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DC Machine

مكائن التيار المستمر

المرحلة الثانية

المحاضرة (1)

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I. Introduction

A device (machine) which makes possible the conversion of energy from **electrical to mechanical** form or from **mechanical to electrical** form is called an **Electromechanical energy conversion device** or **Electromechanical transducer**.

Depending upon the conversion of energy from one from to the other, the electro-mechanical device can be named as motor or generator.

1. **Motor:** An electro-mechanical device (electrical machine) which converts electrical energy or power (EI) into mechanical energy or power (ω T) is called a motor.

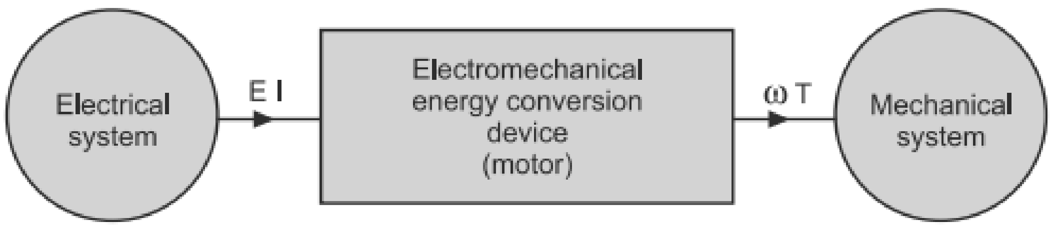


Figure 1. Motor

Electric motors are used for driving industrial machines e.g., hammer presses, drilling machines, lathes, shapers, blowers for furnaces etc., and domestic appliances e.g., refrigerators, fans, water pumps, toys, mixers etc. The block diagram of energy conversion, when the electro-mechanical device works as a motor, is shown in **Fig. 1.**

2. **Generator:** An electro-mechanical device (electrical machine) which convert mechanical energy or power (ω T) into electrical energy or power (EI) is called generator.

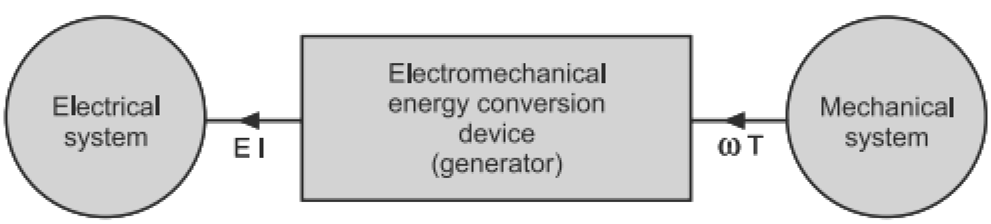


Figure 2. Generator

Generators are used in hydro-electric power plants, steam power plants, diesel power plants, nuclear power plants and in automobiles. In the above said power plants various natural sources of energy are first converted into mechanical energy and then it is converted into electrical energy with the help of generators. The block diagram of energy conversion, when the electro-mechanical device works as a generator, is shown in **Fig. 2**.

1.1 Magnetic Field and its Significance

The region around a magnet where its poles exhibit a force of attraction or repulsion is called **magnetic field**. The existence of the magnetic field at a point around the magnet can also be determined by placing a magnetic needle at that point as shown in **Fig. 3**. Although magnetic lines of force have no real existence and are purely imaginary, yet their concept is very useful to understand various magnetic effects.

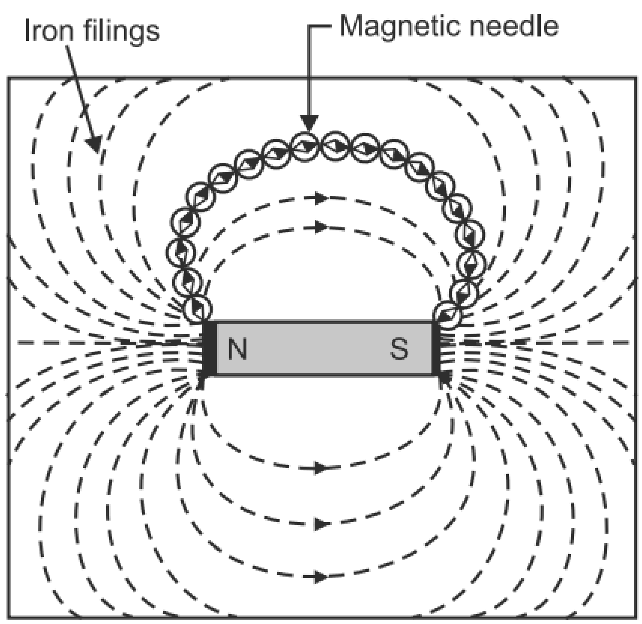


Figure 3. Magnetic field around a bar magnet

1.2 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 4** shows a solenoid having N turns wound on an iron core (ring). When current I **ampere** is passed through the solenoid, magnetic flux ϕ **Weber** is set-up in the core.

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, $B = \frac{\phi}{a}\ \mathrm{Wb/m^2}$

Magnetizing force in the core material.

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

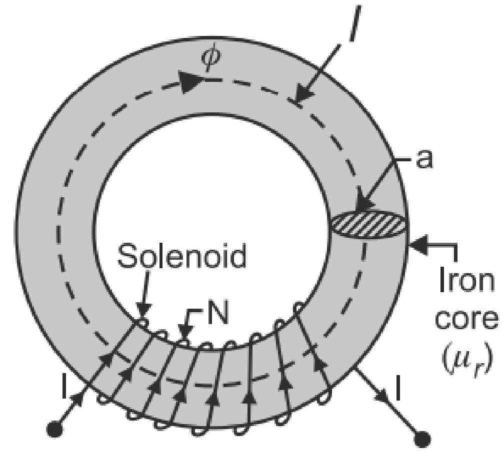


Figure 4. Magnetic circuit

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

$$\text{i.e., } Hl = NI \text{ or } \frac{\phi}{a \mu_0 \mu_r} \times l = NI \text{ or } \phi \quad \mathrm{Wb}$$

The above expression reveals that the amount of flux set-up in the core is

- directly proportional to *N* and *I* i.e., *NI*, called **magnetomotive force** (mmf). It shows that the flux increases if either of the two increases and *vice-versa*.
- 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,

$$\text{Flux } = \frac{\text{m.m.f}}{\text{reluctance}}$$

It may be noted that the above 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 above expression is sometimes referred to as *Ohm's law of magnetic circuits*.

While studying magnetic circuits, generally, 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 number of magnetic lines of force set-up in a magnetic circuit is called *magnetic flux*. Its unit is weber (Wb). It is similar to *electric current I* in electric circuit.
3. The **magnetic flux density** at a point is the flux per unit area at right angles to the flux at that point.
   It is, generally, represented by letter 'B'. Its unit is Wb/m2 or Tesla, i.e.,
   $$B = \frac{\phi}{A} \mathrm{Wb/m^2} \text{ or } \mathrm{T(1Wb/m^2} = 1 \times 10^4 \mathrm{Wb/cm^2)}$$
4. **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 $\mu_0 = 4\pi \times 10^{-7} \mathrm{H/m}$).
   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.
   $$\text{i.e., } \mu_r = \frac{\mu}{\mu_0} \text{ or } \mu = \mu_0 \mu_r$$
   Obviously, the relative permeability of air would be μ_0/μ_0 = 1. The value of relative permeability of all the non-magnetic materials is also 1.

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*, mathematically,
   $$H = \frac{\mathrm{m.m.f}}{\text{length of magnetic path}} = \frac{NI}{l} \ \frac{\mathrm{AT}}{m}$$
6. **Magnetomotive force (m.m.f):** The magnetic pressure which sets-up or tends to set-up magnetic flux in a magnetic circuit is called *magnetomotive force*. As per work law it may be defined as under:
   The work done in moving a unit magnetic pole (1 Wb) once round the magnetic circuit is called *magnetomotive force*. In general

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

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.

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

   It is similar to *resistance* in an electric circuit.

8. **Permeance:** It is a measure of the ease with which flux can be set-up in the material. It is just reciprocal of reluctance of the material and is measured in Wb/AT or *henry*.

$$\text{Permeance} = \frac{1}{\text{reluctance}} = \frac{a\mu_0\mu_r}{l} \text{Wb/AT or H}$$

   It is similar to *conductance* in an electric circuit.

9. **Reluctivity:** It is specific reluctance and similar to *resistivity* in electric circuit.

Example 1: An iron ring of 400 *cm* mean circumference is made from round iron of cross-section 20 cm^2. Its permeability is 500. If it is wound with 400 turns, what **current would be required** to produce a flux of 0.001 Wb?

Sol:

The magnetic circuit is shown in **Fig. 5**.

Mean length of magnetic path, l m = 400 cm = 4 m

Area of X-section of iron ring, $a = 20 \times 10^{-4}$ m^2

Absolute permeability, $\mu_0 = 4\pi \times 10^{-7}$

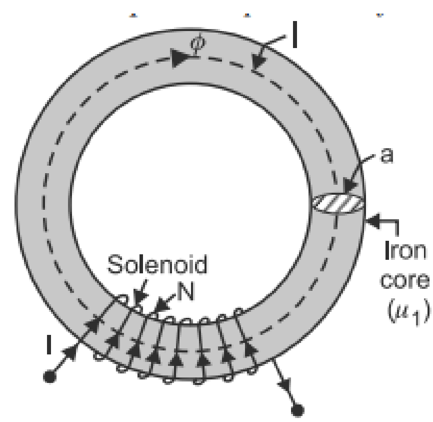


Figure 5. Magnetic circuit

Now mmf = flux × reluctance

where mmf = NI

reluctance = $\frac{l}{a\mu_0\mu_r}$

$$NI = \phi \times \frac{l_m}{a\mu_0\mu_r}$$

$$400 \times I = 0.001 \times \frac{4}{20 \times 10^{-4} \times 4\pi \times 10^{-7} \times 500}$$

$$\text{Current, } I = \frac{0.001 \times 4}{20 \times 10^{-4} \times 4\pi \times 10^{-7} \times 500 \times 400} = \mathbf{7.958\ A} \quad (\textit{Ans.})$$

Example 2: A coil of insulated wire of 500 turns and of resistance 4Ω: is closely wound on iron ring. The ring has a mean diameter of 0.25 *m* and a uniform cross-sectional area of 700 mm^2. **Calculate the total flux in the ring** when a DC supply of 6V is applied to the ends of the winding. Assume a relative permeability of 550.

Sol:

The magnetic circuit is shown in **Fig. 6**.

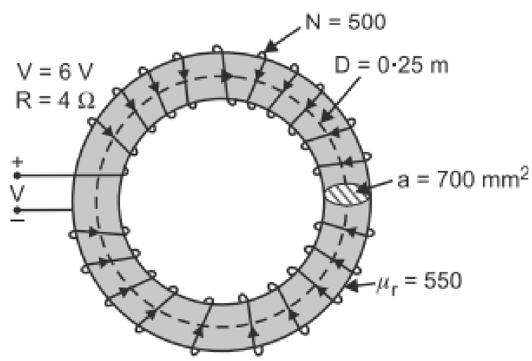


Figure 6. Magnetic circuit

Mean length of iron ring, l = π D = π × 0.25 = 0.25π m

Area of cross-section, a = 700 mm^2 = 700 × 10^{-6} m^2

Now mmf = flux × reluctance

where mmf = NI

reluctance = $\frac{l}{a\mu_0\mu_r}$

$$\text{Current flowing through the coil } I = \frac{\text{Voltage applied across coil}}{\text{Resistance of coil}}$$

$$= \frac{6}{4} = 1.5\text{A}$$

$$NI = \phi \times \frac{l_m}{a\mu_0\mu_r}$$

$$\text{Total flux in the ring, } \phi = \frac{NI}{l/a\mu_0\mu_r} = \frac{NI \times a\mu_0\mu_r}{l}$$

$$= \frac{500 \times 1.5 \times 700 \times 10^{-6} \times 4\pi \times 10^{-7} \times 550}{0.25\pi} = \mathbf{0.462\ mWb} \quad (\textit{Ans.})$$

Example 3: Calculate the relative permeability of an iron ring when the exciting current taken by the 600-turn coil is 1.2 A and the total flux produced is 1 *m* Wb. The mean circumference of the ring is 0.5 *m* and the area of cross-section is 10 cm^2.

Sol:

$$NI = \frac{\phi \times l}{a\mu_0\mu_r}$$

$$\mu_r = \frac{\phi \times l}{a\mu_0 NI}$$

where N = 600 turns; I = 1.2 A; ϕ = 1 m Wb = 1×10^{-3} Wb; $l = 0{\cdot}5$ *m*; a = 10 cm^2 = 10×10^{-4} m^2

$$\mu_r = \frac{1 \times 10^{-3} \times 0.5}{10 \times 10^{-4} \times 4\pi \times 10^{-7} \times 600 \times 1 \cdot 2} = \mathbf{552.6} \quad \textit{(Ans.)}$$

1.3 Hysteresis

Let a ferromagnetic material which is completely demagnetized, i.e. one in which $B = H = 0$ be subjected to increasing values of magnetic field intensity H and the corresponding flux density B measured. The resulting relationship between B and H shown by the curve ***oa*** in **Fig. 7**. At a particular value of H, shown as ***oa***, it become difficult to increase the flux density any further. The material is said to be saturated. Thus, by is the saturation flux density.

If the value of H is now reduced it is found that the flux density follows curve ***ab***. When H is reduced to zero, flux remains in the iron. This remnant flux density is shown as ***ob*** in **Fig. 7**. When H is increased in the opposite direction, the flux density decreases until at a value as shown ***oc***, the flux density has been reduced to zero. The magnetic field intensity ***oc*** *r*equired to remove the residual magnetism, i. e. reduce B to zero is called the coercive force.

Further increase of H in the reverse direction causes the flux density to increase in the reverse direction until saturation is reached as shown by curve ***cd***. If H is varied backwards from ***do*** to ***ob*** the flux density follows the curve ***defa***, similar to curve ***abcd***.

It is seen from **Fig. 7** that the flux density changes lag behind the changes in the magnetic field intensity. This effect is called hysteresis. The closed Fig. ***babcdefa*** is called the Hysteresis loop (or the $\frac{B}{H}$ loop).

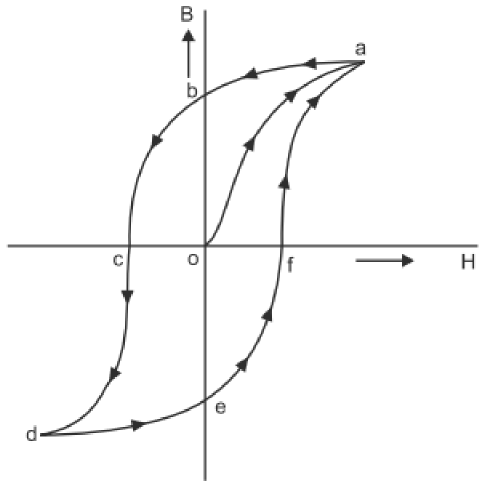
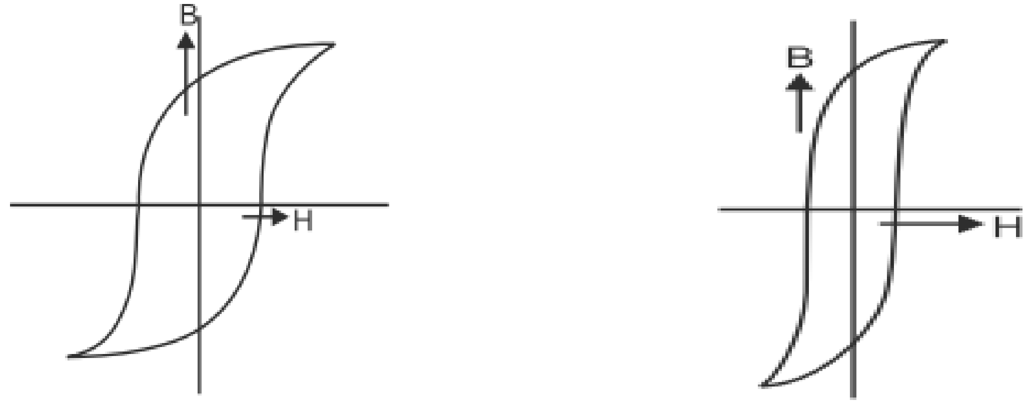


Figure 7. Hysteresis loop.

- **Hysteresis loss:** A disturbance in the alignment of the domains (i.e. groups of atoms) of a ferromagnetic material causes energy to be expended in taking it through a cycle of magnetization. This energy appears as heat in the specimen and is called the hysteresis loss.

The area of a hysteresis loop varies with the type of material. The area, and thus the energy loss, is much greater for hard materials than for soft materials.

- **Hard Magnetic Materials:** Magnetic Materials, which have large hysteresis loop area and hence large energy loss per cycle of magnetization, are classified as hard magnetic materials. The magnetization curve for hard magnetic materials is shown in **Fig. 8(a).** Carbon steel, tungsten steel, cobalt steel and hard ferrites are categorized as the hard-magnetic materials. These materials are suitable for making the instruments and devices, which require permanent magnets.
- **Soft magnetic material:** Some magnetic materials have steep magnetization curve as given in **Fig. 8(b).** These materials have relatively small and narrow hysteresis loop and hence small energy loss per cycle of magnetization. These materials are called soft magnetic materials. Silicon steel, nickel iron alloys and soft ferrites are the soft magnetic materials. These materials can be used for the construction of cores of electrical machines, transformers, electromagnets, reactors, relates etc.



(a) (b)

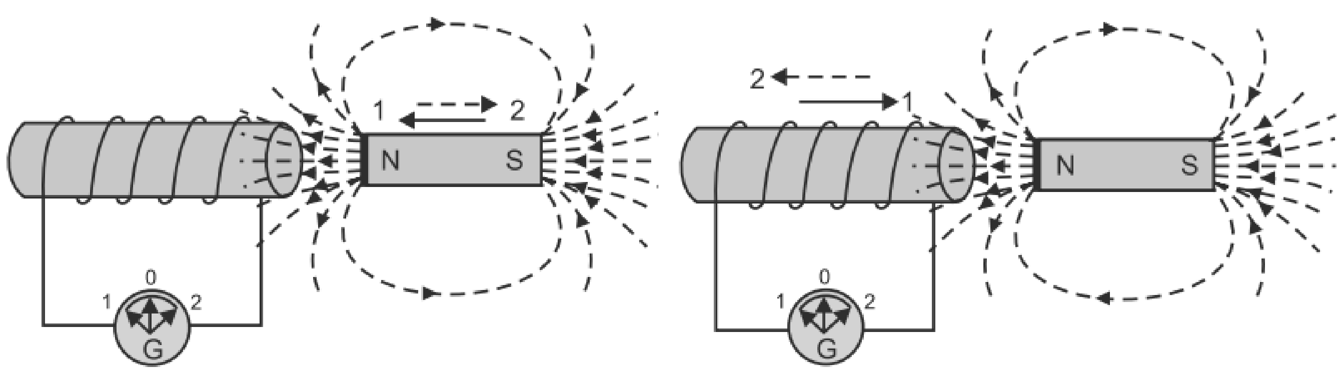
Figure 8. Hysteresis loop for different magnetic materials (a) Hard (b) Soft.

1.4 Electro Magnetic Induction

The phenomenon by which an emf is induced in a circuit (and hence current flows when the circuit is closed) when magnetic flux linking with it changes is called *electro-magnetic induction*.

For illustration, consider a coil having a large number of turns to which galvanometer is connected. When a permanent bar magnet is taken nearer to the coil or away from the coil, as shown in **Fig. 9 (a)**, a deflection occurs in the needle of the galvanometer. Although, the deflection in the needle is opposite is two cases.

On the other hand, if the bar magnet is kept stationary and the coil is brought nearer to the magnet or away from the magnet, as shown in **Fig. 9 (b)**, again a deflection occurs in the needle of the galvanometer. The deflection in the needle is opposite in the two cases.



(a) (b)

Figure 9. Electromagnetic induction (a) Bar Magnetic in Motion (b) Coil in Motion

However, if the magnet and the coil both are kept stationary, no matter how much flux is linking with the coil, there is no deflection in the galvanometer needle.

The following points are worth noting:

- The deflection in the galvanometer needle shows that emf is induced in the coil. This condition occurs only when flux linking with the circuit changes i.e., either magnet or coil is in motion.
- The direction of induced emf in the coil depends upon the direction of magnetic field and the direction of motion of coil.

1.5 Faraday's Laws of Electromagnetic Induction

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

- **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 10 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 i.e., across the field, there is deflection in the galvanometer needle which 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 which indicates that no emf is induced in the conductor.

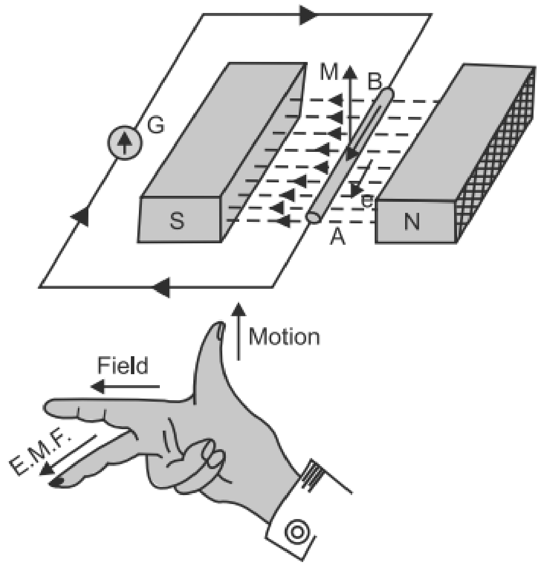


Figure 10. Conductor moving in the field.

For the second statement, consider a coil placed near a bar magnet and a galvanometer connected across the coil, as shown in **Fig. 11**. When the bar magnet (N-pole) is taken nearer to the coil [**see Fig. 11 (a)**], there is deflection in the needle of the galvanometer. If now the bar magnet (N-pole) is taken away from the coil [**see Fig. 11 (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.

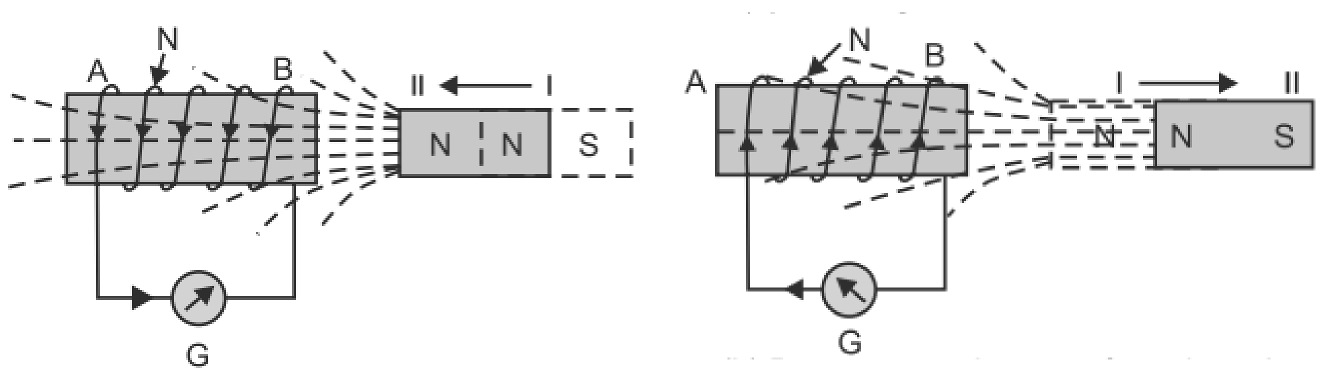


Figure 11. Coil is stationary but bar magnet (field) is moving (a) Bar Magnet taken Mearir The Coil (b) Bar Magnet take away from The Coil.

1.6 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:

- **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 under;

  "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, thumb indicates the direction of motion of conductor then second finger will indicate the direction of induced emf in the conductor."

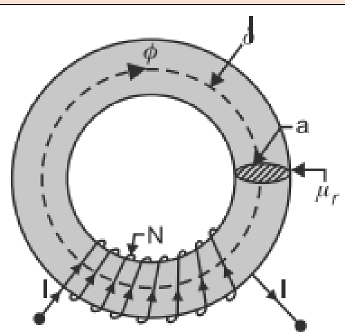
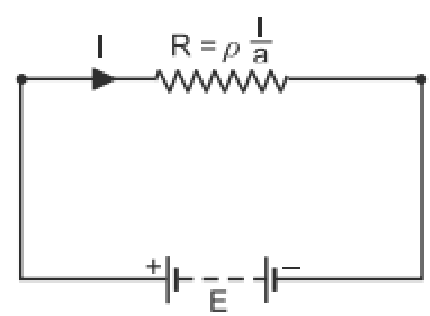
  Its illustration is shown in **Fig. 10.**

- **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 under:

  "In effect, electro-magnetically 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."

Explanation: When N-pole of a bar magnet is taken nearer to the coil as shown in **Fig. 11**, 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 which opposes the movement of the bar magnet. Whereas, when N-pole of the bar magnet is taken away from the coil as shown in **Fig. 11**, the direction of emf induced in the coil is reversed and side 'B' of the coil attains South polarity which again opposes the movement of the bar magnet.

1.7 Comparison between Magnetic and Electric Circuits

Magnetic Circuits	Electrical Circuits
	
Similarities	
1. The closed path for magnetic flux is called magnetic circuit. 2. Flux = mmf/reluctance	1. The closed path for electric current is called electric circuit. 2. Current = emf/resistance

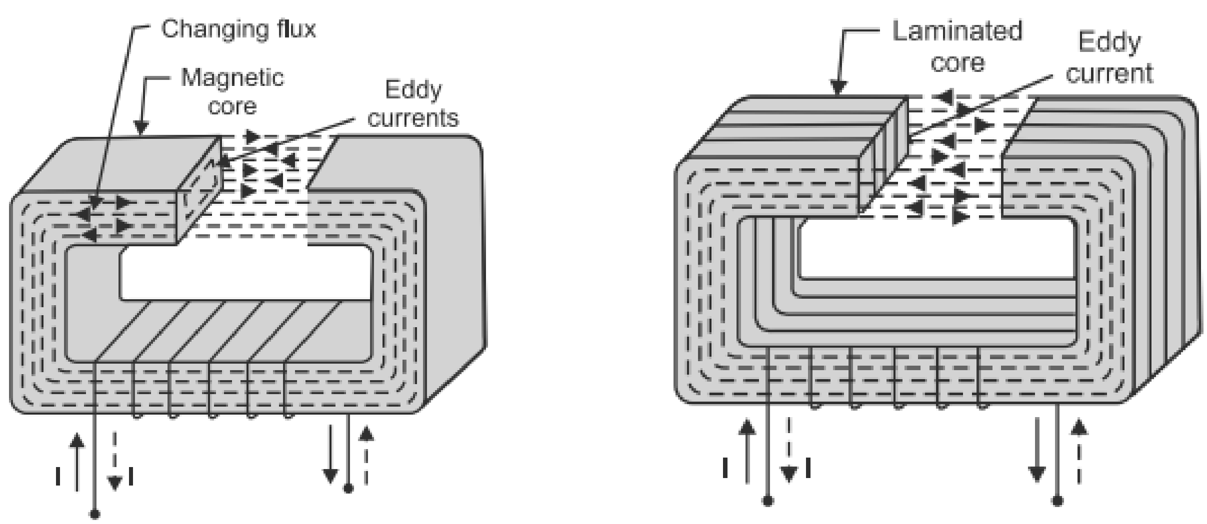
3. Flux, ϕ in Wb 4. mmf in AT 5. Reluctance, $S = \frac{l}{a\mu_0\mu_r}$ AT/Wb 6. Permeance = 1/reluctance 7. Permeability, μ 8. Reluctivity 9. Flux density, $B = \frac{\phi}{a}$ $\mathrm{Wb/m^2}$ 10. Magnetic intensity, *H* = *NI/I*	3. Current, *I* in ampere 4. emf in V 5. Resistance, $R = \rho\frac{l}{a}\Omega$ or $R = \frac{1}{\sigma}\frac{l}{a}\Omega$ 6. Conductance = 1/resistance 7. Conductivity, $\sigma = 1/\rho$ 8. Resistivity 9. Current density, $J = \frac{1}{a}$ $\mathrm{A/m^2}$ 10. Electric intensity, $E = V/d$
Dissimilarities	
1. In fact, the magnetic flux does not flow but it sets up in the magnetic circuit (basically molecular poles are aligned). 2. For magnetic flux, there is no perfect insulator. It can be set-up even in the non-magnetic materials like air, rubber, glass etc. with reasonable mmf 3. The reluctance (*S*) of a magnetic circuit is not constant rather it varies with the value of *B*. It is because the value of μ_r changes considerably with the change in *B*. 4. Once the magnetic flux is set-up in a magnetic circuit, no energy is expanded. However, a small amount of energy is required at the start to create flux in the circuit.	1. The electric current (electrons) actually flows in an electric circuit. 2. For electric current, there are large number of perfect insulators like glass, air, rubber, etc., which do not allow it to follow through them under normal conditions 3. The resistance (***R***) of an electric circuit is almost constant as its value depends upon the value of ρ which is almost constant. However, the value of ρ and ***R*** may vary slightly if temperature changes. 4. Energy is expanded continuously, so long as the current flows through an electric circuit. This energy is dissipated in the form of heat.

1.8 Eddy Current Loss

When a magnetic material is subjected to a changing (or alternating) magnetic field, an emf is induced in the magnetic material itself according to Faraday's laws of electro-magnetic induction. Since the magnetic material is also a conducting material, these emfs. circulate currents within the body of the magnetic material. These circulating currents are known as **eddy currents**. As these currents are not used for doing any useful work, therefore, these currents produce a loss (i^2 R loss) in the magnetic material called eddy current loss. Like hysteresis loss, this loss also increases the temperature of the magnetic material. The hysteresis and eddy current losses in a magnetic material are called *iron losses* or *core losses* or *magnetic losses*.

A magnetic core subjected to a changing flux is shown in Fig. 10. For simplicity, a sectional view of the core is shown. When changing flux links with the core itself, an emf is induced in the core which sets-up circulating (eddy) currents (i) in the core as shown in **Fig. 12 (a)**. These currents produce eddy current loss (i^2 R), where **i** is the value of eddy currents and **R** is resistance of eddy current path. As the core is a continuous iron block of large cross-section, the magnitude of **i** will be very large and hence greater eddy current loss will result.

To reduce the eddy current loss, the obvious method is to reduce magnitude of eddy currents. This can be achieved by splitting the solid core into thin sheets (called laminations) in the planes parallel to the magnetic field as shown in **Fig. 12 (b)**. Each lamination is insulated from the other by a fine layer of insulation (varnish or oxide film). This arrangement reduces the area of each section and hence the induced emf It also increases the resistance of eddy currents path since the area through which the currents can pass is smaller. This loss can further be reduced by using a magnetic material having higher value of resistivity (like silicon steel).



(a) (b)

Figure 12. Production of eddy currents (a) Solid Core (b) Laminated Core.