic material

Flux density, $$B = \frac{\text{Flux}}{\text{Area}} = \frac{\phi}{A}$$

where A is the cross-sectional area of the core. The magnetizing force is expressed in terms of ampere-turns per unit length. That is, magnetizing force H is given as

$$H = \frac{NI}{l}$$

Where l is the length of the flux path.

5.4 HYSTERESIS LOSS AND EDDY CURRENT LOSS IN MAGNETIC MATERIALS

Magnetization of the magnetic material in opposite directions due to application of alternate magnetizing force, involves certain amount of work done. The work done is represented by the area of the hysteresis loop. The hysteresis loop area depends upon the nature of the magnetic material. In selecting the material for the core of any electrical machine and equipment, a study of the hysteresis loop is made. For example, if we want that high flux should be produced by applying a low magnetizing force, and the loop area also be small then we must use a material whose hysteresis loop area should be as shown in Fig. 5.12 (a). A certain percentage of silicon when added to steel provides this kind of B–H characteristic. Silicon steel is used as the core material of transformers, as will be studied in a separate chapter. In Fig. 5.12 (b) is shown the B–H characteristic of the material used for making permanent magnets like alnico (alloy of aluminium, nickel, and cobalt). Here the residual magnetism is large and the negative magnetizing force required to bring down the residual magnetism to zero (which is called the coercive force) is also large.

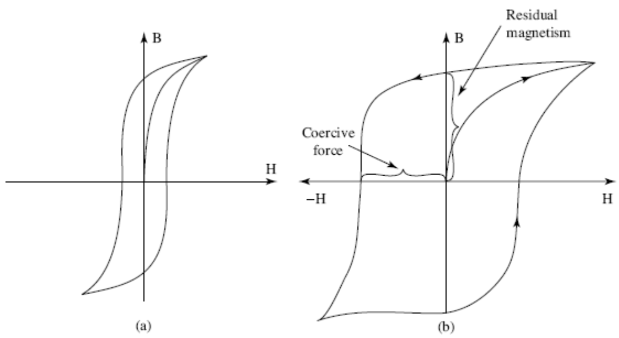

Figure 5.12 (a) Hysteresis loop for silicon steel; (b) hysteresis loop for alnico

5.4.1 Hysteresis Loss

The energy spent in alternate magnetization of the core appears as heat in the magnetic material. An emperical formula to calculate hysteresis loss in a magnetic material has been developed on the basis of experiments.

If the magnetizing force is now reduced, the curve traces a somewhat different path as shown. The negative current provides magnetization in the opposite direction as shown. When the magnetizing force is reduced to zero, there is some magnetism left in the magnetic material, which is known as residual magnetism. In electrical machines, this residual magnetism plays an important role, as which is called hysteresis loss, which will also be studied in detail later. In most electrical machines and equipment attempt is made to reduce hysteresis loss to increase the efficiency of machines and equipment. The magnetization characteristic due to alternating current passing through the coil is represented by a loop, called hysteresis loop as shown in Fig. 5.11 and Fig. 5.12.

The expression for hysteresis loss, W_h is given as

$$W_h = K_h v \; f \; B_m^{1.6} \; W \tag{5.12}$$

Where, K_h is a constant which depends upon the material and the range of flux density, v is the volume of the core material, f is the frequency of alternation of the current passing through the magnetizing coil B_m is the maximum value of flux density in the core in Wb/m^2.

The power of B_m is generally 1.6. However, depending on the quality of the material, the power of B_m may vary from 1.5 to 2.0.

5.4.2 Eddy Current Loss

When a magnetic material is subjected to a changing magnetic field (e.g. the magnetic core of an inductor), EMF is induced in the core. This EMF causes circulating currents in the core. These circulating currents are called eddy currents. Energy in the form of heat is lost in the core due to this eddy current flow. Through experiments, it has been found that eddy current loss depends on the following:

- thickness of the magnetic material, t;
- frequency of current producing the alternating magnetic field, i.e., the frequency of current flowing through the magnetizing coil, f;
- maximum flux density, B_m
- volume of the material, v

$$\text{Eddy current loss, } W_e = k_l \, v \; B_n^2 \, f^2 \, t^2 \; W \tag{5.13}$$

Where k_e is the eddy current coefficient which depends upon the type of the magnetic material.

To reduce eddy current loss in a magnetic material, the thickness is reduced. Laminated sheets are used to build a core instead of using one piece solid core. The sum of hysteresis loss and eddy current loss is called core loss or iron loss.

5.5 MAGNETIC CIRCUITS

All electrical machines and equipment are made of magnetic material as their core. A winding which carries current is placed around the core. The core and the current-carrying coil around the core forms an electro magnet. Thus, we can say that an electro magnet is battery, as shown in Fig. 5.13 (b). The magnetizing force applied is the product of the number of turns of the coil (N) and the current flowing through the coil (I). Let us examine how the magnetizing force, NI magnetizes the magnetic material.

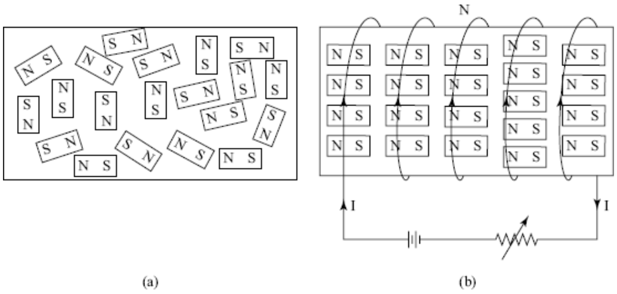

Figure 5.13 (a) Orientation of magnetic dipoles before the application of magnetizing force; (b) on application of the magnetizing force, NI, the magnetic dipoles get oriented in one direction

It is known that a magnetic material is composed of tiny magnets called magnetic dipoles oriented in a random fashion in all directions as shown in Fig. 5.13 (a). The magnetizing force orients these tiny magnets in the direction of magnetization. When the tiny magnets get oriented in a particular direction the material becomes a strong magnet as the magnetism of all the tiny magnets get summed up. In Fig. 5.13, the tiny magnets forming the magnetic material have been shown very much enlarged only to help understanding and bring clarity. In fact, their number is more and they are very very tiny and cannot be observed through naked eyes.

Thus, when magnetized, one side of the bar magnet becomes a strong North pole and the other side becomes a strong South pole. The strength of this electro magnet produced by the magnetizing force is directly proportional to the magnetizing force and inversely proportional to the reluctance of the flux path. Reluctance is the opposition offered to the establishment of flux.

The amount of flux produced by the magnet indicates the strength of the magnet. The more the magnetizing force (MMF), more is the flux produced. The more the opposition to flux path (i.e., reluctance or magnetic resistance) less is the flux produced. This relationship is expressed as

$$\text{Flux} = \frac{\text{MMF}}{\text{Reluctance}}$$

or,

$$\phi = \frac{NI}{S} \tag{5.14}$$

Reluctance is the opposition offered by the material in the flux path to the establishment of the flux. Reluctance in a magnetic circuit is similar to the resistance in an electric circuit.

We have known that resistance, $$R = \rho\frac{l}{A}$$

Similarly, reluctance, $$S = K\frac{l}{A} = \frac{l}{\mu A} \qquad (5.15)$$

Where $$K = \frac{1}{\mu}$$

l = length of the flux path

A = area of cross section of the flux path

μ = permeability of the magnetic material.

It can be observed that reluctance is inversely proportional to permeability for a particular material. That is to say that a material with high permeability allows more flux to be established for a given amount of magnetizing force.

Permeability is the ability of a magnetic material which allows the establishment of flux through it. Thus, permeability is the reciprocal of reluctance of a magnetic material. Permeability of iron is very high as compared to air or any non-magnetic material. For free space, i.e., air, permeability μ_0 is equal to $4p \times 10^{-7}$ H/m. The permeability of any magnetic material is compared with the permeability of free space and is called relative permeability μ_r. Relative permeability of iron is as high as 2000. This means that iron is 2000 times more permeable than air. For the same amount of ampere turns, an iron-core coil will produce about 2000 times more flux than an air-core coil as shown in Fig. 5.14.

For the same amount of ampere turns, the flux produced by an iron-core coil is much more than that produced by an air-core one. Actually, the amount of flux produced in an iron-core coil is much more than what has been shown.

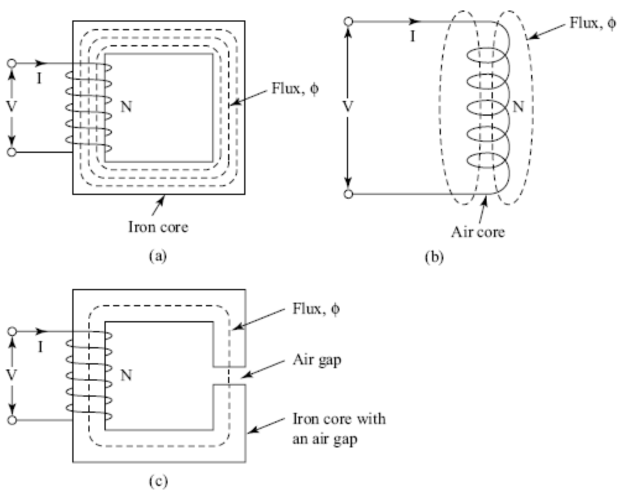

Figure 5.14 An iron-core coil produces more flux than an air-core coil for the same amount of magnetizing force: (a) iron-core coil; (b) air-core coil; (c) coil with iron core and an air gap

turns will be somewhat less as in the case of Fig. 5.14 (a), because the total reluctance of the flux path is now increased. The flux has to cross the air gap whose reluctance is very high as compared to iron. The flux produced will be calculated as

$$\text{Flux, } \phi = \frac{\text{MMF}}{\text{Reluctance of iron path} + \text{Reluctance of air gap}}$$

The magnetic circuits of electrical machines, transformers, electro-magnetic relays, and other electrical equipment are of different shapes and sizes as shown in Fig. 5.15. The current-carrying coil providing the required ampere turns are placed at various convenient locations as shown.

Magnetic field strength, H is defined as the ampere turn per unit length, i.e., as AT/m. Thus,

$$H = \frac{NI}{l} = \frac{AT}{l} \text{ or } AT = H \times l$$

To calculate the ampere turns required to create a required amount of flux we use the relation

$$\phi = \frac{\text{MMF}}{s} = \frac{AT}{l/\mu A} = \frac{AT}{l}\mu A$$

$$= H\mu A$$

or,
$$\frac{\phi}{A} = \mu H$$

or,
$$B = \mu H \text{ and } AT = H \times l$$

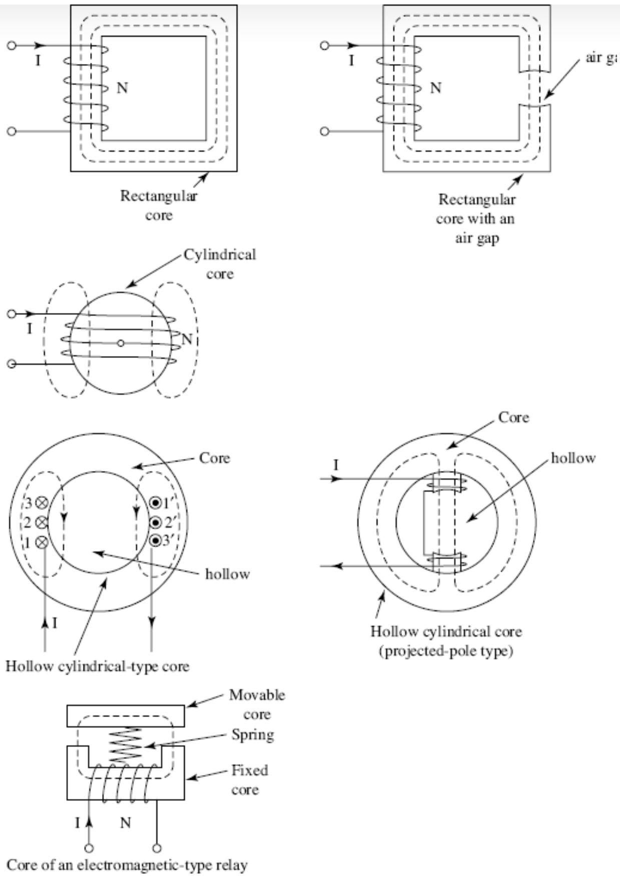

Figure 5.15 Magnetic circuits of different types and shapes used in making electrical machines and devices

The various quantities associated with magnetic circuits are stated as follows.

Magneto motive force (MMF) = Ampere turns = N I

Magnetic field strength $(H) = AT/m = \dfrac{NI}{l}$

Flux density (B) = Flux per unit area = $\dfrac{\phi}{A}$

Permeability $\mu = \mu_o \mu_r$

Permeability of free space (air), $\mu_o = 4p \times 10^{-7}$

Relative permeability (μ_r) = The number of times the material is more permeable than air.

Flux density, $B = \mu H$

$$\phi = BA = \mu HA = \mu_o \mu_r \frac{NI}{l} A$$

$$= \frac{NI}{l/\mu_o \mu_r A}$$

Flux,

$$= \frac{MMF}{S}$$

Reluctance,

$$S = \frac{l}{\mu_o \mu_r A}$$

5.6 COMPARISON BETWEEN MAGNETIC AND ELECTRIC CIRCUITS

Now, we will consider two simple circuits, namely an electric circuit and a magnetic circuit, and establish their similarity as shown in Fig. 5.16.

The comparison has been shown in a tabular form in table 5.1.

There are, however, few points of dissimilarities between the magnetic and electric circuits. For example, flux can pass through air although the reluctance is high whereas current will flow through air only when the air gets ionized; there will be some residual magnetism left in iron when the magnetizing force is removed whereas no current is left in the circuit when the source of EMF is removed; flux does not actually flow in a magnetic circuit (magnetic field is established) whereas current flows in an electric circuit.

Calculation of current or ampere turns required to create a magnetic field of a particular strength will be necessary while designing a magnetic circuit for any electrical equipment. Accordingly, a few solved numerical examples have been included in this chapter.

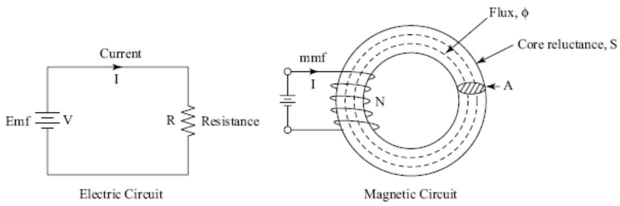

Figure 5.16 Comparison between an electric circuit and a magnetic circuit

Table 5.1 Comparison Between an Electric Circuit and a Magnetic Circuit

Electric Circuit	Magnetic Circuit
Current, I	Flux, f
EMF, V	MMF, N I
Resistance, R	Reluctance, S
$I = \frac{EMF}{Resistance} = \frac{V}{R}$	$\phi = \frac{MMF}{Reluctance} = \frac{NI}{S}$
$R = \rho \frac{l}{a}$	$S = \frac{l}{\mu A}$
$Conductance = \frac{1}{Resistance}$	$Permeance = \frac{1}{Reluctance}$
Electric field intensity = $\frac{V}{l}$	Magnetic field intensity, $H = \frac{AT}{l}$ or, $H = \frac{NI}{l}$

5.7 MAGNETIC LEAKAGE AND FRINGING

Let us consider a magnetic circuit as in Fig. 5.17 (a). The current passing through the winding produces flux which is distributed equally on both sides of the coil as shown.

As shown in Fig. 5.17 (b), most of the flux will flow or pass through the magnetic material which is called the main flux or useful flux. However, a certain percentage of flux will link the coil itself and will not pass through the entire core. This flux is called leakage flux. Leakage flux completes its path through air instead of going through the entire iron path.

In a magnetic circuit with some air gap, when flux has to pass through the air gap, there is tendency of the magnetic flux to spread out at the two edges or sides. This effect is called fringing.

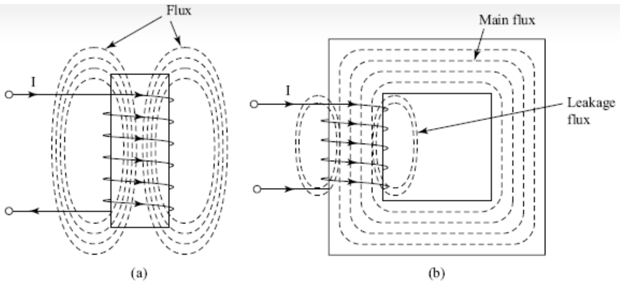

Figure 5.17 (a) Uniform distribution of flux around a current-carrying coil; (b) main flux and leakage flux

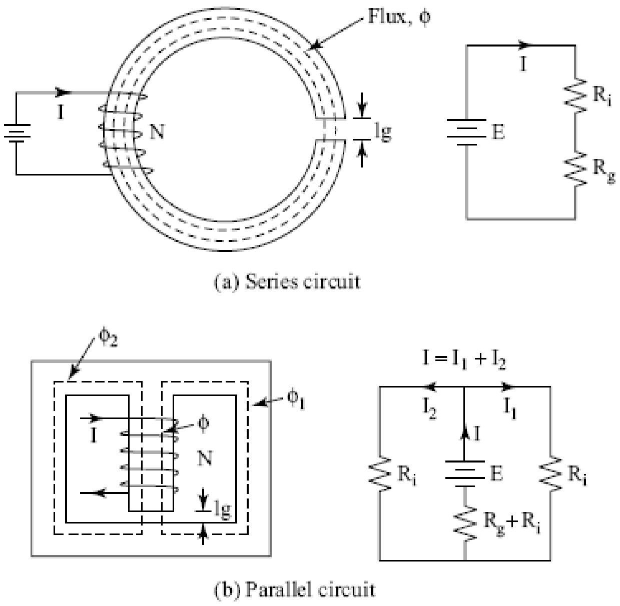

Figure 5.18 Series and parallel magnetic circuits with equivalent electric circuits

5.8 SERIES AND PARALLEL MAGNETIC CIRCUITS

Let us consider two magnetic circuits as shown in Fig. 5.18 (a) and (b) and their equivalent electrical circuits. The equivalence of MMF NI, of the magnetic circuit is EMF E or V of the electric circuit. Magnetic reluctance of the iron path and that of air gap are represented by their equivalent resistances R_i and R_g in the electric circuit. Flux in the magnetic circuit is represented by current in the electric circuit. The magnetizing force, $\frac{NI}{l}$ produces the flux in the core. The opposition to the flux path is provided by iron and the air in the air gap through which the flux has to pass. The reluctance of iron is very low whereas that of air is very high. For a small amount of air gap, the reluctance will be much more than along the length of the iron path.

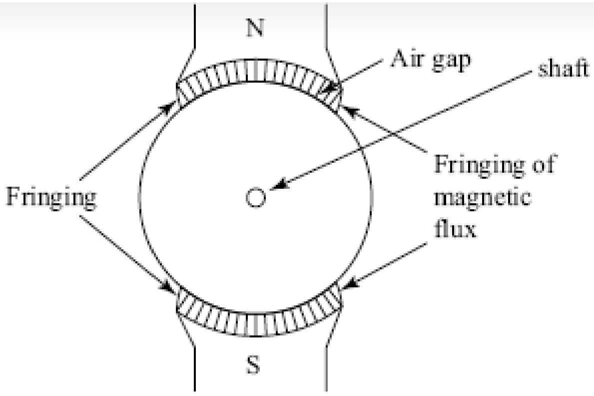

Figure 5.19 Fringing of flux at the corners of the North pole and South pole of an electrical machine

5.9 ATTRACTIVE FORCE OR THE LIFTING POWER OF ELECTROMAGNETS

An electromagnet is often used to pull or lift iron pieces or objects made of iron. This is possible due to the energy stored in the magnetic field of the electromagnet.

In Fig. 5.20 is shown an electromagnet having N number of turns and the coil carrying a current, I. The cross-sectional area of the core is A. An iron piece is separated from the electromagnet by a distance, *l*. We will calculate the energy stored in the magnetic field and the lifting power of the electromagnet.

Energy stored in a magnetic field is given by

$$W = \frac{1}{2} L I^2 \text{ J}$$

Putting $L = N\frac{\phi}{I}$ we get

$$W = \frac{1}{2} N \phi I \text{ J}$$

Again $H = \frac{NI}{\ell}$ and $\phi = B \times A$

Therefore, $W = \frac{1}{2} NI\phi = \frac{1}{2} H \times \ell \times B \times A$

$$= \frac{1}{2} H B A \ell \text{ J}$$

Again, $B = \mu_o H$,

or, $H = \frac{B}{\mu_o}$

Considering the magnetic field in the air gap between the magnet and the piece of iron,

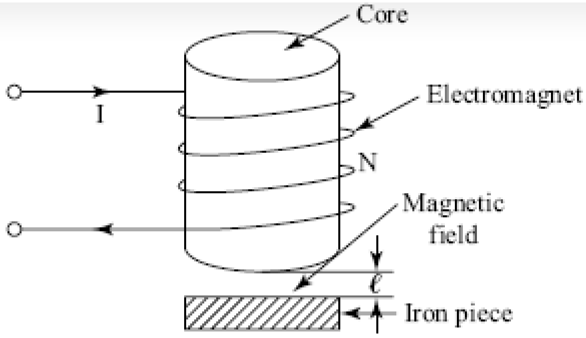

Figure 5.20 Lifting power of an electromagnet

(A × *l*) is the volume of the air gap between the electromagnet and the iron piece.

Force, $F = \text{Work done per unit length}$

$$= \frac{W}{\ell}$$

or, $$F = \frac{B^2 A}{2\mu_o} \text{ N} \tag{5.17}$$

The stored energy of the magnetic field between the electromagnet and the piece of iron is able to pull the iron piece towards it. When the exciting coil of the electromagnet is energized by passing current, the force of attraction will pull the iron near to the face of the electromagnet. Such electromagnets can be used to pull or lift large amount of magnetic material and shift the material from one place to the other. Thus, the lifting power of the electromagnet can be used to do some mechanical work for us. For example, electromagnets are used to lift iron ores from the place of storage and bring them for processing when required.

Example 5.2 A circular iron ring of mean diameter 25 cm and cross-sectional area 9 cm^2 is wound with a coil of 100 turns and carries a current of 1.5 A. The relative permeability of iron is 2000. Calculate the amount of flux produced in the ring.

Solution:

Mean length of flux path, $\ell = \pi D = 3.14 \times 25 \text{ cm} = \frac{3.14 \times 25}{100} \text{ m} = 0.785 \text{ m}$

Flux, $$\phi = \frac{MMF}{Reluctance} = \frac{NI}{\ell / \mu_o \mu_r A} = \frac{100 \times 1.5}{0.785 / 4\pi \times 10^{-7} \times 2000 \times 9 \times 10^{-4}}$$

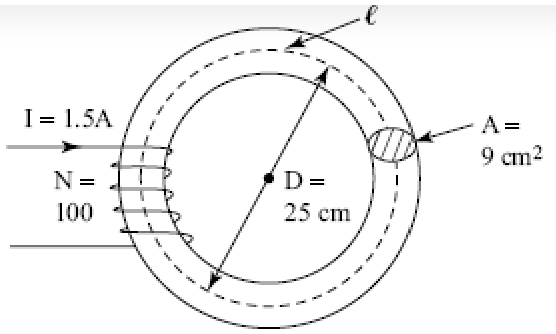

Figure 5.21

$$= \frac{150}{348 \times 10^3} = \frac{150}{348} \times 10^{-3}$$

$$= 0.431 \times 10^{-3}\ \text{Wb}$$

$$= 0.431\ \text{mWb}$$

Example 5.3 A rectangular shape iron core has an air gap of 0.01 cm. The mean length of the flux path through iron is 39.99 cm. The relative permeability of iron is 2000. The coil has 1000 turns. The cross-sectional area of the core is 9 cm^2. Calculate the current required to produce a flux of 1 mWb in the core.

Solution:

Total reluctance of the flux path = Reluctance of iron path + Reluctance of air gap,

$$S = S_i + S_g$$

$$S = \frac{l_i}{\mu_o \mu_r A} + \frac{l_g}{\mu_o A}$$

Note: the iron path permeability is m which is equal to $\mu_0 \mu_r$ whereas for the air gap the permeability is μ_0 only.

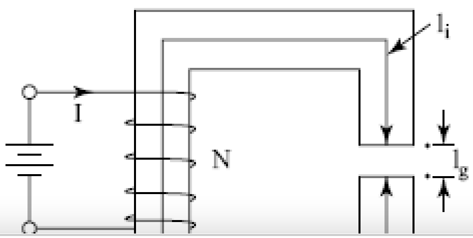

Figure 5.22

Substituting the given values,

$$S = \frac{39.09\times10^{-2}}{4\pi\times10^{-7}\times2000\times9\times10^{-4}} + \frac{0.01\times10^{-2}}{4\pi\times10^{-7}\times9\times10^{-4}}$$

$$= \frac{10^6}{4\pi}\left[\frac{39.09}{18}+\frac{100}{10}\right] = \frac{295.45\times10^5}{36\pi}$$

Flux, $$\phi = \frac{NI}{S} = \frac{1000\ I}{S}$$

∴ $$I = \frac{\phi\times S}{1000} = \frac{1\times10^{-3}\times295.45\times10^5}{36\pi\times1000} = \frac{29.545}{36\pi} = 0.26\text{A}$$

Example 5.4 A magnetic circuit is having its winding on its central limb. The cross-sectional area of the central limb is 10 cm^2 whereas the cross-sectional area of the outer limbs is 5 cm^2. The effective length of the central limb is 16 cm and that of the outer limbs is 25 cm. Calculate the current required to flow through the winding which has 1000 turns to produce a flux of 1.2 mWb in the central limb. Assume that for a flux density of 1.2 Wb/m^2, the magnetizing force required is 750 AT/m. Draw the equivalent electric circuit.

Solution:

The details of the magnetic circuit are shown in Fig. 5.23.

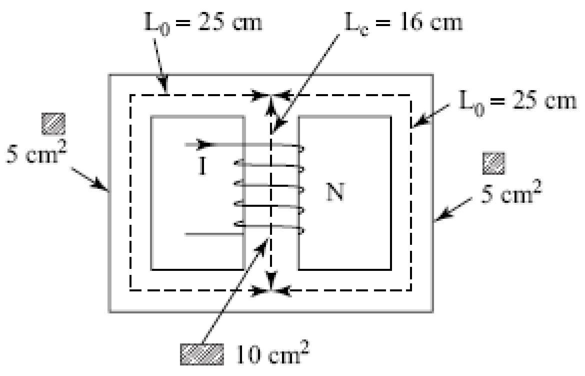

Figure 5.23

The equivalent electric circuit is drawn as shown in Fig. 5.24.

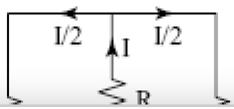

Figure 5.24

This is an example of a parallel circuit. As current in an electric circuit gets divided into two parallel branches, the flux produced in the central limb will get divided into the two outer limbs.

We will calculate the MMF required for the central limb as also for any of the outer limbs which will maintain the desired flux in the core. For a flux density of 1.2 Wb/m^2, the value of H has been given. Let us calculate the flux density in the central limb first.

Flux density in the central limb,

$$B_c = \frac{\phi_c}{A_c} = \frac{1.2 \times 10^{-3}}{10 \times 10^{-4}} = 1.2\ Wb/m^2$$

The Flux density in the outer limb will be the same as that in the central limb since half the flux is available in each of the outer limbs and their cross-sectional area is half of that of the central limb.

$$B_o = \frac{\phi_o}{A_o} = \frac{0.6 \times 10^{-3}}{5 \times 10^{-4}} = 1.2\ Wb/m^2$$

The corresponding H i.e., AT/m for flux density of 1.2 Wb/m^2 has been given as 750.

The total MMF required = MMF required for the central limb + MMF required for one outer limb (and not for both the limbs).

Since $H = \frac{MMF}{l}$, $MMF = H \times l$

Total MMF required $= \frac{750 \times 16}{100} + \frac{750 \times 25}{100} = 307.5$ [considering length in m]

$AT = 307.5 = NI$

$N = 1000$

$I = \frac{307.5}{1000} = 0.3075\ A$

Example 5.5 An iron ring of mean length of an iron path of 100 cm and having a uniform cross-sectional area of 10 cm^2 is wound with two magnetizing coils as shown. The direction of current flowing through the two coils are such that they produce flux in the opposite directions. The permeability of iron is 2000. There is a cut in the ring creating an air gap of 1 mm. Calculate the flux available in the air gap.

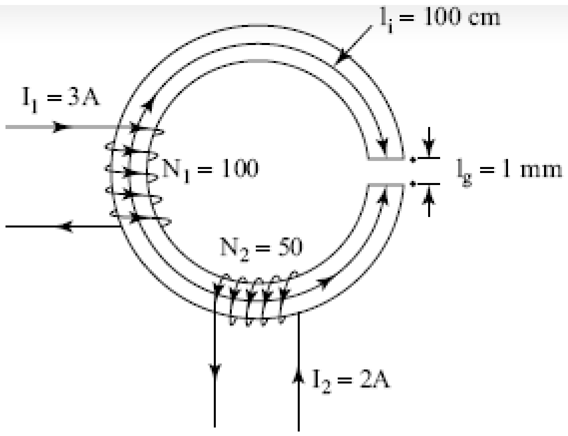

Figure 5.25

Solution:

The net MMF will be the resultant effect of MMF of the two coils in producing the flux in the core. As in Fig. 5.25, the flux produced by the MMF of the two coils are in opposite directions. Thus, the resultant MMF will be the difference of these two MMFs.

Resultant MMF $= N_1 I_1 - N_2 I_2$

$= 100 \times 3 - 50 \times 2$

$= 200$

Total reluctance, $S = S_i + S_g$

$$= \frac{l_i}{\mu_o \mu_r A_i} + \frac{l_g}{\mu_o A_g}$$ [we have considered the reluctance of $\mu_o \mu_r$ for iron and m_o for air]

Since $A_i = A_g$, i.e., the cross-sectional area of the iron path is the same as that of the air gap,

$$S = \frac{1}{\mu_o A}\left[\frac{l_i}{\mu_r} + l_g\right]$$

Substituting values

$$S = \frac{1}{4\pi \times 10^{-7} \times 10 \times 10^{-4}}\left[\frac{50 \times 10^{-2}}{2000} + 1 \times 10^{-3}\right]$$

$$S = \frac{10^{10}}{4\pi}[25 \times 10^{-5} + 1 \times 10^{-3}]$$

$$= \frac{10^{10}}{4\pi} 10^{-3}[25 \times 10^{-2} + 1]$$

$$= \frac{10^{7}}{4\pi}[1.25] = 10^{6}$$

Flux,

$$\phi = \frac{MMF}{S} = \frac{200}{10^{6}} = 2 \times 10^{-4} = 0.2 \text{ mWb}$$

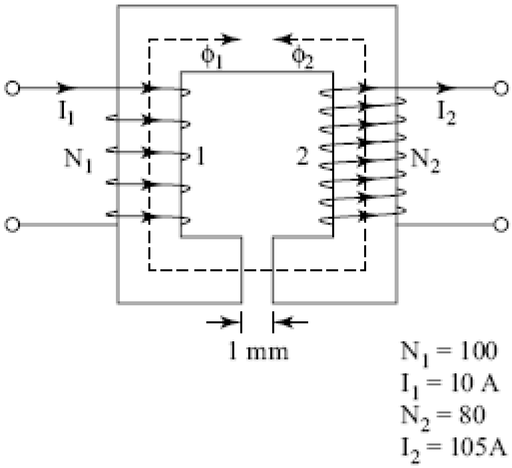

Figure 5.26

Solution:

Applying Fleming's thumb rule we can see that the ampere turns of coil 2 produce flux in the opposite direction as the flux produced by the ampere turns of coil 1.

Total MMF $= N_1 I_1 - N_2 I_2$

$= 100 \times 10 - 80 \times 1.5$

$= 880$ AT

Total reluctance = Reluctance of iron + Reluctance of air gap

$$= \frac{l_i}{\mu_o \mu_r A} + \frac{l_g}{\mu_o A} = \frac{1}{\mu_o A}\left[\frac{l_i}{\mu_r} + l_g\right]$$

Substituting values

Total Reluctance $$= \frac{1}{4\pi \times 10^{-7} \times 10 \times 10^{-4}}\left[\frac{(40 \times 10^{-2} - 1 \times 10^{-3})}{2000} + 1 \times 10^{-3}\right]$$

$$= \frac{10^{10}}{4\pi}\left[\frac{399 \times 10^{-3}}{2000} + 1 \times 10^{-3}\right]$$

$$= \frac{10^{7}}{4\pi}\left[\frac{399}{2000} + 1\right]$$

$= 0.955 \times 10^{6}$ AT/Wb.

Core Flux $$= \frac{\text{MMF}}{\text{Reluctance}} = \frac{880}{0.955 \times 10^{6}} = 921.5 \times 10^{-6}$$

$= 0.9215 \times 10^{-3}$ Wb

The air gap flux is the same as the core flux as the whole of the core flux crosses the air gap and there is no fringing.

Example 5.7 A parallel magnetic circuit with 2000 turns on its central limb has been shown in Fig. 5.27. The air gaps are 2 mm each. The mean diameter of the circular magnetic path is 20 cm

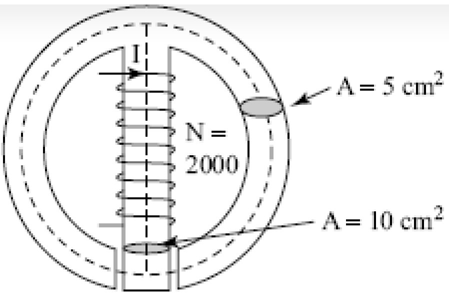

Figure 5.27

The cross-sectional area of the central limb is 10 cm^2 while the cross section of the outer limbs is 5 cm^2. A few readings from the magnetization curve are given below.

B in Wb/m^2	1.0	1.1	1.2	1.3	1.4
H in AT/m	550	650	750	820	870

Calculate the current, I which must flow through the coil so as to produce a flux of 1.1 mWb in the central limb.

Solution:

The flux from the central limb will get equally divided in the two outer limbs. So that flux in the outer limbs will be 0.55 mWbs.

The flux density will be the same throughout as flux density, B is

for central limb $$B = \frac{\phi}{A} = \frac{1.1 \times 10^{-3}}{10 \times 10^{-4}} = 1.1\ \text{Wb/m}^2,\ \text{or Tesla}$$

for outer limbs $$B = \frac{\phi}{A} = \frac{0.55 \times 10^{-3}}{5 \times 10^{-4}} = 1.1\ \text{Wb/m}^2,\ \text{or Tesla}$$

The magnetic field strength, H corresponding to B = 1.1 Wb/m^2 is 650 AT/m.

We have to calculate the AT required to be provided for one of the parallel paths, i.e., for the central limb, one outer limb, and one air gap.

length of central limb, l_c = diameter = 20 cm

length of the outer limbs, (including air gap)

$$l_o = \frac{\pi d}{2} = \frac{3.14 \times 20}{2} = 31.4\,\text{cm}$$

length of air gap, l_g = 2 mm = 0.2 cm

(a) NI for central limb

(a) NI for central limb $= H \times l_c = 650 \times \frac{20}{100} = 130$

(b) NI for outer limb

$$= H \times (l_o - l_g) = 650 \frac{(31.4 - 0.2)}{100}$$

$$= 650 \times \frac{31.2}{100} = 202.8$$

NI for air gap = $H_g \times l_g$

we have to calculate H_g for air

$$B = \mu_o H \text{ as } \mu_r = 1$$

$$H = \frac{B}{\mu_o} = \frac{1.1}{4\pi \times 10^{-7}} = 8.758 \times 10^5 \text{ AT/m}$$

(c) NI for air gap = $H_g \times l_g = 8.758 \times 10^5 \times 2 \times 10^{-3} = 1751.6$

Total AT required = a + b + c
= 130 + 202.8 + 1751.6
= 2084.6

Total number of turns of the exciting coil placed on the central limb, N = 2000.

Current, $I = \frac{\text{Total AT}}{N}$

$$= \frac{2084.6}{2000} = 1.04 \text{ A}$$

Example 5.8 An iron ring is made up of two different materials A and B having a relative permeability of 1000 and 1500, respectively. The length L_A and L_B of the two materials used are 75 cm and 25 cm, respectively. The air gap length is 2 mm. The cross-sectional area of the core is 10 cm^2. The magnetizing coil has 1000 turns and a current of 5 A is allowed to flow through it. Calculate the flux produced in the air gap.

Solution:

We know, $\phi = \frac{\text{MMF}}{\text{Total reluctance}}$

Total reluctance, S = Reluctance of part A + Reluctance of part B + Re-

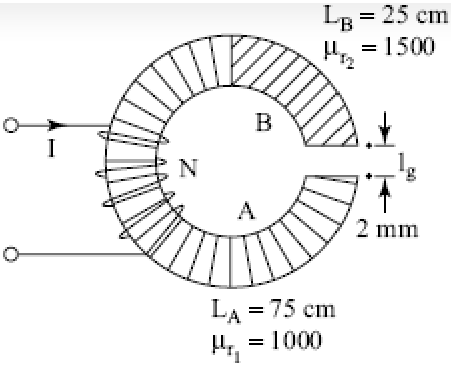

Figure 5.28

$$S = \frac{L_A}{\mu_o \mu_{r_1} A} + \frac{L_B}{\mu_o \mu_{r_1} A} + \frac{l_g}{\mu_o A}$$

$$= \frac{0.75}{4\pi \times 10^{-7} \times 1000 \times 10 \times 10^{-4}} + \frac{0.25}{4\pi \times 10^{-7} \times 1500 \times 10 \times 10^{-4}}$$

$$+ \frac{2 \times 10^{-3}}{4\pi \times 10^{-7} \times 10 \times 10^{-4}}$$

$$= 10^4\,[59.7133 + 13.2696 + 1592.3566]$$

$$= 10^4 \times 1665.3395$$

$$= 16.653395 \times 10^6 \text{ AT/Wb}$$

Flux, $$\phi = \frac{\text{mmf}}{\text{Reluctance}} = \frac{NI}{S} = \frac{1000 \times 5}{16.653395 \times 10^6}$$

$$= 0.3 \times 10^{-3} \text{ Wb}$$

$$= 0.3 \text{ mWb}$$

Example 5.9 For the core shown in Fig. 5.29, it is required to produce a flux of 2 mWb in the limb CD. The entire core has a rectangular cross section of 2cm × 2cm. The magnetizing coil has 800 turns. The relative permeability of the material is 1200. Calculate the amount of magnetizing current required.

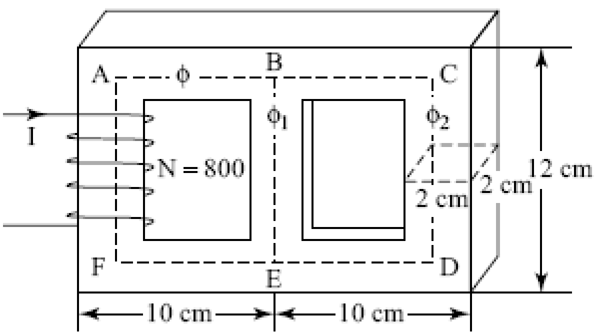

Figure 5.29

Length BC = ED = AB = EF = 8 cm

Length BCDE = 8 + 10 + 8 = 26 cm

Length BAFE = 8 + 10 + 8 = 26 cm

Length BE = 10cm; μ_r = 1200

Total flux, $\phi = \phi_1 + \phi_2$

N = 800, $\phi_2 = 2 \times 10^{-3}$ Wb, current, I = ?

Let us draw the equivalent electrical circuit of the given magnetic circuit. The equivalent electric circuit will be as shown in Fig. 5.30.

The voltage drop across CD is $I_2 R_2$.

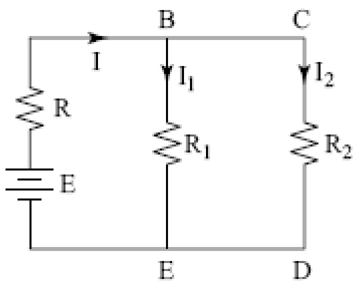

Figure 5.30

The voltage drop across BE is equal to the voltage drop cross CD.

Therefore,

$$I_1 R_1 = I_2 R_2$$

or,

$$I_1 = I_2 \frac{R_2}{R_1}$$

For the magnetic circuit, from the analogy of the above equivalent electric circuit, we can write

$$\phi_1 = \phi_2 \frac{S_2}{S_1}$$

S_2 is the reluctance of path BCDE

$$S_2 = \frac{1}{\mu_o \mu_r A} = \frac{26 \times 10^{-2}}{4\pi \times 10^{-7} \times 1200 \times 4 \times 10^{-4}}$$

$$S_1 = \frac{10 \times 10^{-2}}{\mu_o \mu_r A} = \frac{10 \times 10^{-2}}{4\pi \times 10^{-7} \times 1200 \times 4 \times 10^{-4}}$$

$$\phi_1 = \phi_2 \frac{S_2}{S_1} = 2 \times 10^{-3} \frac{26}{10} = 5.2 \times 10^{-3} \text{ Wb}$$

$$\phi = \phi_1 + \phi_2 = 2 \times 10^{-3} + 5.2 \times 10^{-3} = 7.2 \times 10^{-3} \text{ Wb}$$

AT required for portion BAFE (=26cm) = $\phi \times S_3$

$$= \frac{7.2 \times 10^{-3} \times 26 \times 10^{-2}}{4\pi \times 10^{-7} \times 1200 \times 4 \times 10^{-4}} = 3105$$

AT required for portion BE = $\phi_1 \times S_1$

$$= \frac{5.2 \times 10^{-3} \times 10 \times 10^{-2}}{4\pi \times 10^{-7} \times 1200 \times 4 \times 10^{-4}}$$

$$= 862$$

In the electric circuit, we see that by applying KCL

$$E - IR - I_1 R_1 = 0$$

or, $$E = IR + I_1 R_1$$

Similarly, for the magnetic circuit

Total AT = AT required for portion BAFF + AT required for the portion BE

= 3105 + 862

= 3967.

The number of turns of the exciting coil is 800.

$$AT = NI = 3967$$

$$I = \frac{3967}{N} = \frac{3967}{800} = 4.95 \text{ A}$$

the iron is 20 cm and the length of air gaps is 1 mm each. The exciting coil has 8000 turns and carries a current of 50 mA when excited. The cross-sectional area of the core is 0.5 cm^2. The permeability of iron is 500. Calculate the flux density and the magnetic pull produced in the armature (i.e., on the moving part).

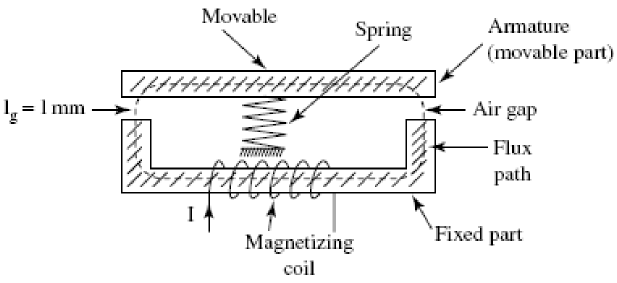

Figure 5.31

Solution:

Total reluctance of the flux path = Reluctance of the path through the iron + Reluctance of the two air gaps. The length of each of the air gaps, l_g = 1 mm. We have to take into account $2l_g$ as the total air gap to the flux path.

$$B = \frac{\mu_0 I}{2\pi r}$$

Flux, density,

$$B = \frac{\phi}{A} = \frac{104.7 \times 10^{-3}}{0.5 \times 10^{-4}} = 0.2094\,\text{Wb/m}^2$$

From equation 5.17, the force or the pull on the armature by each pole,

$$F = \frac{B^2 A}{2\mu_o} = \frac{(0.2094)^2 \times 0.5 \times 10^{-4}}{2 \times 4\pi \times 10^{-7}} = 4.16\,\text{N}$$

Example 5.11 An overhead electrical power transmission line carries a current of 100A. The direction of current flow through the line is from the West to the East direction. What is the direction of the magnetic field produced and what is its value 1 m below the overhead line?

Solution:

The magnitude of the magnetic field, B is expressed as

$$B = \frac{4\pi \times 10^{-7} \times 100}{2\pi \times 1} = 20 \times 10^{-6} \text{ Wb/m}^2 = 20 \times 10^{-6} \text{ Tesla}$$

Substituting values of μ_0, I, and r as 4π 3 10^{27}, 100A and 1m, respectively,

$$F_1 = BI_2 = \frac{\mu_0 I_1 \times I_2}{2\pi r_1} \quad N$$

The field produced is at right angles to the length of the current-carrying conductor.

Example 5.12 A rectangular coil ABCD of size 20 cm × 10 cm is placed 1 cm away from a long current-carrying conductor with its longer sides parallel to the conductor. A current of 100 A is flowing through the long conductor while the coil is carrying a current of 10 A. Calculate the resultant force developed on the coil.

Solution:

Force will be developed between the longer sides of the coil and the conductor as they are parallel to each other. There will be force of attraction with one coil side and force of repulsion with the other. The difference between the two forces will be the resultant force acting on the coil. There will be no force developed on the sides which are perpendicular to the conductor as shown in Fig. 5.32.

Force experienced per unit length by a current-carrying conductor due to flux density created by the other current-carrying conductor is

$$F_1 = BI_2 = \frac{\mu_0 I_1 \times I_2}{2\pi r_1} \quad N$$

Force of attraction between the conductor and side AB

$$F_1 = \frac{\mu_0 I_1, I_2\, l}{2\pi r_1}$$

Force of repulsion between the conductor and side CD

$$F_2 = \frac{\mu_0 I_1 I_2 l}{2\pi r}$$

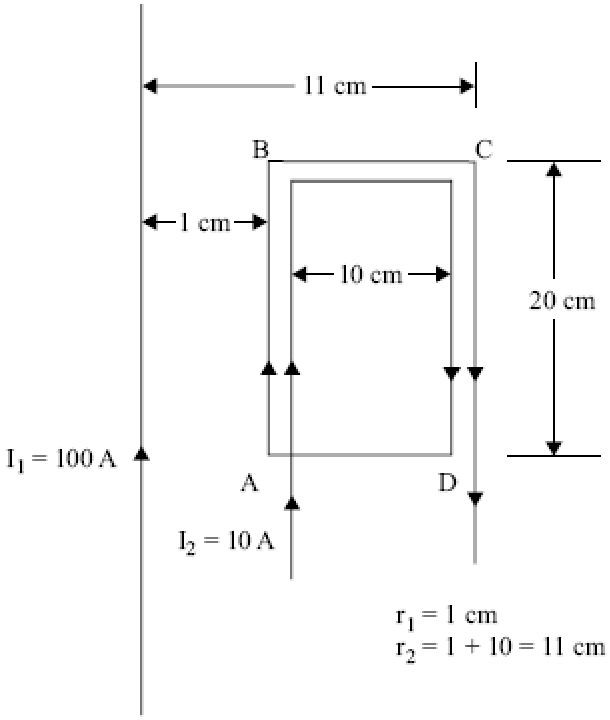

Figure 5.32

Substituting the values

$$F_1 - F_2 = \frac{4\pi \times 10^{-7} \times 100 \times 10 \times 0.2}{2\pi}\left[\frac{1}{0.01} - \frac{1}{0.11}\right]$$

$$= 3.63 \times 10^{-3} \text{ N}$$

Example 5.13 A horse-shoe-type iron-core electromagnet is wound with 500 turns and is required to lift heavy iron bars of 200 kg each time. The area of cross section of each of the poles of the horse-shoe magnet is 0.01 m^2. The mean length of the flux path through the electromagnet is 0.5 m. Calculate the value of the exciting current through the coil. The relative permeability of the flux path is 1000.

Solution:

A weight of 200 kg has to be lifted by both the poles of the electromagnet. Thus, each pole will have to lift a load of 100 kg. The force of attraction which is also called the lifting power of the electromagnet is

$$F = \frac{B^2 A}{2\mu_0}$$

or, $$B = \sqrt{\frac{F \times 2\mu_0}{A}}$$

Putting the values,

$$F = 100 \text{ kg} = 100 \times 9.8 \text{ N}$$

$$B = \sqrt{\frac{100 \times 9.8 \times 2 \times 4\pi \times 10^{-7}}{0.01}}$$

$$= 0.5 \text{ Wb/m}^2$$

Again

$$B = \mu H$$

or, $$H = \frac{B}{\mu} = \frac{B}{\mu_0 \mu_r} = \frac{0.5}{4\pi \times 10^{-7} \times 1000} = 400$$

We know

$$H \times l = AT = NI$$

or, $$I = \frac{H \times l}{N} = \frac{400 \times 0.5}{500} = 0.4 \text{ A}$$

5.10 REVIEW QUESTIONS

A. Short Answer Type Questions

1. Explain why the core of an electromagnet is made of magnetic material like iron.

2. Distinguish between an electromagnet and a permanent magnet.

3. What is meant by magnetization of a magnetic material?

4. Explain the following terms: MMF, reluctance, flux density, permeability, relative permeability, magnetic field intensity.

5. What is meant by magnetic saturation of a magnetic material?

6. Differentiate between electric resistance and magnetic reluctance.

7. Compare a magnetic circuit with an equivalent electric circuit.

8. What is meant by Hysteresis loss and Eddy current loss? On what factors does hysteresis loss depend?

9. On what factors does attractive power of an electromagnet depend?

10. Explain briefly magnetic leakage and fringing.

B. Numerical Problems

11. An iron ring of 19.1 cm mean diameter has a cross-sectional area of 8 cm^2. The ring has an air gap of 5 mm. The winding on the ring has 500 turns and carries a current of 5 A. Calculate the flux produced in the air gap. The relative permeability of iron is 750.

12. The air gap of a magnetic circuit is 2 mm long and 25 cm^2 in cross section. Calculate the reluctance of the air gap. How much ampere turns will be required to produce a flux of 1.2 mWb in the air gap?

[Ans 0.636×10^6 AT/Wb; 764]

13. An iron ring of mean length 50 cm has an air gap of 1 mm. The ring is provided with a winding of 200 turns through which a current of 1 A is allowed to flow. Find the flux density across the air gap. Assume the relative permeability of iron as 300.

[Ans B = 0.094 Wb/m^2]

14. A magnetic core has a cross-sectional area of 16 cm^2. The air gap length is 2 mm. Length of the iron path is calculated as 73.8 cm. The exciting coil has 2000 turns. Calculate the current which is required to flow through the winding to create an air gap flux of 4 mWb. Assume relative permeability of the core material as 2000.

[Ans I = 2.356 A]

15. The armature and the field magnets of an electrical machine has been shown in Fig. 5.33. The air gap between the poles and the armature has been kept as 10 mm. The pole area is 0.1 m^2 and the flux per pole is 0.15 Wb. Calculate the mechanical force exerted by each pole on the armature. Also calculate the energy stored in the air gaps.

[Ans F = 89523 N; W = 1655.3 J]

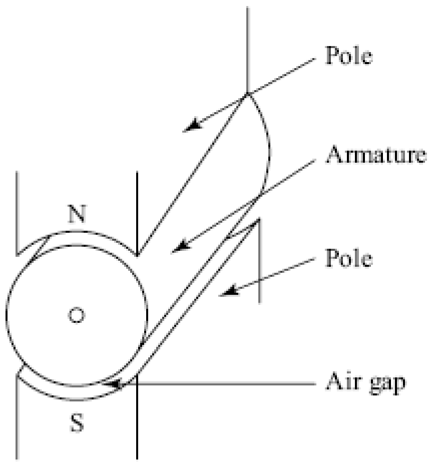

Figure 5.33

through the winding a flux density of 1.2 Wb/m^2 is produced in the 1 mm air gap. The inner diameter of the ring is 20 cm and the outer diameter is 25 cm. The thickness of the ring is 2 cm. Calculate the magnetic field intensity in the material and in the air gap. Also calculate the relative permeability of the magnetic material, i.e., iron.

[Ans 771 AT/m; 9.55×10^5 AT/m; 1238]

17. A steel ring has a mean diameter of 159.23 mm and cross-sectional area of 3 cm^2. The ring has an air gap of 1 mm. Determine the current required in the exciting coil having 250 turns to produce a flux of 0.2 mWb in the air gap. Take the permeability of iron to be 1200.

[Ans I = 3.3 A]

18. An iron ring of mean diameter of 10 cm and cross-sectional area of 8 cm^2 is wound with a wire having 300 turns. The permeability of iron is 500. What current should be passed through the winding wire so that a flux density of 1.2 Wb/m^2 is produced in the core?

[Ans I = 2A]

19. Fig. 5.34 shows a magnetic circuit. Calculate the current required to be passed through the central limb winding so as to produce a flux of 1.6 mWb in this limb. Length of iron in the central limb is 15 cm. Cross-sectional area of the central limb is 8 cm^2 and that of the outer limbs is 4 cm^2.

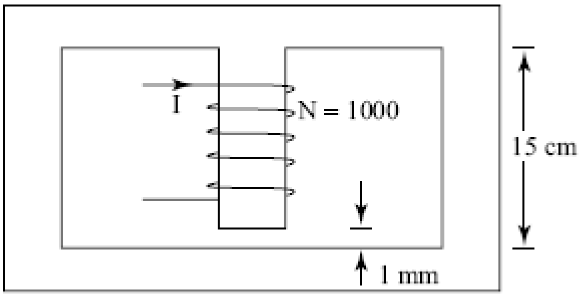

Figure 5.34

The mean length of iron of the outer limbs is 32 cm each. Given that for iron for a flux density of 2.0 Wb/m^2 the value of H is 800 AT/m.

1. A magnetic circuit and an electric circuit can be compared as

- flux is analogous to current
- reluctance is analogous to resistance
- MMF is ≠ analogous to EMF
- all these as in (a), (b), and (c).

2. The relationship of flux, reluctance and MMF is

$$\text{(a)} \quad \text{flux} \ \frac{\text{MMF}}{\text{Reluctance}}$$

$$\text{(b)} \quad \text{flux} = \text{MMF} \times \text{reluctance}$$

$$\text{(c)} \quad \text{flux} \ \frac{\text{Reluctance}}{\text{MMF}}$$

$$\text{(d)} \quad \text{flux} \ \frac{\text{EMF}}{\text{Reluctance}}.$$

3. Relative permeability of air is

- a. equal to 0
- equal to 1
- equal to ∞
- around 2000.

4. A magnetic circuit is said to be saturated when an increase in the field intensity results in

- decrease in flux density
- proportional increase in flux density
- very marginal increase in flux density
- sudden increase in flux density.

5. Which of the following is applicable for magnetic circuits?

- Thevenin’s Theorem
- Maximum Power Transfer Theorem
- Norton’s Theorem
- Kirchhoff’s Laws.

6. Material used for making a permanent magnet should have

- large hysteresis loop area
- small hysteresis loop area
- low coercieve force
- low saturation flux density.

7. The value of permeability of iron may be taken as

- unity

8. Unit of reluctance of a magnetic circuit is

- a. AT/Wb
- Wb/AT
- Wb-Cm
- Wb/m2.

9. A magnetic circuit of uniform cross-sectional area of length 50 cm is wound uniformly by 250 turns of a coil and carries a current of 4 A. The magnetic field strength or the magnetizing force produced is

- 1000 AT/m
- 2000 AT/m
- 1000 AT/cm
- 2000 AT/cm.

10. Self inductance of a coil can be expressed as

- $L = N\dfrac{d\phi}{di}$
- $L = N\dfrac{d\phi}{dt}$
- $L = N\dfrac{di}{dt}$
- $L = N^2\dfrac{d\phi}{dt}$.

11. Coupling co-efficient, k of a mutual inductor is

- $k = M\sqrt{L_1L_2}$
- $k = M\sqrt{\dfrac{L_1}{L_2}}$
- $k = \dfrac{M}{\sqrt{L_1L_2}}$
- $k = \dfrac{M^2}{\sqrt{L_1L_2}}$.

12. Self inductance of a coil can be expressed as

- $L = \dfrac{\mu N^2 A}{l}$
- $L = \dfrac{\mu N A}{l}$

- $L = \frac{\mu N^2 A}{l^2}$.

13. Self inductance of an air-core coil can be increased by introducing

- a. a copper rod inside the core
- a wooden rod inside the core
- an iron rod inside the core
- none of these.

14. The coefficient of coupling of two coils of 4 mH and 16 mH is 0.5. The mutual inductance between them is

- 2 mH
- 4 mH
- 8 mH
- 16 mH.

15. The permeability of a magnetic material means

- its ability to allow establishment of lines of force in it
- its ability to allow flow of current through it
- the opposition it would offer to establishment of flux in it
- its ability to provide high reluctance path to the magnetic flux.

Answers to Multiple Choice Questions

1. (d)
2. (a)
3. (b)
4. (c)
5. (d)
6. (a)
7. (d)
8. (a)
9. (b)
10. (a)
11. (c)
12. (a)
13. (c)
14. (b)
15. (a)