5.3 MAGNETIC CIRCUIT AND ITS ANALYSIS

The closed path followed by magnetic flux is called a magnetic circuit. A magnetic circuit usually consists of magnetic materials having high permeability (e.g., iron, soft steel, etc.). In this circuit, magnetic flux starts from a point and finishes at the same point after completing its path.

Figure 5.2 shows a solenoid having N turns wound on an iron core (ring). When current I ampere is passed through the solenoid, magnetic flux ϕ Wb is set up in the core.

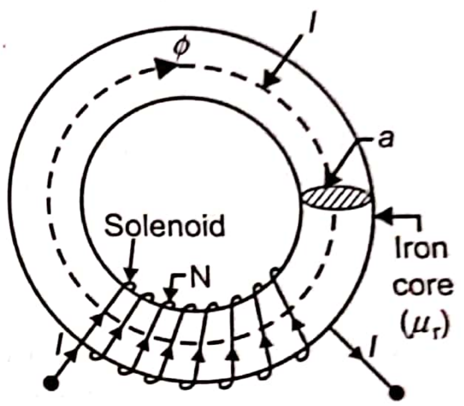

Fig. 5.2 Magnetic circuit

Let l = mean length of magnetic circuit in m;

a = area of cross-section of core in m^2;

μ_r = relative permeability of core material.

Flux density in the core material, $B = \dfrac{\phi}{a}$ Wb/m^2

Magnetising force in the core material

$$H = \frac{B}{\mu_0 \mu_r} = \frac{\phi}{a\mu_0 \mu_r} \text{ AT/m}$$

According to work law, the work done in moving a unit pole once round the magnetic circuit (or path) is equal to the AT enclosed by the magnetic circuit.

Therefore, $$Hl = NI \quad \text{or} \quad \frac{\phi}{a\mu_0\mu_r} \times l = NI \quad \text{or} \quad \phi = \frac{NI}{(l/a\mu_0\mu_r)} \text{ Wb}$$

This expression reveals that the amount of flux set up in the core is

1. directly proportional to N and I, that is, NI called magneto-motive force (mmf). It shows that the flux increases if either of the two increases and vice versa.

2. inversely proportional to ($l/a\mu_0\mu_r$) called reluctance of the magnetic path. In fact, reluctance is the opposition offered to the magnetic flux by the magnetic path. The lower is the reluctance, the higher will be the flux and vice versa.

Thus, $$\boxed{\text{Flux} = \frac{\text{mmf}}{\text{Reluctance}}}$$

It may be noted that the abovementioned expression has a strong resemblance to Ohm's law for electric current (I = emf/resistance). The mmf is analogous to emf in electric circuit, reluctance is analogous to resistance, and flux is analogous to current. Because of this similarity, the abovementioned expression is sometimes referred to as Ohm's law of magnetic circuits.

5.4 IMPORTANT TERMS

Generally, while studying magnetic circuits, we come across the following terms:

1. **Magnetic field:** The region around a magnet where its poles exhibit a force of attraction or repulsion is called magnetic field.
2. **Magnetic flux (ϕ):** The amount of magnetic lines of force set up in a magnetic circuit is called magnetic flux. Its unit is weber (Wb). It is analogous to electric current, I, in electric circuit.

   The magnetic flux density at a point is the flux per unit area at right angles to the flux at that point.

   Generally, it is represented by letter 'B'. Its unit is Wb/m² or Tesla, that is,

$$B = \frac{\phi}{A}\ \text{Wb/m}^2 \text{ or T } (1\ \text{Wb/m}^2 = 1 \times 10^4\ \text{Wb/cm}^2)$$

3. **Permeability:** The ability of a material to conduct magnetic lines of force through it is called the permeability of that material.

   It is generally represented by μ (mu, a Greek letter). The greater the permeability of a material, the greater is its conductivity for the magnetic lines of force and vice versa. The permeability of air or vacuum is the poorest and is represented as μ_0 (where $\mu_0 = 4\pi \times 10^{-7}$ H/m).
4. **Relative permeability:** The absolute (or actual) permeability μ of a magnetic material is much greater than absolute permeability of air μ_0. The relative permeability of a magnetic material is given in comparison with air or vacuum.

   Hence, the ratio of the permeability of material μ to the permeability of air or vacuum μ_0 is called the relative permeability μ_r of the material.

Therefore, $$\mu_r = \frac{\mu}{\mu_0} \quad \text{or} \quad \mu = \mu_0\mu_r$$

   Obviously, the relative permeability of air would be $\mu_0\mu_r = 1$. The value of relative permeability of all the non-magnetic materials is also 1. However, its value is as high as 8,000 for soft iron, whereas its value for Mu metal (iron 22% and nickel 78%) is as high as 120,000.
5. **Magnetic field intensity:** The force acting on a unit north pole (1 Wb) when placed at a

point in the magnetic field is called the magnetic intensity of the field at that point. It is denoted by H. In magnetic circuits, it is defined as mmf per unit length of the magnetic path. It is denoted by H, and mathematically, it can be given as

$$H = \frac{\text{mmf}}{\text{Length of magnetic path}} = \frac{NI}{l}\ \text{AT/m}$$

6. **Magneto-motive force (mmf):** The magnetic pressure that sets up or tends to set up magnetic flux in a magnetic circuit is called magneto-motive force. As per work law, it may be defined as the work done in moving a unit magnetic pole (1 Wb) once round the magnetic circuit is called mmf. In general,

$$\text{mmf} = NI \text{ ampere turns (or AT)}$$

It is analogous to emf in an electric circuit.

7. **Reluctance (S):** The opposition offered to the magnetic flux by a magnetic circuit is called its *reluctance*.

It depends upon length (l), area of cross section (a), and permeability ($\mu = \mu_0 \mu_r$) of the material that makes up the magnetic circuit. It is measured in AT/Wb.

Reluctance,
$$S = \frac{l}{a \mu_0 \mu_r}$$

It is analogous to resistance in an electric circuit.

5.15 FARADAY'S LAWS OF ELECTROMAGNETIC INDUCTION

Michael Faraday summed up conclusions of his experiments regarding electromagnetic induction into two laws, known as *Faraday's laws of electromagnetic induction.*

5.15.1 First Law

This law states that 'Whenever a conductor cuts across the magnetic field, an emf is induced in the conductor'.

or 'Whenever the magnetic flux linking with any circuit (or coil) changes, an emf is induced in the circuit'.

Figure 5.27 shows a conductor placed in the magnetic field of a permanent magnet to which a galvanometer is connected. Whenever the conductor is moved upward or downward, that is across the field, there is deflection in the galvanometer needle that indicates that an emf is induced in the conductor. If the conductor is moved along (parallel) the field, there is no deflection in the needle that indicates that no emf is induced in the conductor.

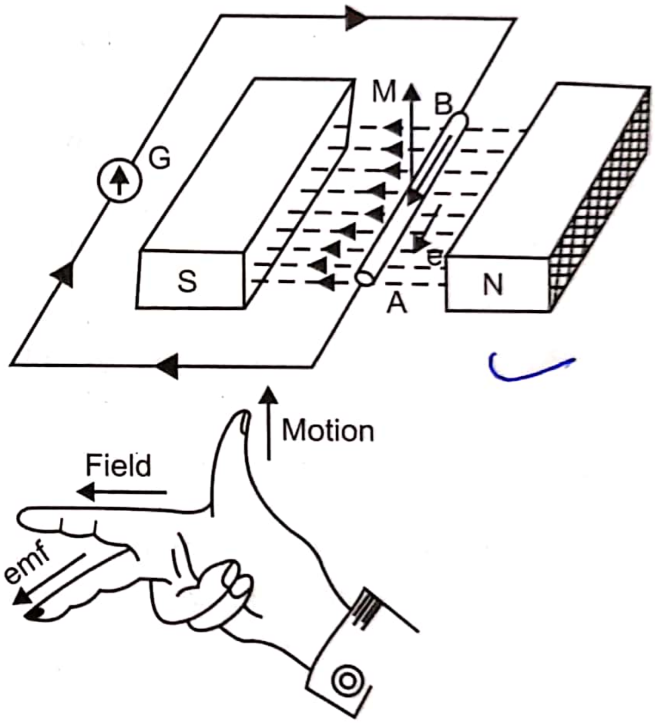

Fig. 5.27 Phenomenon for Faraday's laws of electromagnetic induction

For the second statement, consider a coil placed near a bar magnet and a galvanometer connected across the coil, as shown in Figure 5.28. When the bar magnet (N-pole) is taken near to the coil (see Fig. 5.28 (a)), there is deflection in the needle of the galvanometer. Now, if the bar magnet (*N*-pole) is taken away from the coil (see Fig. 5.28 (b)), again there is deflection in the needle of galvanometer but in opposite direction. The deflection in the needle of galvanometer indicates that emf is induced in the coil.

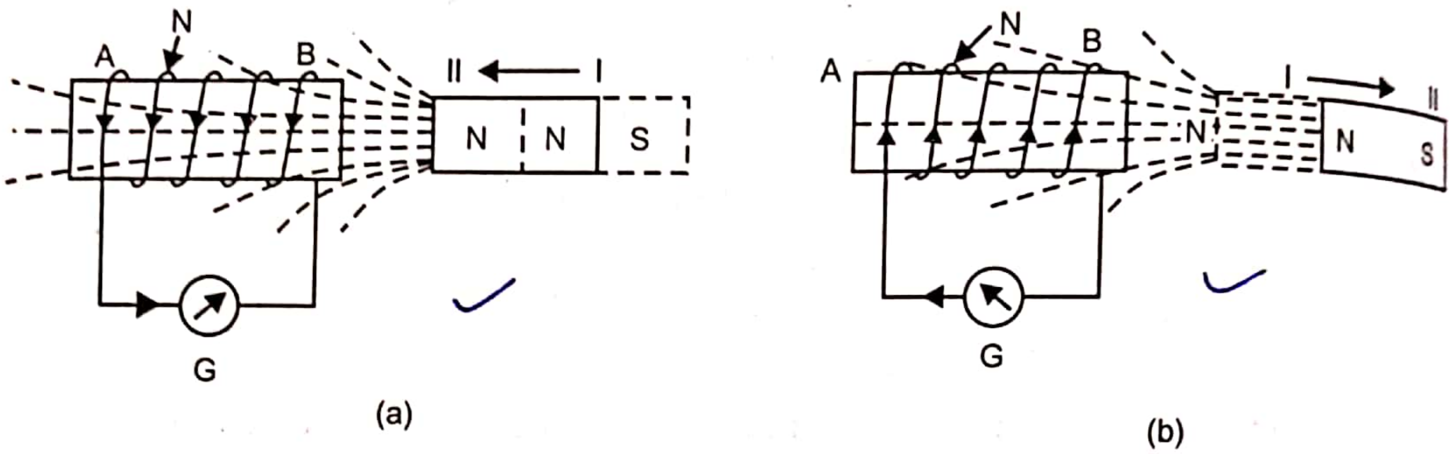

Fig. 5.28 Electromagnetic induction (a) Magnetic bar taken nearer to the coil (b) Magnetic bar taken away to the coil

5.15.2 Second Law

This law states that 'The magnitude of induced emf in a coil is directly proportional to the rate of change of flux linkages.'

$$\text{Rate of change of flux linkages} = \frac{N(\phi_2 - \phi_1)}{t} \text{ Wb-turns/s}$$

where N = number of turns of the coil; $(\phi_2 - \phi_1)$ = change of flux in Wb
t = time in seconds for the change

According to Faraday's second law of electromagnetic induction,

$$\text{Induced emf, } e \propto \frac{N(\phi_2 - \phi_1)}{t}$$

$$e = \frac{N(\phi_2 - \phi_1)}{t} \text{ (taking proportionality constant as unity)}$$

$$\text{In differential form, } e = N\frac{d\phi}{dt} \text{ V}$$

Usually, a minus sign is given to the right-hand side expression that indicates that emf is induced in such a direction that opposes the cause (*i.e.*, change in flux) that produces it (according to Lenz's law).

$$e = -N\frac{d\phi}{dt} \text{ V}$$

5.16 DIRECTION OF INDUCED EMF

The direction of induced emf and hence current in a conductor or coil can be determined by either of the following two methods:

1. **Fleming's Right-hand Rule:** This rule is applied to determine the direction of induced emf in a conductor moving across the field and is stated as
   'Stretch first finger, second finger, and thumb of your right-hand mutually perpendicular to each other. If first finger indicates the direction of magnetic field and thumb indicates the direction of motion of conductor, then second finger will indicate the direction of induced emf in the conductor.'
   Its illustration is shown in Figure 5.27.
2. **Lenz's Law:** This law is more suitably applied to determine the direction of induced emf in a coil or circuit when flux linking with it changes. It is stated as
   'In effect, electromagnetically induced emf and hence current flows in a coil or circuit in such a direction that the magnetic field set up by it always opposes the very cause which produces it.'

When *N*-pole of a bar magnet is taken near to the coil, as shown in Figure 5.28 (a), an emf is induced in the coil, and hence, current flows through it in such a direction that side '*B*' *of* the coil attains North polarity that opposes the movement of the bar magnet. While *N*-pole of the bar magnet is taken away from the coil, as shown in Figure 5.28 (b), the direction of emf induced in the coil is reversed and side 'B' of the coil attains South polarity that again opposes the movement of the bar magnet.

5.17 INDUCED EMF

When flux linking with a conductor (or coil) changes, an emf is induced in it. This change in flux linkages can be obtained in the following two ways:

1. By either moving the conductor and keeping the magnetic field system stationary or moving the magnetic field system and keeping the conductor stationary; in such a way, the conductor cuts across the magnetic field (as in the case of DC and AC generators). The emf induced in this way is called *dynamically induced emf.*
2. By changing the flux linking with the coil (or conductor) without moving either coil or field system. However, the change of flux produced by the field system linking with the coil is obtained by changing the current in the field system (solenoid), as in transformers. The emf induced in this way is called *statically induced emf.*