Unit - I

Chapter

1

Electric and Magnetic Circuits

Syllabus :

EMF, Current, Potential difference, Power and Energy, MMF, Magnetic force, Permeability, Hysteresis loop, Reluctance, Leakage factor and BH curve, Analogy between electric and magnetic circuits, Electromagnetic induction, Faraday's laws of electromagnetic induction, Lenz's law, Dynamically induced emf, Statically induced emf : (a) Self induced emf (b) Mutually induced emf, Equations of self and mutual inductance.

Chapter Contents

1.1 Introduction to Electricity :

Before discussing any advanced concepts in electrical engineering, it is necessary to get introduced ourselves to some of the basic concepts such as electromotive force (emf), potential, potential difference, current etc. or resistance, effects of temperature on its value etc.

1.1.1 Electrical Quantities :

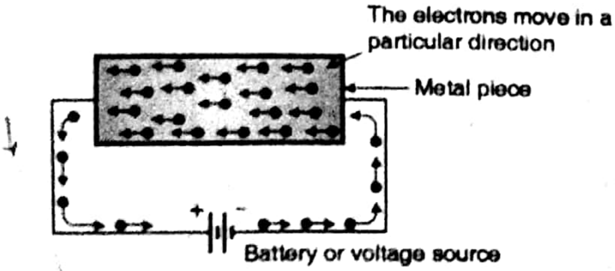
Following are some of the important parameters in electricity. We are going to discuss them in the following sections of this chapter.

1. Electromotive Force (EMF)
2. Current
3. Resistance
4. Potential difference.

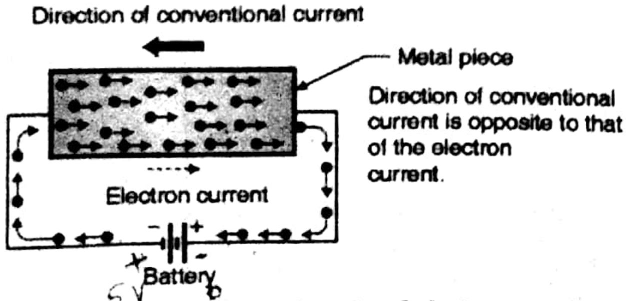
1.2 Concept of EMF and Current :

1.2.1 Concept of EMF :

- EMF is the short form of electromotive force. All the metals contain a large number of free electrons which move randomly in all the directions, inside the metal piece, if no external source is connected.
- If a battery or voltage source is connected across a metal piece as shown in Fig. 1.2.1, then the free electrons will move in the direction of positive end of the external dc source. This happens due to the electric force or pressure by the external battery.
- The electrical force or pressure that causes the electrons to move in a particular direction is called as the **electromotive force i.e. EMF.**



(A-2) **Fig. 1.2.1 : Concept of EMF**



(A-3) **Fig. 1.2.2 : Conventional and electron currents**

- The units of e.m.f. is **volts** and e.m.f. is also called as voltage or potential difference. It is denoted by V or sometimes by E.

1.2.2 Concept of Current :

Definition :

- An electric current is defined as the movement of electrons or flow of electrons inside a conducting material. It is denoted by I and measured in ampere (A).

Electron current :

The current due to flow of electrons is called as electron current. The electron current flows from the negative end of the battery to the positive end as shown in Fig. 1.2.2.

Conventional current :

- Conventionally the current is said to be flowing from higher potential to lower potential i.e. from a positive potential to a negative potential. Hence even though the actual electron current flows from the negative to positive terminal, the **conventional current** is said to flow from the positive end of the battery to the negative end of the battery. (Fig. 1.2.2).
- Thus the direction of flow of conventional current is always opposite to that of the electron current.

Relation between charge and current :

- Current is defined as the flow of electrons. Higher the number of flowing electrons, higher is the value of current. But each electron carries a constant charge on it.
- We can define the current as flow of charge per unit time OR current is defined as the rate of change of charge with respect to time.
- Mathematically the charge - current relation can be defined as,

$$I = \frac{Q}{t} \text{ Amperes} \qquad ...(1.2.1)$$

Where I = Average current in amperes

Q = Total charge flowing

t = Time in seconds required for the flow of charge

1.3 Concept of Electric Potential and Potential Difference :

Consider the two charged particles having similar charges as shown in Fig. 1.3.1. As the charge are similar, there is a force of repulsion between them.

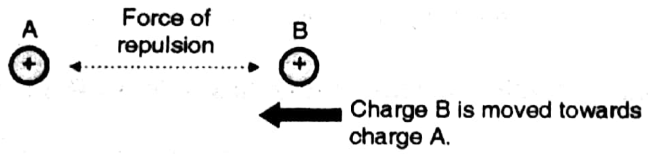
1.3.1 Definition of Electric Potential :

- If charge B is to be brought closer to charge A, then work has to be done against this force of repulsion.
- This work done against the force of repulsion to bring a charge closer to the other one is called as **electric potential**, and it is measured in **volts**.

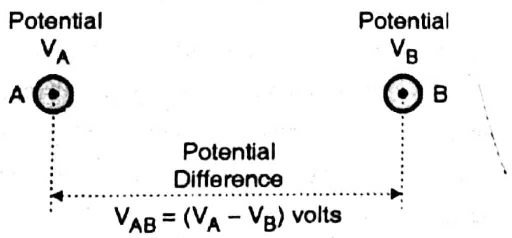
1.3.2 Potential Difference (P.D.) :

Definition :

- Potential difference between any two points is defined as the difference between the electric potentials at those points. Refer Fig. 1.3.2 in which the potential at point A is V_A volts and that at point B is V_B.



(A-4) **Fig. 1.3.1 : Similar charges repel each other**



(A-5) **Fig. 1.3.2 : Concept of potential difference**

- Therefore the potential difference between A and B is given by V_{AB}.

$$\therefore \; V_{AB} = (V_A - V_B) \text{ volts}$$

- The potential difference is measured in volts.

Positive and negative P.D. :

- If the potential at point A is higher than that at point B i.e. if $V_A > V_B$ then the potential difference V_{AB} will be positive.
- But if the potential at point A is lower than that at point B i.e. if $V_A < V_B$ then the potential difference V_{AB} is negative.

Effect of potential difference :

- The main effect of potential difference is the flow of electric current from the point of higher potential to the point of lower potential, if the two points are connected to each other with a conducting wire.
- If the potential difference between the two points is zero then no current will flow between them.

1.4 Concept of Resistance (R) :

Definition of resistance :

- Resistance of a material is defined as the opposition to flow of current. It is measured in ohms (Ω). Its symbol is R. Every material (metals, semiconductors, inductors) has resistance. Resistance of metal is low while insulators have a very high resistance.
- Resistance of metals is small hence they are good conductors of electric current (opposition to the flow of current is less).
- Certain materials like plastic, wood, glass do not allow the current to pass through them easily, hence they are called as bad conductors or insulators.

Mathematical expression for resistance (Law of resistance) :

The mathematical expression for the resistance of a conductor is,

$$R = \rho \frac{l}{a} \qquad ...(1.4.1)$$

Where ρ = Resistivity of a material and it is constant.

l = Length of the conductor and

a = Cross sectional area

1.4.1 Factors Affecting the Resistance Value :

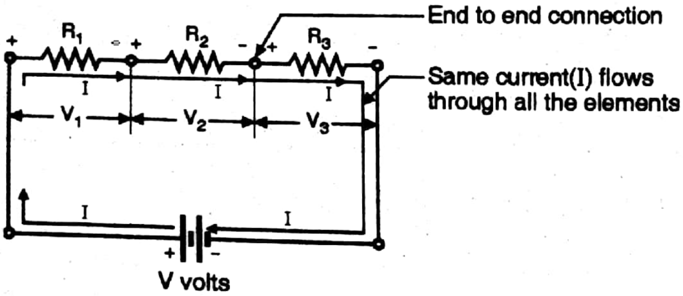
From Equation (1.4.1) it is clear that the resistance R is directly proportional to the resistivity of the material "ρ" and length of the conductor "l" and it is inversely proportional to the cross sectional area "a" of the conductor.

Temperature :

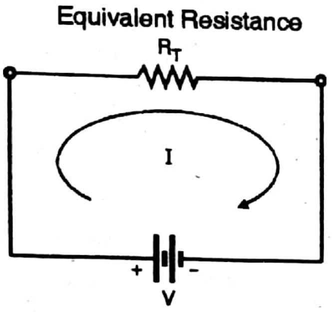
The temperature is not included in Equation (1.4.1), but it is one more factor that decides the value of R. Due to change in temperature the length of a conductor will change which will change the value of R. Generally with increase in temperature, the value of R increases.

1.4.2 Series Circuit (Resistors in Series) :

– Fig. 1.4.1(a) shows three resistors R_1, R_2 and R_3 connected in series with each other. Note that the end of one regsistor is connected to the end of another resistor, to form a link.



(a) Series circuit (Resistors in series)



(b) The complete series circuit can be replaced by the equivalent resistance R_T

(A-7) Fig. 1.4.1

– All the elements in a series link are connected in this manner. Therefore series circuit is also called as end to end or cascade connection.

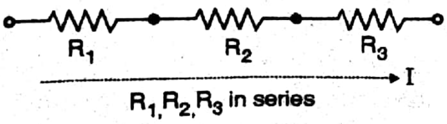
– Also note that all the elements connected in the series circuit will carry the same current I.

– As shown in Fig. 1.4.1(a) the series combination of resistors R_1, R_2 and R_3 is connected across the dc voltage source with a terminal voltage V volts. The voltage drops across the individual resistors are V_1, V_2 and V_3 respectively.

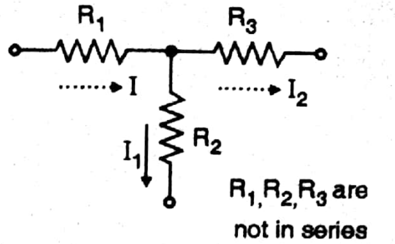
Conditions to be satisfied for series connection :

1. There should be end to end connection.
2. Current through the elements should be same.

Fig. 1.4.1(c) shows resistors satisfying both the conditions while Fig 1.4.1(d) shows resistors with end to end connection but current not the same.



(c) Both conditions satisfied



(d) Second condition is not satisfied

(A-82) Fig. 1.4.1

Resistance of series combination :

– For three resistors R_1, R_2 and R_3 in series as shown in Fig. 1.4.1(a), it can be proved that the expression for equivalent resistance is as follows :

$$R_T = R_1 + R_2 + R_3 \qquad ...(1.4.2)$$

– Thus the equivalent resistance of a series circuit is equal to the sum of resistances connected in series.

– For "n" resistors connected in series the equivalent resistance is given by,

$$R_T = R_1 + R_2 + ... + R_n \qquad ...(1.4.3)$$

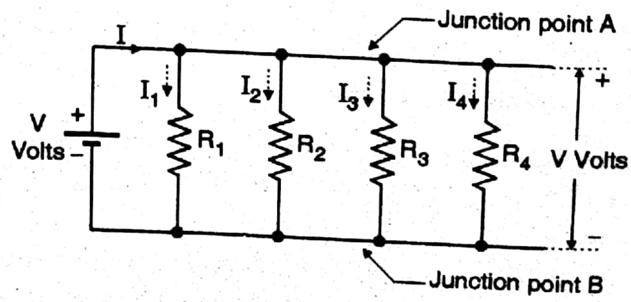
– We can replace the complete series circuit by the equivalent resistance R_T as shown in Fig. 1.4.1(b).

1.4.3 Parallel Circuit (Resistors in Parallel) :

– Fig. 1.4.2 shows the resistors R_1, R_2, R_3 and R_4 connected in parallel with each other.

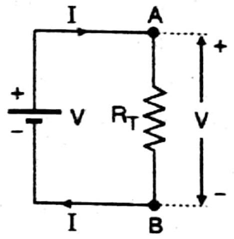
– As shown in Fig. 1.4.2(a), in parallel connection, resistors are connected across each other. That means one end of each resistor is connected to a junction point A, while the other end of each resistor is connected to the other junction point B.

– The parallel combination of the four resistors is connected across the voltage source V. The current flowing through each resistor has a different value but the voltage across each resistor is the same i.e. V volts.



(a) Resistors in parallel

Fig. 1.4.2 (Contd...)

$\equiv$ 

(b) Parallel combination can be replaced by the equivalent resistance R_T

(A-8) **Fig. 1.4.2**

Conditions to be satisfied for parallel connection :

1. The resistors should appear across each other.
2. Voltage across all the parallel elements is the same.

Resistance of parallel combination :

- It can be proved that the value of the equivalent resistance as,

$$\frac{1}{R_T} = \frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\frac{1}{R_4} \qquad ...(1.4.4)$$

- In general for "n" resistors connected in parallel, the equivalent resistance is given by,

$$\frac{1}{R_T} = \frac{1}{R_1}+\frac{1}{R_2}+...+\frac{1}{R_n} \qquad ...(1.4.5)$$

- We can replace the complete parallel circuit by the equivalent resistance R_T as shown in Fig. 1.4.2(b). The equivalent resistance is smaller than the smallest resistance in the parallel circuit.

Effective resistance of two resistors in parallel :

For two resistors connected in parallel, the expression for effective resistance [Equation (1.4.5)] gets modified as,

$$\frac{1}{R_T} = \frac{1}{R_1}+\frac{1}{R_2} = \frac{R_2+R_1}{R_1 R_2}$$

$$\therefore\ R_T = \frac{R_1 R_2}{R_1+R_2} \qquad ...(1.4.6)$$

1.4.4 Power :

- Power in a dc circuit is equal to the product of voltage and current.

$$P = V \times I \qquad ...(1.4.7)$$

- The unit of power is Watt. Power is also defined as the rate of transfer of energy with respect to time.

1.4.5 Electrical Energy :

Electrical energy is defined as the product of electric power and the time. Therefore the unit of energy will be watt-hour.

$$E = P \times t \qquad ...(1.4.8)$$

1.4.6 Relation between Voltage, Current, Resistance : Ohm's Law :

The relation between voltage, current and resistance in a circuit is given by the Ohm's law. It states the relation between V, I and R as :

$$V = I \times R \text{ or } I = \frac{V}{R} \qquad ...(1.4.9)$$

Ex. 1.4.1 : A coil consists of 2000 turns of copper wire having a cross sectional area of 0.8 mm^2. The mean length per turn is 80 cm and the resistivity of copper wire is 0.02 micro-ohm-meter. Find the resistance of the coil and power absorbed by the coil when connected across 110 V d.c. supply.

Soln. :

Given : $N = 2000$, $a = 0.8\ mm^2 = 0.8 \times 10^{-6}\ m^2$,

Mean length per turn = 80 cm = 0.8 m,

$\rho = 0.02\ \mu\Omega\text{-m} = 0.02 \times 10^{-6}\ \Omega\text{-m}$, $V_s = 110$ Volts

To find : R, P

1. **Resistance (R) :**

Total length of the copper wire = 0.8 m × 2000 turns = 1600 m

$$\therefore\ R = \rho \times \frac{l}{a} = 0.02 \times 10^{-6} \times \frac{1600}{0.8 \times 10^{-6}}$$

$$= 40\ \Omega \qquad \text{...Ans.}$$

2. **Power absorbed (P) :**

$$P = \frac{V_s^2}{R} = \frac{(110)^2}{40} = 302.5\ W \qquad \text{...Ans.}$$

1.5 Concept of Electrical Work, Power and Energy :

1. **Electric work :**

- An electric work is the work done to transfer a charge from one point to the other. The unit of electric work done is **Joules.**

- One joule of electric work is defined as the amount of work done to move a unit charge (1 coulomb) through the potential difference of 1 volt.
- Hence work done to move a charge of Q coulomb through a potential difference of V volts is given by,

$$W = Q \times V \text{ Joules} \quad ...(1.5.1)$$

But $I = \frac{Q}{t}$ $\therefore Q = I \times t$ where t = Time in seconds

$$\therefore W = V \times I \times t \text{ Joules} \quad ...(1.5.2)$$

- We have already defined the terms voltage and current for the electrical system in the earlier sections. Now let us define the energy and power in this section.

2. Concept of power (P) : UT 1

- The electric power is due to voltage as well as current.
- It is defined as the product of voltage and current.

$$\therefore \text{Power } P = V \times I \quad ...(1.5.3)$$

- The power is denoted by P and it is measured in watts (S.I. units). Thus electric power is proportional to voltage as well as current.
- If two lamps A and B are of 40 W and 100 W respectively then lamp B receives more power for the same applied voltage.
- Substituting I = V/R we get an alternate expression for power as,

$$P = V \times \frac{V}{R} = \frac{V^2}{R} \text{ Watt} \quad ...(1.5.4)$$

- And substituting V = IR in Equation (1.5.4) we get,

$$P = \frac{(IR)^2}{R} = \frac{I^2 R^2}{R} = I^2 \times R \text{ Watt} \quad ...(1.5.5)$$

3. Concept of energy (E) : UT 1

- The electric energy is defined as the product of power and time.

$$\therefore \text{Energy} = \text{Power (P)} \times \text{Time (t)} \quad ...(1.5.6)$$

- The S.I. units of energy are Watt-second or Joules.
- The alternate expression for energy is,

$$E = V \times I \times t \text{ Joules} \quad ...(1.5.7)$$

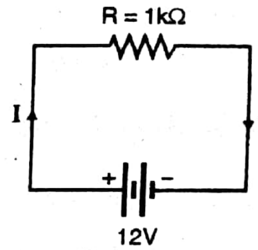
- Practically the electrical energy is expressed in watt hour or kWh.
- The electricity meters installed by the electricity board are basically the energy meters which measure the electricity consumption in kWh.

Ex. 1.5.1 : A resistance of 1 kΩ is connected across a 12 V battery, for 2 hours. Calculate the power dissipated in the resistor and the energy associated with it.

Soln. :

Step 1 : Draw the circuit diagram :

The required circuit diagram is as shown in Fig. P. 1.5.1.



(A-2730) **Fig. P. 1.5.1**

Step 2 : Calculate current and power :

$$V = IR \quad \text{...ohm's law}$$

$$\therefore I = \frac{V}{R} = \frac{12}{1000} = 12 \text{ mA}$$

$$= 12 \times 10^{-3} \text{ A}$$

$$\therefore P = V \times I = 12 \times 12 \times 10^{-3}$$

$$= 144 \times 10^{-3} \text{ W}$$

$$P = 144 \text{ mW}$$ **...Ans.**

Step 3 : Calculate energy :

$$E = P \times t = 144 \times 10^{-3} \times 2 \times 3600$$

$$t = 2 \text{ hours} = 2 \times 3600 \text{ sec}$$

$$\therefore E = 1036.8 \text{ W-sec or Joules}$$ **...Ans.**

Ex. 1.5.2 : Four 60 W, 230 V lamps remain on for four hours a day. Calculate the monthly electricity bill, if the rate is ₹ 5/- per unit.

Soln. :

- The monthly electricity bill is based on the energy consumed in kWh (kilo watt hour).
- One unit corresponds to 1 kWh.
- Energy consumed in one month is given by,

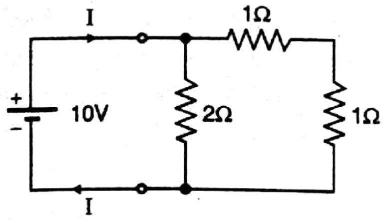
$$E = P \times t = 60 \text{ W} \times 4 \text{ hours} \times 30 \text{ days}$$

$$= 7200 \text{ Watt-hours} = 7.2 \text{ kWh}$$

So number of units per month = 7.2

$\therefore$ Monthly bill $= 7.2 \times 5 =$ ₹ 36/- **...Ans.**

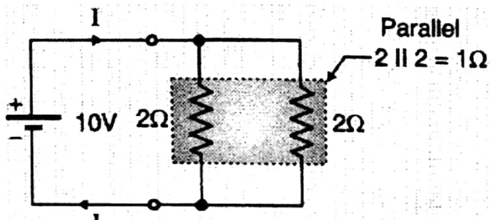
Ex. 1.5.3 : For the circuit shown in Fig. P. 1.5.3(a). Calculate the power supplied by the battery.



(A-2731) **Fig. P. 1.5.3(a)**

Soln. :

Step 1 : Calculate current I :



(A-2732) **Fig. P. 1.5.3(b)**

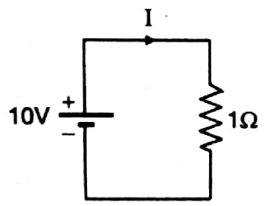


Fig. P. 1.5.3(c)

Fig. P. 1.5.3(c) shows the simplified circuit

$$\therefore \quad I = V/R = 10/1 = 10 \text{ A}$$

Step 2 : Calculate power :

$$P = V \times I = 10 \times 10 = 100 \text{ W} \quad \textbf{...Ans.}$$

This is the power supplied by the battery.

Ex. 1.5.4 : A furnace takes a current of 10 ampere from a 200 V D.C. supply for 8 hours. Calculate energy consumed in kWh.

Soln. :

Given : $I = 10$ A, $V = 200$ V, $t = 8$ hours

To find : Energy in kWh.

Step 1 : Calculate power :

$$P = V \times I = 200 \times 10 = 2000 \text{ W} = 2 \text{ kW}$$

Step 2 : Calculate energy :

$$E = P \times t = 2 \text{ kW} \times 8 \text{ h}$$

$$E = 16 \text{ kWh} \quad \textbf{...Ans.}$$

Ex. 1.5.5 : An electric heater is marked 230 Volts, 750 Watts. What current it takes ? What is its hot resistance ? Determine the cost of using it for 10 hours at ₹ 2 per unit.

Soln. :

Given : $V = 230$ Volts, $P = 750$ Watts

To find : R, cost of using for 10 hours

Step 1 : Find the hot resistance :

The power rating corresponds to the hot condition of the heater that is when current is flowing through it.

$$\therefore \quad P = \frac{V^2}{R}$$

where R = Hot resistance

$$\therefore \quad R = \frac{V^2}{P} = \frac{(230)^2}{750} = 70.53 \ \Omega \quad \textbf{...Ans.}$$

Step 2 : Find cost of using the heater :

One unit corresponds to 1 kilowatt hour

$$\therefore \quad 1 \text{ unit} = 1 \text{ kilowatt hour}$$
$$= 1000 \text{ watt-hour}$$

If the heater is used for 10 hours then the corresponding energy is given by,

$$E = P \times \text{time}$$
$$= 750 \times 10 \text{ hours}$$
$$E = 7500 \text{ watt-hours}$$
$$\therefore \quad E = \frac{7500}{1000} = 7.5 \text{ kW-hours} = 7.5 \text{ units}$$

$\therefore$ Cost of using the heater for 10 hours is given by

$$\text{Cost} = \text{Number of units} \times \text{Cost per unit}$$
$$= 7.5 \times 2 = ₹\ 15/- \quad \textbf{...Ans.}$$

Ex. 1.5.6 : Calculate current, resistance and energy consumed by an oven rated 230 V, 1 kW when used for 20 hours.

Soln. :

Given :

Oven = 230 V, 1 kW, $t = 20$ hours $= 20 \times 3600$ sec.

1. Current I and Resistance R :

Resistance of the oven filament

$$R = \frac{V^2}{P} = \frac{(230)^2}{1 \times 10^3} = 52.9 \ \Omega \quad \textbf{... Ans.}$$

$$\therefore \quad \text{Current} \quad I = \frac{V}{R} = \frac{230}{52.9} = 4.35 \text{ Amp} \quad \textbf{... Ans.}$$

2. Energy consumed E :

$$E = P \times t = V \times I \times t$$
$$= 230 \times 4.35 \times (20 \times 3600)$$
$$= 72 \times 10^6 \text{ J or } 72 \text{ M J} \quad \textbf{... Ans.}$$

Ex. 1.5.7 : Calculate current, resistance and energy consumed by an electric iron rated 230 V, 2 kW when used for 12 hours.

Soln. :

Given :

$V = 230\ V,\ \ P = 2\ kW,\ \ t = 12 \text{ hours} = 12 \times 3600 \text{ sec.}$

Find : 1. Current 2. Resistance 3. Energy consumed

Step 1 : Calculate current and resistance :

$$R = \frac{V^2}{P} = \frac{(230)^2}{2 \times 10^3} = 26.45\ \Omega \quad \text{...Ans.}$$

$$\therefore \text{ Current } I = \frac{V}{R} = \frac{230}{26.45} = 8.695 \text{ Amp.} \quad \text{...Ans.}$$

Step 2 : Calculate energy consumed E :

$$E = Pt = V \times I \times t$$

$$= 230 \times 8.695 \times 12 \times 3600$$

$$\therefore E = 86400000$$

$$= 86.4 \times 10^6 \text{ J or } 86.4 \text{ MJ} \quad \text{...Ans.}$$

Ex. 1.5.8 : The rating of electric geyser is 250 V, 3 kW. How much current does it take and what is its hot resistance ? Also calculate the energy consumed by it in one hour.

Soln. :

Given : $V = 250\ V,\ P = 3\ kW$

To find : 1. Current 2. Hot resistance

3. Energy consumed in 1 hr.

Step 1 : Calculate resistance and current :

$$\text{Resistance } R = V^2 / P = (250)^2 / 3000$$

$$= 20.83\ \Omega \quad \text{...Ans.}$$

$$\text{and current } I = V/R = 250/20.83$$

$$= 12\ A \quad \text{...Ans.}$$

Step 2 : Calculate energy consumed in one hour :

Energy consumed in one hour = P × time

$$E = 3000\ W \times 1\ hr = 3000\ Wh$$

$$= 3\ kWh = 3 \text{ units} \quad \text{...Ans.}$$

1.6 Magnetism :

- The relationship between the magnetism and electric current was first discovered by a scientist Oersted way back in the yearly years of nineteenth century.
- He discovered that a conductor carrying a current is always surrounded by a magnetic field along the length of the conductor. This is known as electromagnetism.
- Electromagnetism is a branch of electrical engineering that studies the magnetic effects of an electric current. We are now going to discuss about some fundamental concepts of electromagnetism.

1.6.1 Magnet :

Definition :

It is a piece of solid substance which exhibits a property of attracting small pieces of certain materials such as iron, steel etc.

Types of magnets :

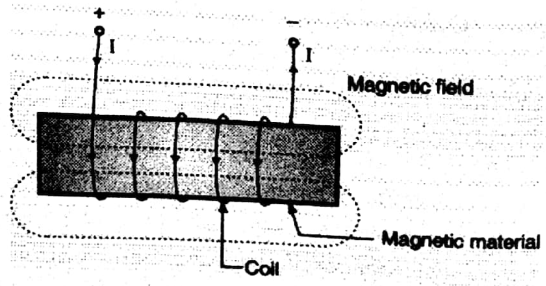
- Magnets are of two types :

  1. Natural magnets. 2. Electromagnets

- The natural magnets have the properties of magnetism naturally present whereas electromagnets are formed by passing an electric current through an insulated wire wound around a certain material.
- That material then acts as a magnet as long as the current is flowing. But it loses its magnetic properties as soon as the current stops flowing.

1.6.2 Electromagnets :

- As shown in Fig. 1.6.1, whenever an electric current passes through a conductor or a coil, a magnetic field gets developed across it, and the coil starts acting as an electromagnet.
- If the coil is wound on a piece of some magnetic material, then that piece will start acting as a magnet.
- It is interesting to know that an electromagnet loses its magnetic properties as soon as current passing through the coil reduces to zero.



(A-432) **Fig. 1.6.1 : An electromagnet**

1.7 Important Definitions Related to Magnetism :

1.7.1 Magnetic Field :

- The magnetic field is defined as the region near a magnet within which the effect or influence of the magnet is felt.
- The influence of a magnet i.e. presence of magnetic field can be tested by using a simple compass neddle or by using an another magnet.

1.7.2 Magnetic Flux ϕ :

- The magnetic flux is defined as the total number of lines of force in a magnetic field. It is denoted by ϕ and measured in **Weber.**

1.7.3 Magnetic Flux Density (B) :

- The flux per unit area (A), measured in a plane perpendicular to the flux is defined as the flux density. It is measured in Tesla (T) and denoted by B.

$\therefore$ Magnetic flux density $B = \frac{\phi}{A}$ Tesla.

1.7.4 Magnetic Field Strength (H) :

- The magnetic field strength at a point in the magnetic field is defined as the force experienced by a unit North pole placed at that point in the magnetic field. It is denoted by H.
- Note that the unit N-pole is the N-pole with a pole strength of 1 Wb.
- Higher the value of the force experienced stronger will be the field. The magnetic field strength is measured in Newtons per weber (N / Wb) or ampere per metre (A/m) or ampere turns per meter (AT/m).

$$H = \frac{\text{Ampere} \cdot \text{Turns}}{\text{Length in metre}} \qquad ...(1.7.1)$$

- Magnetic field strength is also called as magnetic field intensity.
- The relation between B and H is as follows :

$$B = \mu \cdot H$$

where μ is called as permeability.

1.8 Permeability : I-Scheme : W-18

Definition :

- Permeability is an important property of materials. It is defined as the ability of a material to carry the flux lines. If a material allows the flux lines to pass through it easily then the material is said to have a high permeability.
- On the other hand, if a material does not allow the flux lines to pass through it easily, then it is said to have a low permeability.
- All the magnetic materials such as iron, steel etc. have high permeability whereas materials like wood have low permeability. For any material we can define two different types of permeability :

1. Absolute permeability 2. Relative permeability

1.8.1 Absolute Permeability (μ) :

- The magnetic field strength (H) is the cause and the magnetic flux density (B) is the effect.

Definition :

- The ratio of magnetic flux density (B) in a particular medium (other than vacuum or air) to the magnetic field strength (H) which produces that flux density is defined as the **Absolute Permeability (μ)** of that material. It is denoted by μ and measured in Henry per meter.

$\therefore$ Absolute permeability $(\mu) = \frac{B}{H}$ Henry per meter ...(1.8.1)

$$\text{OR } B = \mu H \text{ tesla} \qquad ...(1.8.2)$$

1.8.2 Permeability of Free Space or Vacûum (μ_0) :

Definition :

- If the medium in which the magnet is kept is air or vacuum, then the ratio of flux density B and magnetic field strength (H) is defined as the permeability of free space or vacuum or air.
- It is denoted by μ_0 and measured in Henry/meter.

$$\therefore \mu_0 = \frac{B}{H} \text{ in vacuum or air} \qquad ...(1.8.3)$$

The value of μ_0 is $4 \pi \times 10^{-7}$ H/m and it always remains constant.

1.8.3 Relative Permeability (μ_r) :

Definition :

- The relative permeability is defined as the ratio of flux density in a particular medium produced by a magnet to the flux density in air or vacuum by the same magnet under the identical operating conditions.

$$\therefore \mu_r = \frac{B}{B_0} \quad \text{...(with same H)} \quad \text{...(1.8.4)}$$

Where B = Flux density in a medium.

B_0 = Flux density in air or vacuum

- As μ_r is the ratio of two flux densities, it is a unit less quantity.

Expression for μ :

We know that $B = \mu H$ ...for the given medium

$B_0 = \mu_0 H$ ...for air/vacuum

- Substituting these values into Equation (1.8.4) we get,

$$\mu_r = \frac{\mu H}{\mu_0 H} = \frac{\mu}{\mu_0}$$

$$\therefore \mu = \mu_0 \mu_r \text{ H/m} \quad \text{...(1.8.5)}$$

- This is the required expression for the permeability of a medium in terms of relative permeability and the permeability of the free space or vacuum.

> **Note :** The value of μ_0 is always constant but the value of μ need not always remain constant. It keeps changing.

Important relations between magnetic terms :

- The three quantities namely flux density, permeability and magnetizing force are related to each other by the following expression :

$$B = \mu H$$

But $\mu = \mu_0 \times \mu_r$

$$\therefore B = \mu_0 \mu_r H \quad \text{...(1.8.6)}$$

For air $\mu = \mu_0$ ...since $\mu_r = 1$ ...(1.8.7)

- For certain materials such as nickel iron alloy the permeability can be very high say 100,000.

1.9 Definitions Concerning Magnetic Circuits :

1.9.1 Magnetomotive Force (MMF) :

I-Scheme : W-18

- We know that in electric circuits, the electrons flow due to Electromotive Force (EMF). On the same lines we can define the Magnetomotive Force (MMF) for a magnetic circuit.

Definition :

- It is defined as the force responsible for the flow of flux or generation of flux. The magnetic field strength (H) is decided by m.m.f. MMF is denoted by F and measured in Ampere Turns (AT).
- Mathematically m.m.f. is given by,

$$\text{m.m.f. } (F) = N \times I \text{ ampere turns} \quad \text{...(1.9.1)}$$

Here N = Number of turns of the magnetizing coil.

I = Current through the coil.

- Alternatively, m.m.f. can be defined as work done on a unit magnetic pole to take it around a closed magnetic circuit once. The work done is expressed in joules.

1.9.2 Reluctance (S) :

Definition :

- Reluctance is defined as the opposition to the flow of flux in a material. It is similar to the resistance to the flow of electric current in an electrical circuit.
- Reluctance is denoted by S. Mathematically it is expressed as,

$$S = \frac{Kl}{a} \quad \text{...(1.9.2)}$$

where K = Constant of proportionality,

l = Length of the magnetic circuit in metre.

a = Area of cross section in m^2.

- The unit for measurement of reluctance is Ampere/Weber or siemence. As will be discussed later on, the reluctance can also be defined as the ratio of magnetomotive force (m.m.f.) and the flux (φ).

$$\therefore S = \frac{\text{m.m.f.}}{\text{Flux}} = \frac{F}{\phi} \quad \text{...(1.9.3)}$$

But $F = N \times I$

$$\therefore \text{Reluctance, } S = \frac{N \times I}{\phi} \text{ AT/Wb} \quad \text{...(1.9.4)}$$

1.9.3 Permeance :

Definition :

- It is defined as the reciprocal of reluctance. As reluctance represents the opposition to the flow of flux, the permeance represents the property of a magnetic material to allow the flux to pass through it.

$$\therefore \text{Permeance} = \frac{1}{\text{Reluctance}} \quad ...(1.9.5)$$

– It is measured in Wb/A.

Ex. 1.9.1 : A wooden ring has a mean diameter of 20 cm and uniform cross section 3 cm^2. It is uniformly wound with a coil of 600 turns, find :

1. Magnetic field strength produced within the coil by a current of 2.5 A.
2. Flux density produced by this current.

Soln. :

Given : d = 20 cm, a = 3 cm^2, N = 600, I = 2.5 A, wooden ring.

To find : H and B.

Step 1 : Find the length *l* :

$$l = 2\pi r = 2\pi \frac{d}{2} = \pi d$$

$$= \pi \times 20 \times 10^{-2} = 0.628 \text{ m}$$

Step 2 : Find mmf and H :

$$\text{mmf} = N \times I = 600 \times 2.5 = 1500 \text{ AT}$$

$$H = \frac{\text{mmf}}{\text{length}} = \frac{1500}{0.628} = 2388.53 \text{ AT/m} \quad \text{...Ans.}$$

Step 3 : Find B :

$$B = \mu_0 \mu_r H$$

But μ_r = 1 for a nonmagnetic material such as wood.

$$\therefore B = \mu_0 H = 4\pi \times 10^{-7} \times 2388.53$$

$$= 3 \times 10^{-3} \text{ Tesla} \quad \text{...Ans.}$$

Ex. 1.9.2 : An iron ring of mean length 50 cm has 500 turns of winding. The relative permeability of iron is 600. When a current of 3 A flows in the winding. Determine flux density.

Soln. :

Given : $l = 50 \text{ cm} = 0.5 \text{ m}$, N = 500, $\mu_r = 600$, I = 3 A.

To find : B.

Step 1 : Find mmf :

$$\text{mmf } F = N \times I = 500 \times 3 = 1500 \text{ AT.}$$

Step 2 : Find reluctance :

$$S = \frac{1}{\mu_0 \mu_r a} = \frac{0.5}{4\pi \times 10^{-7} \times 600\, a} = \frac{663.15}{a}$$

where a = Cross sectional area.

Step 3 : Find ϕ and B :

$$\phi = \frac{F}{S} = \frac{1500}{663.15 / a}$$

$$\therefore B = \frac{\phi}{a} = \frac{1500}{663.15}$$

$$= 2.26 \text{ Wb/m}^2 \text{ or } 2.26 \text{ Tesla} \quad \text{...Ans.}$$

Ex. 1.9.3 : An iron ring of mean circumference 0.8 meter is uniformly wound with 550 turns of wire. Calculate the value of flux density that a current of 1.1 Amp would produce in the ring. Assume $\mu_r = 1400$.

Soln. :

Given : Mean length = 0.8 m,

Number of turns, N = 550, Current = 1.1 Amp,

$\mu_r = 1400$,

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

To find : Flux density B = ?

1. **Calculating magnetic field strength (H) :**

$$H = \frac{NI}{l} = \frac{550 \times 1.1}{0.8}$$

$$H = 756.25 \text{ AT/m} \quad \text{...Ans.}$$

2. **Absolute permeability :**

$$\mu = \mu_0 \mu_r = \frac{B}{H} = \frac{B}{756.25} \quad \text{...Ans.}$$

3. **Hence relative permeability is given by,**

$$\therefore \mu_r = \frac{\mu}{\mu_0} = \frac{\left(\frac{B}{756.25}\right)}{4\pi \times 10^{-7}}$$

$$\therefore B = 4\pi \times 10^{-7} \times 1400 \times 756.25$$

$$B = 1.3 \text{ Tesla} \quad \text{...Ans.}$$

Ex. 1.9.4 : An iron ring with mean circumference 80 cm and cross sectional area 10 cm^2 is uniformly wound with 500 turns of wire. Determine the current required to set up a flux density of 1.2T in the ring. Assume $\mu_r = 1000$ for iron.

Soln. :

Given :

Iron ring, $l = 80 \text{ cm} = 0.8 \text{ m}$, $a = 10 \text{ cm}^2 = 10 \times 10^{-4} \text{ m}^2$,

N = 500, B = 1.2 T, $\mu_r = 1000$

To find : I

Step 1 : **Find H :**

$$\mu = \frac{B}{H} \quad \therefore \; H = \frac{B}{\mu} = \frac{B}{\mu_0 \mu_r}$$

$$\therefore \; H = \frac{1.2}{4\pi \times 10^{-7} \times 1000} = 954.93 \text{ AT/m.}$$

Step 2 : **Find mmf F :**

$$F = H \times l = 954.93 \times 0.8 = 763.94 \text{ AT.}$$

Step 3 : **Find I :**

$$F = N \times I \quad \therefore \; 763.94 = 500 \times I$$

$$\therefore \; I = 1.53 \text{ Amp.}$$ **...Ans.**

Ex. 1.9.5 : Determine the mmf required to set up a flux density of 1.2 Wb/m^2 in an iron ring having diameter of 25 cm long. The cross sectional area of ring is 25 cm^2 and relative permeability for iron is 1000.

Soln. :

Given :

$a = 25 \text{ cm}^2 = 25 \times 10^{-4} \text{ m}^2$, diameter $d = 25 \text{ cm} = 0.25$ m,

$B = 1.2 \text{ Wb/m}^2$, $\mu_r = 1000$

To find : MMF required

Step 1 : **To find H :**

$$H = \frac{B}{\mu_0 \mu_r}$$

$$\therefore \; H = \frac{1.2}{4\pi \times 10^{-7} \times 1000} = 954.93 \text{ AT/m}$$

Step 2 : **To find mmf F :**

$$F = H \times l$$

Where $l = 2\pi r = 2\pi \times \frac{d}{2} = \pi \cdot d = \pi \times 0.25 = 0.785$ m

$$\therefore \; F = 954.93 \times 0.785 = 749.62 \text{ AT}$$ **... Ans.**

Ex. 1.9.6 : An iron ring with cross sectional area of 100 mm^2 and mean circumference of 90 cm is uniformly wound with 1500 turns of wire. Determine the current required to set up flux density of 1.2 Wb/m^2 in the ring. Assume relative permeability = 1000 for iron.

Soln. :

Given : Iron ring, $l = 90$ cm $= 0.9$ m, $N = 1500$,

$B = 1.2 \text{ Wb/m}^2$, $\mu_r = 1000$,

$a = 100 \text{ mm}^2 = 100 \times 10^{-6} \text{ m}^2$,

To find : I

Step 1 : **Find H :**

$$\mu = \frac{B}{H}$$

$$\therefore \; H = \frac{B}{\mu} = \frac{B}{\mu_0 \mu_r} = \frac{1.2}{4\pi \times 10^{-7} \times 1000}$$

$$= 954.93 \text{ AT/m}$$

Step 2 : **Find mmf F :**

$$F = H \times l = 954.93 \times 0.9 = 859.437 \text{ AT}$$

Step 3 : **Find current I :**

$$F = N \times I$$

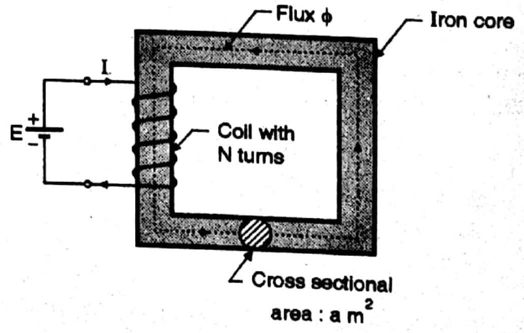
$$\therefore I = \frac{F}{N} = \frac{859.437}{1500} = 0.572$$

$$\therefore \; I = 0.572 \text{ Amp}$$ **...Ans.**

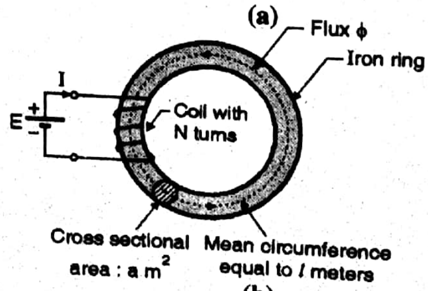
1.10 Magnetic Circuit :

Definition :

- A magnetic circuit is defined as the closed path followed by the magnetic lines of force i.e. flux. This is very similar to the definition of an electric circuit which states, that the electric circuit is the closed path provided for the electrical current.
- Quantities associated with a magnetic circuit are m.m.f., flux and reluctance, permeability etc.
- Two simple magnetic circuits are as shown in Fig. 1.10.1. The circuit of Fig. 1.10.1(a) consists of an iron core of cross sectional area "a" m^2 and the mean length of the core is l metre.
- A coil with N number of turns is wound on the iron core. The current flowing through this coil is I amperes. Due to this current flowing through the coil, a magnetic flux (ϕ) is established in the core. This flux completes its path through the core as shown in Fig. 1.10.1(a).



(a)



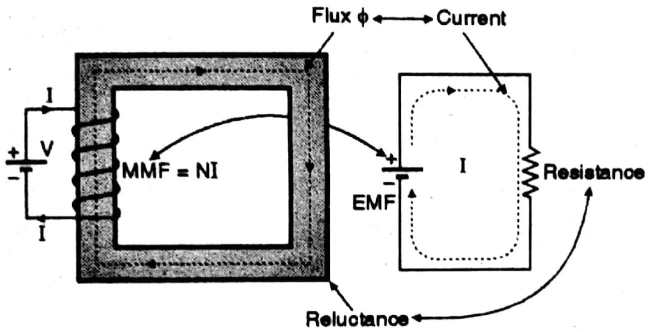
(b)

(A-456) **Fig. 1.10.1 : Simple magnetic circuits**

- The magnetic circuit can also use an iron ring as shown in Fig. 1.10.1(b). All the other basic things are same as that of the magnetic circuit of Fig. 1.10.1(a).

1.10.1 Analogy between Magnetic and Electrical Circuits :

- The magnetic and electrical circuits can be compared closely by referring to their circuit diagrams shown in Fig. 1.10.2.



(a) Magnetic circuit (b) Electric circuit

(A-457) **Fig. 1.10.2 : Comparisons of magnetic and electrical circuit**

Comparisons between electric circuit and magnetic circuit :

Similarities :

Sr. No.	Electric Circuit	Magnetic Circuit
1.	**Current** - Flow of Electrons through conductor is current, it is measured in Amp.	**Flux** - Lines of force through a medium from N pole to S pole form flux. It is measured in Weber.
2.	**EMF** - It is driving force for current, measured in Volts.	**MMF** - It is driving force for flux, measured in amp - turn.
3.	**Resistance** - It is opposition of conductor to current measured in ohms.	**Reluctance** - It is opposition offered by magnetic path to flux measured in AT/Wb.
4.	Resistance is directly proportional to length of conductor.	Reluctance is directly proportional to length of magnetic path.
5.	Resistance is inversely proportional to cross sectional area of conductor.	Reluctance is inversely proportional to cross sectional area of magnetic path.
6.	Resistance depends upon nature of conductor material (l)	Reluctance varies inversely according to permeability of medium $\frac{l}{\mu}$
7.	For electric circuit $I = \frac{EMF}{Resistance}$	For magnetic circuit $\phi = \frac{MMF}{Reluctance}$
8.	Conductance $= \frac{1}{Resistance}$	Permeance $= \frac{1}{Reluctance}$
9.	For electrical circuits we define the conductance.	For magnetic circuits we define permeability.
10.	Current density δ = I/a A/m^2	Flux density B = ϕ/a tesla
11.	Electric circuit is a closed path for current.	Magnetic circuit is a closed path for magnetic flux.
12.	The KVL and KCL are applicable to the electrical circuits.	The Kirchhoff's flux and m.m.f. laws are applicable to the magnetic circuit.

Dissimilarities :

Sr. No.	Electric Circuit	Magnetic Circuit
1.	Current is actual flow of electrons.	Flux is direction of force - Nothing actually flows between N pole and S pole.
2.	Energy is required to produce current and to maintain it.	Energy is required to produce flux but not for its maintenance.
3.	Current does not pass through air.	Flux can pass through air also.

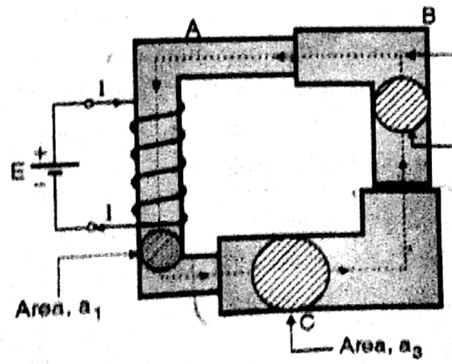
Sr. No.	Electric Circuit	Magnetic Circuit
4.	Resistance is almost constant. It can vary slightly due to change in temperature.	Reluctance depends on permeability. Hence it can vary to a great extent due to the variations in the flux density. But reluctance does not change much with temperature.
5.	We can use insulation to define the path of current.	There is no insulator for magnetic flux. Hence its path cannot be defined.

1.11 Composite Magnetic Circuits :

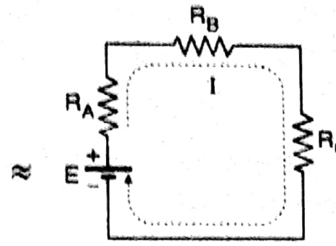
- In the simple magnetic circuits discussed so far, we have considered the core of only one material, with only one cross sectional area.
- But in practice the magnetic circuit can be made up of several different parts with different lengths, different materials and different cross sectional areas. Such magnetic circuits are known as the composite magnetic circuits.
- The composite magnetic circuits can be of two types, namely series magnetic circuits and parallel magnetic circuits.

1.11.1 Series Magnetic Circuit :

- Fig. 1.11.1 shows a series magnetic circuit. This is because it consists of three parts A, B and C which are connected one after the other to form a chain.
- The lengths of these parts are l_1, l_2 and l_3 respectively whereas the cross sectional area are a_1, a_2 and a_3 respectively. The relative permeabilities of the three parts are μ_{r1}, μ_{r2} and μ_{r3} respectively.



(a) A series magnetic circuit



(b) Equivalent electrical circuit

(A-458) Fig. 1.11.1

Expression for the total reluctance (S) :

- Let a coil of N number of turns be wound on any one of parts and let the current through the coil be I amperes. Hence the total m.m.f. is given by,

$$\text{m.m.f.} = F = N \times I \quad \text{AT} \quad ...(1.11.1)$$

- This m.m.f. establishes a flux (ϕ), which is same for all the three parts of the magnetic circuit. As the flux through all the paths is same, we call it as a series magnetic circuit.
- Let S_1, S_2 and S_3 be the reluctances of individual parts A, B and C. These are expressed as,

$$S_1 = \frac{l_1}{\mu_0 \mu_{r1} a_1}, \; S_2 = \frac{l_2}{\mu_0 \mu_{r2} a_2} \text{ and } S_3 = \frac{l_3}{\mu_0 \mu_{r3} a_3}$$

- If the m.m.f of the three parts are F_1, F_2 and F_3 respectively then,

$$\text{Total m.m.f. } F = F_1 + F_2 + F_3 \quad ...(1.11.2)$$

$$= \phi S_1 + \phi S_2 + \phi S_3 \quad ...(1.11.3)$$

$$\therefore F = \phi (S_1 + S_2 + S_3) \quad ...(1.11.4)$$

$$\therefore F = \phi S \quad ...(1.11.5)$$

- Where S represents the equivalent reluctance of the series magnetic circuit which is given by,

$$S = S_1 + S_2 + S_3$$

$$= \frac{l_1}{\mu_0 \mu_{r1} a_1} + \frac{l_2}{\mu_0 \mu_{r2} a_2} + \frac{l_3}{\mu_0 \mu_{r3} a_3} \quad ...(1.11.6)$$

- Thus the total reluctance of a series circuit is equal to the sum of the reluctances of the individual parts of the series magnetic circuit.

Expression for the total Ampere turns (MMF) of the series magnetic circuit :

- We can prove that the expression for the total mmf

$$\therefore \; F = H_1 l_1 + H_2 l_2 + H_3 l_3 \quad ...(1.11.7)$$

where H_1, H_2 and H_3 are the magnetic field strength of the three parts A, B and C.

Important points about a series circuit :

- The flux (ϕ) through all the parts of the series circuit is same.
- The total mmf (F) is equal to the sum of mmfs of different parts.

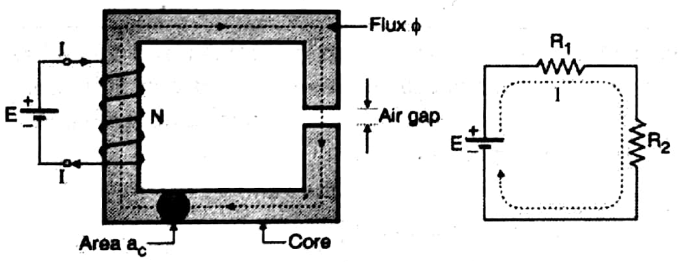
$$F = N \times I = F_1 + F_2 + F_3$$

- The total reluctance (S) is equal to the sum of reluctances of individual parts.

$$\therefore \; S = S_1 + S_2 + S_3$$

1.11.2 A Series Magnetic Circuit with Air Gap :

- Fig. 1.11.2 shows a magnetic core with a small air gap. We can use the principle of series magnetic circuit here.



(a) Series magnetic circuit with air gap **(b) Electrical equivalent**

(A-459) **Fig. 1.11.2**

- Note that even with the presence of small air gap, the magnetic circuit gets complete because flux can pass through air. This would not have been possible for an electrical circuit.
- Let the mean length of the iron core be l_c and that of the air gap be l_g. Let S_c be the reluctance of the core and let S_g be the reluctance of the air gap.
- Then the total reluctance

$$S = S_c + S_g \quad ...(1.11.8)$$

$$\text{But } S_c = \frac{l_c}{\mu_0 \mu_{rc} a_c} \text{ and } S_g = \frac{l_g}{\mu_0 a_c}$$

- The expression for S_g has been written by assuming that the cross sectional area of the air gap is equal to that of the core and the absolute permeability of air i.e. $\mu = \mu_0$.
- Hence the total reluctance is given by,

$$S = \frac{l_c}{\mu_0 \mu_{rc} a_c} + \frac{l_g}{\mu_0 a_c} \quad ...(1.11.9)$$

- Total MMF = F = mmf of the core + mmf of the air gap,

$$\therefore \; F = F_c + F_g = \phi S_c + \phi S_g$$
$$= \phi (S_c + S_g) \quad ...(1.11.10)$$

1.11.3 Solved Examples :

Ex. 1.11.1 : An iron ring of mean circumference of 80 cm is uniformly wound with 500 turns wire.
Calculate the value of flux density that a current of 1 A would produce in the ring. Assume relative permeability 1400.

Soln. :

Given : $l = 80$ cm = 0.8 m, N = 500, I = 1 A, $\mu_r = 1400$

To find : Flux density B

Step 1 : Calculate magnetic field strength H :

$$H = \frac{NI}{l} = \frac{500 \times 1}{0.8} = 625 \text{ AT/m}$$

Step 2 : Calculate absolute permeability μ :

$$\mu = \mu_0 \mu_r = 4\pi \times 10^{-7} \times 1400$$
$$\mu = 1.759 \times 10^{-3}$$

Step 3 : Calculate the flux density B :

$$\mu = \frac{B}{H}$$
$$\therefore \; B = \mu \times H = 1.759 \times 10^{-3} \times 625$$
$$\therefore \; B = 1.0995 \approx 1.1 \text{ Tesla}$$ **...Ans.**

Ex. 1.11.2 : A coil of 500 turns and resistance of 20 ohm is wound uniformly on an iron ring of mean circumference 50 cm and cross sectional area 4 cm^2. It is connected to 24 V d.c. supply. Relative permeability of the material = 800. Find :

1. MMF
2. Magnetising force
3. Total flux
4. Reluctance

Soln. :

Given : N = 500, R = 20 Ω, $l = 50$ cm = 0.5 m
$a = 4 \text{ cm}^2 = 4 \times 10^{-4} \text{ m}^2, V = 24 \text{ V}, \mu_r = 800$

To find : 1. MMF 2. Magnetizing force H

3. Flux ϕ 4. Reluctance S

Step 1 : Find current and MMF :

$$I = \frac{V}{R} = \frac{24}{20} = 1.2 \text{ Amp.}$$

$$\text{MMF} = N \times I = 500 \times 1.2$$

$$= 600 \text{ AT} \quad \text{...Ans.}$$

Step 2 : Find H :

$$H = \frac{N \times I}{l} = \frac{600}{0.5} = 1200 \text{ AT/m...Ans.}$$

Step 3 : Find reluctance S :

$$S = \frac{l}{\mu_0 \mu_r a} = \frac{0.5}{4\pi \times 10^{-7} \times 800 \times 4 \times 10^{-4}}$$

$$\therefore S = 1.2433 \times 10^6 \text{ AT/Wb} \quad \text{...Ans.}$$

Step 4 : Find total flux ϕ :

$$\phi = \frac{\text{MMF}}{S} = \frac{600}{1.2433 \times 10^6}$$

$$\therefore \phi = 4.825 \times 10^{-4} \text{ Wb} \quad \text{...Ans.}$$

Ex. 1.11.3 : A mild steel material having a cross-sectional area of 10 cm^2 and a mean circumference of 40 cm has a coil of 180 turns wound around it. Find Ampere-turns and current required to produce a flux of 800 μWb in the ring. [Assume $\mu_r = 380$]

Soln. :

Given : $a = 10 \text{ cm}^2 = 10 \times 10^{-4} \text{ m}^2$, $l = 40 \text{ cm} = 0.4 \text{ m}$,

$N = 180$, $\phi = 800 \ \mu\text{Wb}$, $\mu_r = 380$.

Step 1 : Calculate reluctance S :

$$S = \frac{l}{\mu_0 \mu_r a} = \frac{0.4}{4\pi \times 10^{-7} \times 380 \times 10 \times 10^{-4}}$$

$$= 837657.6 \text{ AT/Wb}$$

Step 2 : Calculate ampere turns :

$$\text{mmf (Amp Turns)} = S \times \phi$$

$$= 837657.6 \times 800 \times 10^{-6}$$

$$= 670.13 \text{ AT} \quad \text{...Ans.}$$

Ex. 1.11.4 : An iron ring has a cross sectional area of 400 mm^2 and a mean diameter of 25 cm. It is wound with 500 turns. If the relative permeability is 250, find the total flux set up in the ring. The coil resistance is 474 Ω and supply voltage across the coil is 20 V.

Soln. :

Given : Iron ring $a = 400 \text{ mm}^2$, $d = 25 \text{ cm}$, $\mu_r = 250$,

$N = 500$,

$R = 474 \ \Omega$ and $V = 20$ Volts.

To find : Total flux set up in the ring.

Step 1 : Find current I and MMF :

$$I = \frac{V}{R} = \frac{20}{474}$$

$$= 0.042 \text{ Amps. or } 42 \text{ mA}$$

$$\text{MMF} = N \times I = 0.042 \times 500 = 21 \text{ AT}$$

Step 2 : Find reluctance S :

$$S = \frac{l}{\mu_0 \mu_r \times a}$$

$$\text{But } l = \pi d = 25\pi = 78.58 \text{ cm}$$

$$\therefore l = 0.7854 \text{ m}$$

$$\text{Area a} = 400 \text{ mm}^2 = 400 \times 10^{-6} \text{ meters}$$

$$\therefore S = \frac{0.7854}{4\pi \times 10^{-7} \times 250 \times 400 \times 10^{-6}}$$

$$= \frac{0.7854}{1.2566 \times 10^{-7}} = 6250014.6$$

$$= 6.25 \times 10^6 \text{ Siemence}$$

$$\therefore \text{Flux} = \frac{\text{MMF}}{S} = \frac{21}{6.25 \times 10^6} = 3.36 \ \mu\text{Wb} \quad \text{...Ans.}$$

Ex. 1.11.5 : An iron ring 15 cm in diameter and 10 cm^2 in cross sectional area is wound with 200 turns. For a flux density of 1 Wb/m^2 and permeability of 500 find :

1. Reluctance of the iron ring
2. Flux in the ring
3. M.M.F. required for iron ring.
4. Exciting current.

Soln. :

Given : $d = 15 \text{ cm} = 0.15 \text{ m}$, $a = 10 \text{ cm}^2 = 10 \times 10^{-4} \text{ m}^2$,

$N = 200$, $B = 1 \text{ Wb/m}^2$, $\mu_r = 500$

To find : 1. S 2. ϕ 3. mmf 4. I

1. Reluctance (S) :

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

$$\text{But } l = \pi \times d = 0.15 \pi \text{ m}$$

$$\therefore S = \frac{0.15\pi}{4\pi \times 10^{-7} \times 500 \times 10 \times 10^{-4}}$$

$$= 7.5 \times 10^{+5} \text{ Siemence} \quad \text{...Ans.}$$

2. Flux ϕ :

$$B = \frac{\phi}{a}$$

$$\therefore \phi = B \times a = 1 \times 10 \times 10^{-4} = 1 \text{ mWb} \quad \text{...Ans.}$$

3. MMF F :

$$F = \phi \times S = 1 \times 10^{-3} \times 7.5 \times 10^{+5}$$

$$= 750 \text{ AT} \qquad \text{...Ans.}$$

4. Current I :

$$F = N \times I \quad \therefore \quad 750 = 200 \times I$$

$$\therefore I = 3.75 \text{ Amp} \qquad \text{...Ans.}$$

Ex. 1.11.6 : A solenoid 50 cm long and 10 cm in diameter is wound with 1500 turns find :

1. Inductance
2. Energy stored in the magnetic field, when a current of 4 A flows.

Soln. :

Given : Solenoid, d = 10 cm = 0.1 m., N = 1500, l = 50 cm = 0.5 m

To find : 1. L 2. Energy E if I = 4 A.

1. Inductance L :

Cross sectional area of the solenoid $a = \pi r^2 = \dfrac{\pi d^2}{4}$

$$a = \frac{\pi \times (0.1)^2}{4} = 7.85 \times 10^{-3} \text{ m}^2$$

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

$$= \frac{0.5}{4\pi \times 10^{-7} \times 1 \times 7.85 \times 10^{-3}}$$

$$\therefore S = 50686287.61 \text{ Siemence.}$$

$$\therefore \text{Inductance } L = \frac{N^2}{S} = \frac{(1500)^2}{50686287.61}$$

$$= 0.044 \text{ H} \qquad \text{...Ans.}$$

2. Energy :

$$E = \frac{1}{2} L I^2 = \frac{1}{2} \times 0.044 \times (4)^2$$

$$= 0.352 \text{ W} \qquad \text{...Ans.}$$

Ex. 1.11.7 : An iron ring of cross sectional area 6 cm^2 is wound with a wire of 100 turns and a sow cut of 2 mm, calculate the magnetizing current required to produce a flux 0.1 mWb. Its mean length of magnetic path is 30 cm and relative permeability of iron is 470.

Soln. :

Given : $a = 6 \text{ cm}^2 = 6 \times 10^{-4} \text{ m}^2$,

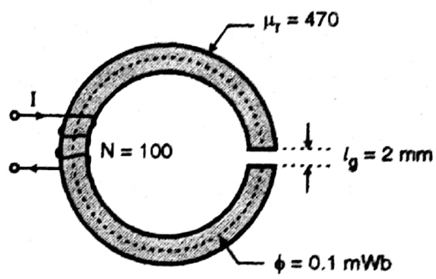
$\phi = 0.1 \text{ mWb} = 1 \times 10^{-4}$ Wb, N = 100 turns,

$l_g = 2 \text{ mm} = 2 \times 10^{-3}$ m,

$l_r = 30 \text{ cm} = 0.3$ m, $\mu_r = 470$

To find : Current I

Step 1 : Draw the magnetic circuit :



(A-2905(a)) **Fig. P. 1.11.7 : Magnetic circuit**

Step 2 : Ampere turns for iron (F_i) :

Reluctance of iron

$$S_i = \frac{l_r}{\mu_0 \mu_r a} = \frac{0.3}{4\pi \times 10^{-7} \times 470 \times 6 \times 10^{-4}}$$

$$= 846.568 \times 10^3 \text{ S}$$

$\therefore$ Ampere turns for iron,

$$F_i = \phi \times S_i$$

$$\therefore F_i = 1 \times 10^{-4} \times 846.568 \times 10^3 = 84.66 \text{ AT}$$

Step 3 : Ampere turns for air (F_a) :

Reluctance of air gap

$$S_a = \frac{l_g}{\mu_0 \mu_r a} = \frac{2 \times 10^{-3}}{4\pi \times 10^{-7} \times 1 \times 6 \times 10^{-4}}$$

$$= 2.6526 \times 10^6 \text{ S}$$

$\therefore$ Ampere turns for air gap,

$$F_a = \phi \times S_a$$

$$\therefore F_a = 1 \times 10^{-4} \times 2.6525 \times 10^6 = 265.26 \text{ AT}$$

Step 4 : Magnetizing current (I) :

Total ampere turns

$$F = F_i + F_a = 84.66 + 265.26 = 349.92 \text{ AT}$$

$$\text{But } F = N \times I$$

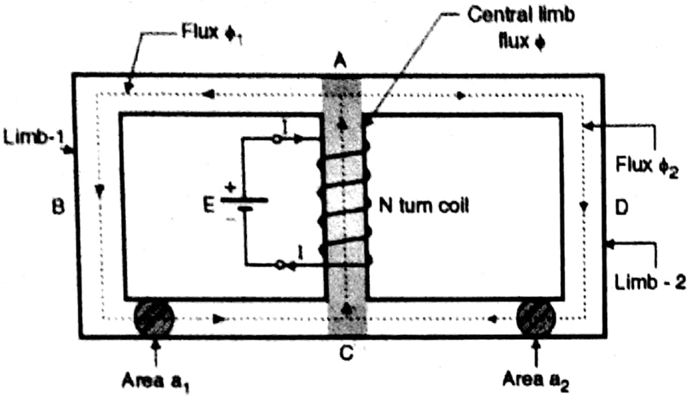
$$\therefore 349.92 = 100 \times I$$

$$\therefore I = \frac{349.92}{100} = 3.4992 \text{ A.} \qquad \text{...Ans.}$$

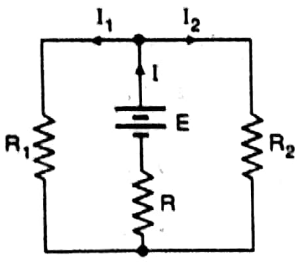
1.12 Parallel Magnetic Circuit :

– A magnetic circuit that consists of more than one path for the flux is called as **parallel magnetic circuit.**

- In a parallel magnetic circuit reluctances appear to be in parallel. This is similar to a parallel electrical circuit in which resistors are connected in parallel which provide more than one path for the flow of current.
- Fig. 1.12.1(a) shows a series parallel magnetic circuit and Fig. 1.12.1(b) indicates the equivalent electrical circuit.



(a) Series parallel magnetic circuit



(b) Electrical equivalent

(A-465) **Fig. 1.12.1**

- An N turn coil is placed on the central limb of the core and current I is forced to flow through it.
- Due to this current, flux ϕ is developed in the central limb of the core. At point A this flux will get divided into two paths namely ABCA and ADCA as shown in Fig. 1.12.1(a).
- The total flux ϕ is given by,

$$\phi = \phi_1 + \phi_2 \qquad ...(1.12.1)$$

- This situation is very similar to the current division taking place in a parallel electric circuit as shown in Fig. 1.12.1(b).
- Thus the magnetic circuit shown in Fig. 1.12.1(a) is analogous to a parallel electrical circuit.

1.12.1 Expression for the Total MMF (Ampere-Turns) :

- Let us assume that there are three arms or three limbs of the core as follows :

Limb - 1 : A-B-C

Limb - 2 : A-D-C

Central Limb : A-C

- Let the mean lengths of Limb-1, Limb-2 and the central limb be denoted by l_1, l_2 and l_c respectively. And let their reluctances be represented by S_1, S_2 and S_c respectively. And let the flux through limb-1, limb-2 and central limb be ϕ_1, ϕ_2 and ϕ_c respectively.
- Then the total mmf is given by,

1. MMF for path ABCA :

$$F = \text{MMF of path ABC} + \text{MMF of path AC.}$$

$$\therefore F = \phi_1 S_1 + \phi_c S_c \qquad ...(1.12.2)$$

- This is because Limb-1 and central limb are in series, with each other.

2. MMF of path ADCA :

$$F = \text{MMF of path ADC} + \text{MMF of path AC.}$$

$$\therefore F = \phi_2 S_2 + \phi_c S_c \qquad ...(1.12.3)$$

- This is because Limb-2 and the central limb are in series with each other.
- Equations (1.12.2) and (1.12.3) shows that the total mmf (F) is equal to the sum of the mmf of the central limb and the mmf of either limb 1 or limb 2.
- The total mmf can also be expressed as follows :
  - For loop ABCA,

$$\text{MMF(F)} = H_1 l_1 + H_c l_c \qquad ...(1.12.4)$$

  - and For loop ADCA,

$$\text{MMF(F)} = H_2 l_1 + H_c l_c \qquad ...(1.12.5)$$

1.12.2 Expression for the Reluctance of a Parallel Magnetic Circuit :

- When a magnetic circuit consists of two or more parallel paths then each path will require the same mmf.
- If S_1, S_2, S_3 ... etc. are the reluctances of these parallel paths then the equivalent reluctance S for the parallel combination is given by,

$$\frac{1}{S} = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots \qquad ...(1.12.6)$$

- This is again same as that of a parallel resistive electrical circuit where the equivalent resistance is given by,

$$\frac{1}{R} = \frac{1}{R_1}+\frac{1}{R_2}+\frac{1}{R_3}+\ldots \quad \text{...(1.12.7)}$$

1.12.3 Parallel Magnetic Circuit with Air Gap :

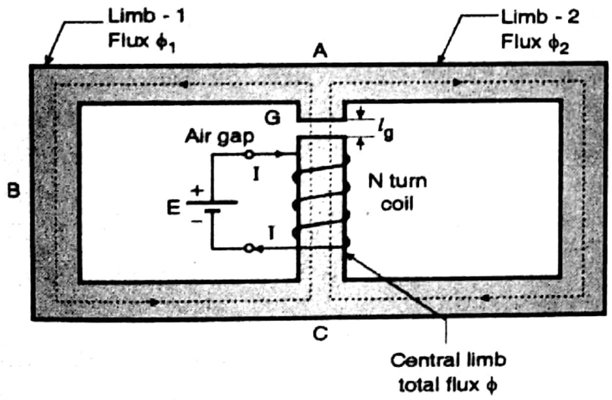
- As in case of the series magnetic circuit, the air gap can be present in the parallel magnetic circuit as well. This air gap can be present in any of three limbs. But in Fig. 1.12.2 we have shown it in the central limb.
- The behaviour of this magnetic circuit is exactly the same as that of the parallel magnetic circuit discussed in section 1.12. Hence its analysis also can be carried out on the same lines. The only difference will be in the analysis of the central limb of the core.
- The central limb now becomes a series combination of the air gap and the iron core. Refer Fig. 1.12.2(a) to write,

Length of path AC = Length of path AG + length of path GC

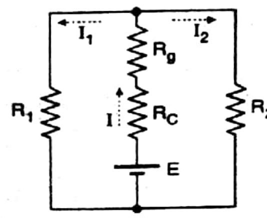
$$\therefore \ AC = l_i + l_g \quad \text{...(1.12.8)}$$

where l_i = Length of iron core in the central limb and

l_g = Length of the air gap.



(a) Parallel magnetic circuit with air gap



(b) Electrical equivalent

(A-467) **Fig. 1.12.2**

- The mmf required by the central limb is given by,

$$(\text{m.m.f})_{\text{central limb}} = (\text{mmf})_{\text{iron path}} + (\text{mmf})_{\text{air gap}} \quad \text{...(1.12.9)}$$

- In section 1.12.1 we have derived that,

Total mmf = (mmf of the central limb) + (mmf of limb-1 or 2)

- Now substituting for the mmf of the central limb we get

$$\text{Total mmf} = (\text{mmf})_{\text{iron path of central limb}} + (\text{mmf})_{\text{air gap}} + (\text{mmf of limb 1 or 2}).$$

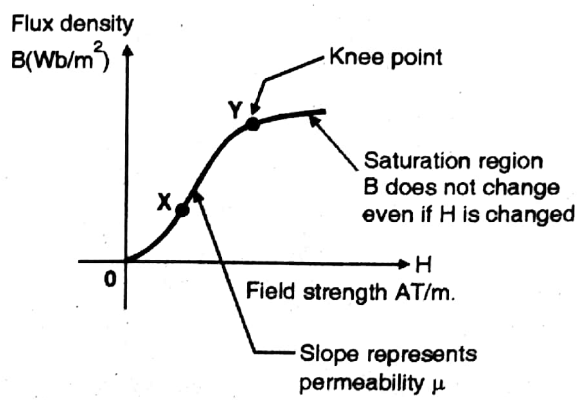
> **Note :** The air gap can be present in any of the three limbs. It is possible that more than one air gaps can be present. But under such circumstances the procedure of circuit analysis will be the same.

1.13 B-H Curve or Magnetization Curve :

I-Scheme : W-18

- The B-H curve or magnetization curve is the graphical relationship between B and H, with H plotted on the X-axis and B on the Y-axis.
- Fig. 1.13.1 shows the typical magnetization curve.

Current I			
Field strength H			
Flux density B			



(A-471) **Fig. 1.13.1 : Magnetization curve**

Description of the B-H curve :

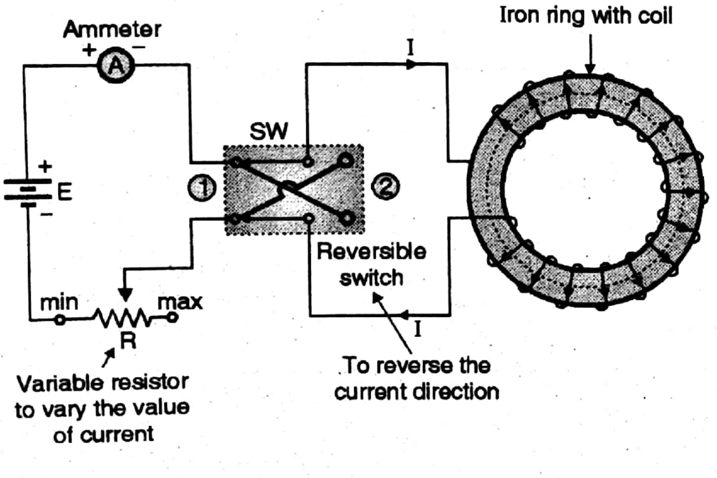
- The B-H curve of Fig. 1.13.1 can be described by dividing it into 3-regions.
- **Region OX :** For zero current H = 0 and B is also zero. The flux density B then increases gradually as the value

of H is increased. However B changes slowly in this region.

- **Region X-Y :** In this region, for small change in H, there is a large change in B. The B-H curve is almost linear in this region. This linearity comes to an end at point Y and the B-H curve starts bending. Point Y is called as the knee point.
- **Region beyond Y (Saturation Region) :** After point Y, the change in B is small even for a large change in H. Finally the B-H curve will tend to be parallel to X axis. This region is called as **saturation region** which indicates the magnetic flux saturation in the core. That means even if we change current I, there will be change in H but no change in B.

1.13.1 Magnetic Hysteresis and Hysteresis Loop :

- We have plotted the B-H curve only by increasing the magnetizing current. But now we will plot the B-H curve for one complete cycle of magnetization (increasing current) and demagnetization (decreasing current).
- The B-H curve will then be called as **a hysteresis curve or hysteresis loop.** The setup to plot the hysteresis loop is as shown in Fig. 1.13.2.

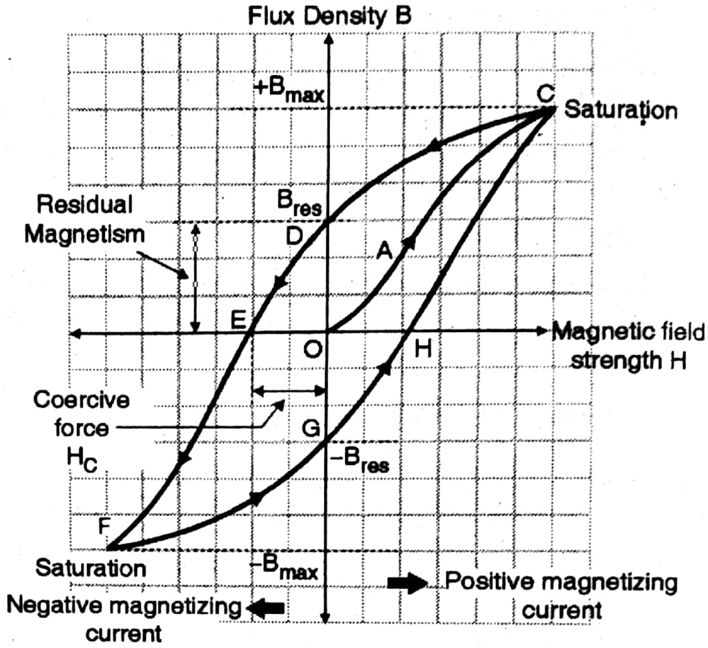


(A-472) **Fig. 1.13.2 : Setup to plot the hysteresis curve**

- We can plot the hysteresis loop for a given material by following the steps given below.

Steps :

1. Increase the current in the positive direction in suitable steps. For each value of I, calculate B and H and plot the points.
2. Now decrease the positive current in suitable steps upto zero and for each value of I, calculate B and H and plot the points.
3. Now increase the current in the negative direction in suitable steps and plot the points.
4. Finally decrease the negative current to zero and plot the points. The complete hysteresis curve or loop is as shown in Fig. 1.13.3.



(A-473) **Fig. 1.13.3**

1. Residual magnetism (B_{res}) or retentivity :

- Refer the hysteresis loop of Fig. 1.13.3.
- It is interesting to note that the value of magnetic flux density B is not zero for I = 0 and H = 0. This non-zero value of B is called as the residual magnetism $B_{res.}$ as shown in Fig. 1.13.3. The portion of hysteresis loop corresponding to this step is C to D.
- The residual flux density is also called as remanent flux density. This property of a magnetic material is called as the Retentivity.

2. Coercive force (H_C) :

- The value of magnetic field strength required to wipe out the residual flux density is called as the coercive force (H_C).
- The process of reducing the magnetic flux density (B) to zero is called as demagnetization of the core.

1.13.2 Hysteresis Loss :

- Due to the presence of magnetic hysteresis a fraction of applied power will be lost in the form of heat.

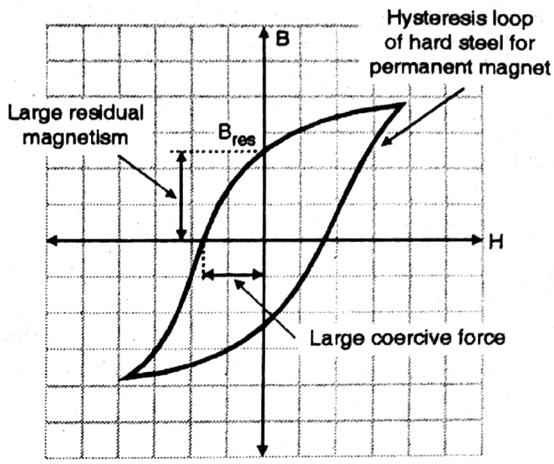
- The portion of power lost corresponds to the difference between the energy stored and the energy returned back by the magnetic core.
- This is called as hysteresis loss.

Factors affecting the hysteresis loss :

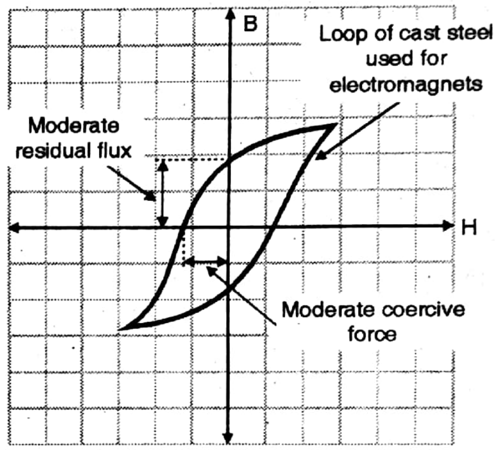
- The factors affecting the hysteresis loss are :
  1. Frequency of magnetization.
  2. Area enclosed by the hysteresis loop.
  3. Volume of the material.
- **Area of the hysteresis loop :** The hysteresis loss is directly proportional to the area under the hysteresis loop. Therefore for the low loss materials the hysteresis loop is narrow. This is the significance of hysteresis loop.

1.13.3 Magnetization Curves for Magnetic and Non-magnetic Materials :

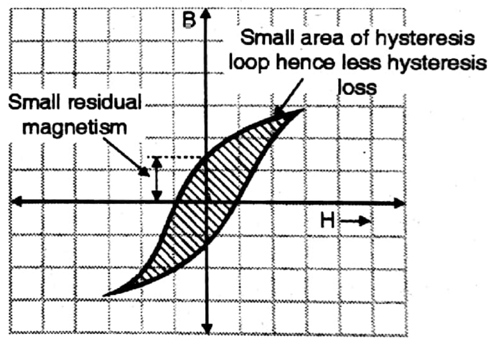
- The magnetic materials used for different applications need to have different characteristics. A proper magnetic material can be selected for a given application by looking at its hysteresis loop.
- The area of shape of the BH curve are very important in selecting a material for a particular application.
- Materials with a large hysteresis loop are used for producing the permanent magnets. Such a hysteresis loop represents a large residual flux and hence a large coercive force.
- Hence materials such as the hard steel with some tungsten, cobalt or chromium is used for such an application. The hysteresis loop of the hard steel is shown in Fig. 1.13.4(a).
- Now refer Fig. 1.13.4(b). It is the hysteresis loop of cast steel material. All the values such as residual magnetism and coercive force are moderate. Hence this material can be used for making the electromagnets.
- Now refer Fig. 1.13.4(c) which shows the hysteresis loop of the sheet steel. The residual magnetism is very small.
- The coercive force required for demagnetization of the core is also very small. The area under the hysteresis loop is very small. Hence such a material is used for the transformers, ac machines etc.
- Fig. 1.13.4(d) shows the hysteresis loop of a non magnetic material such as air. The permeability for such materials is $\mu = \mu_0$ i.e. constant. Hence the hysteresis loop of a non-magnetic material is a straight line passing through origin.



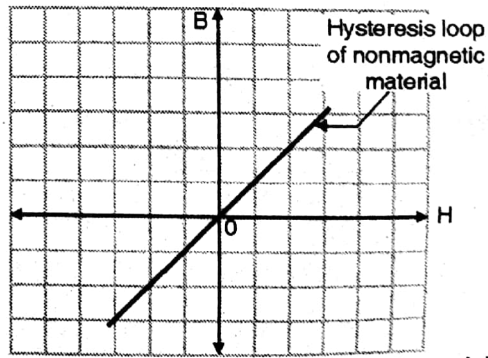
(a) Hard steel



(A-474) **(b) Cast steel**



(c) Hysteresis loop for sheet steel



(d) Hysteresis loop for non-magnetic material

(A-475) **Fig. 1.13.4**

1.13.4 Factors Affecting the Hysteresis Loss :

The factors affecting the hysteresis loss are :

1. Frequency of magnetization.
2. Volume of the material.
3. Area enclosed by the hysteresis loop.

1. Frequency :

The frequency here corresponds to the number of cycles of magnetization per second. The hysteresis loss is directly proportional to the frequency.

2. Volume of the material :

The hysteresis loss is proportional to the volume of the material. In fact the hysteresis loss per unit volume in one cycle is equal to the area under the hysteresis loop.

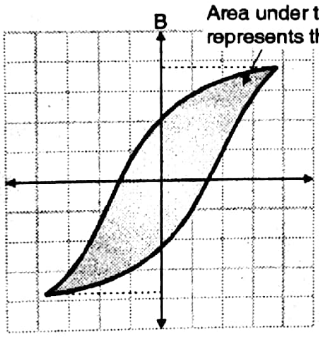
Hysteresis Loss/Volume = Area under hysteresis loop

3. Area of the hysteresis loop :

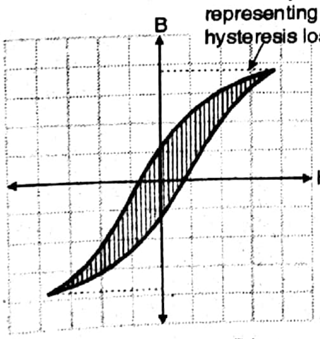
The hysteresis loss is directly proportional to the area under the hysteresis loop. For the low loss materials the hysteresis loop is narrow.

How to minimize the hysteresis loss ?

The hysteresis loss can be minimized by reducing the operating frequency, by reducing the volume of the material and by selecting a material which has a narrow hysteresis loop.



(a) Area under the hysteresis loop represents the hysteresis loss



(b)

(A-2906) **Fig. 1.13.5**

1.14 Electromagnetic Induction :

- There are many ways of generating emf such as using the chemical reaction (batteries), use of active transducers such as photocell or thermocouples. But the most popular and practically accepted method is to use the principle of electromagnetic induction.

Definition :

- **Electromagnetic induction** is the phenomenon of Voltage induction in a conductor which is placed in the magnetic field. The generation of emf due to electromagnetic induction was first obtained by the English scientist **Michael Faraday** in 1831.
- Michael Faraday then formulated two laws of electromagnetic induction.

1.14.1 Faraday's Laws of Electromagnetic Induction :

I-Scheme : W-18

1. Faraday's First Law :

The first law states that whenever the magnetic lines of force (flux lines) linking with a coil or conductor changes, an emf gets induced in the coil or conductor. Such an emf is present as long as this change is taking place.

2. Faraday's Second Law :

- Whenever a conductor cuts or is cut by the magnetic flux, an emf is induced in the conductor the magnitude of which is proportional to the rate at which the conductor cuts or is cut by the magnetic field.
- In short the second law can be stated as the magnitude of the induced emf is directly proportional to the rate of change of flux linkage where,

Flux linkage = Flux × Number of turns of coil.

Expression for the induced emf :

- The expression for induced emf is as follows :

$$e = N\frac{d\phi}{dt} \text{ Volts} \quad ...(1.14.1)$$

- This is the desired expression for the induced emf. Here "$d\phi$" represents the change in flux and "dt" represents the corresponding change in time. Thus $d\phi$ / dt represents the rate of change of flux.

1.14.2 Direction of Induced E.M.F. :

The direction of induced emf and induced current in a conductor does not remain same.

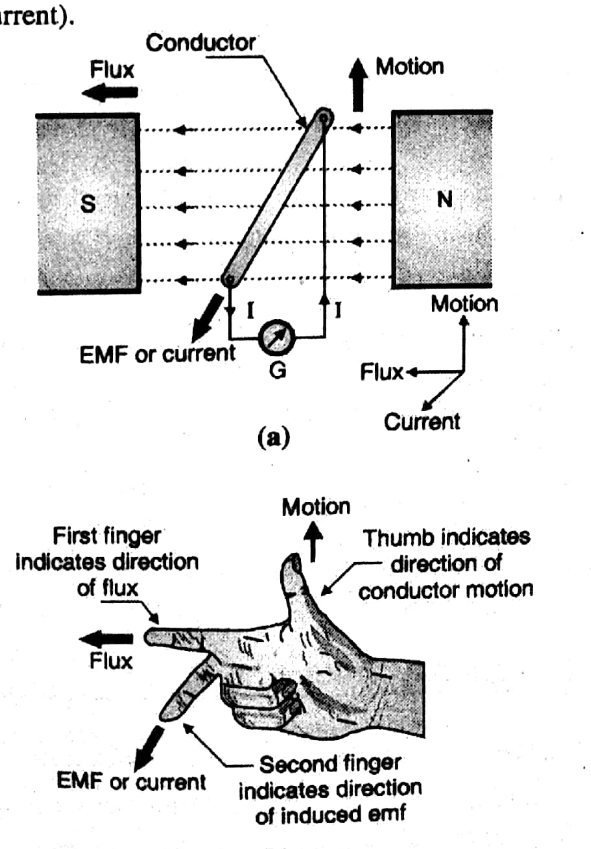
- In fact it has a definite relation with the direction of the flux lines and the direction of movement of the conductor.
- There are two methods available for deciding the direction of the induced emf. They are as follows :
  1. To use the Fleming's right hand rule.
  2. To use the Lenz's law.

1.14.2.1 Fleming's Right Hand Rule :

Fleming's right hand rule can be used to obtain the direction of induced e.m.f. For that refer to Fig. 1.14.1, where the conductor is moving in right angles to the field.

Statement of the rule :

- Let the thumb and first two fingers of the right hand be arranged in right angles with each other as shown in Fig. 1.14.1(b).
- Let the first finger point in the direction of lines of force (N to S pole), and the outstretched thumb point the direction of conductor motion. Then the second finger indicates the direction of the induced e.m.f. (or current).



(A-480) **Fig. 1.14.1 : Illustration of Fleming's right hand rule**

1.14.2.2 Lenz's Law :

This rule was set by the German scientist Heinrich Lenz.

Statement : UT 1

- The direction of induced emf produced due to the process of electromagnetic induction is always such that, it will set up a current to oppose the basic cause responsible for inducing the emf.
- In other words the induced emf will always oppose the cause behind its production. This is represented mathematically by a negative sign in the expression for the induced voltage.
- That means,

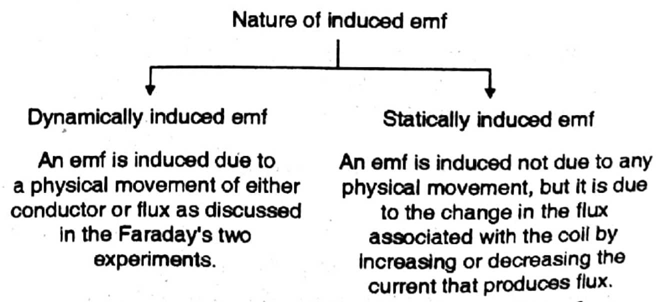
$$e = -N\frac{d\phi}{dt} \qquad ...(1.14.2)$$

Negative sign indicates that induced emf opposes the cause producing it.

(A-482)

1.15 Nature of the Induced E.M.F. :

- If the flux linkage with a conductor changes due to either magnet movement or due to the coil movement, an emf gets induced into the conductor.
- The change in flux linkage can be practically obtained using one of the following two methods :
  1. Dynamically induced e.m.f.
  2. Statically induced e.m.f.
- The principles of dynamically and statically induced emfs are as follows :



(A-485) **Fig. 1.15.1 : Principle of induced emfs**

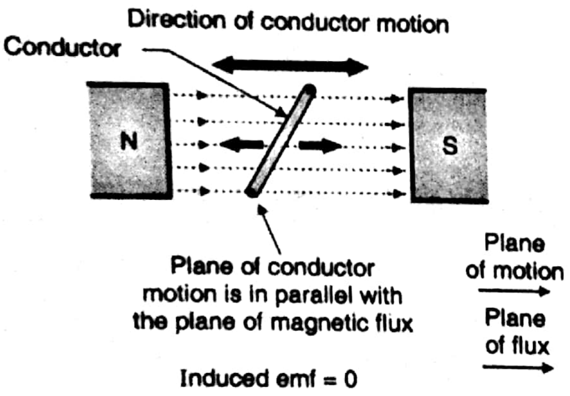
1.16 Dynamically Induced E.M.F. :

As stated in Fig. 1.16.1 the dynamically induced e.m.f.

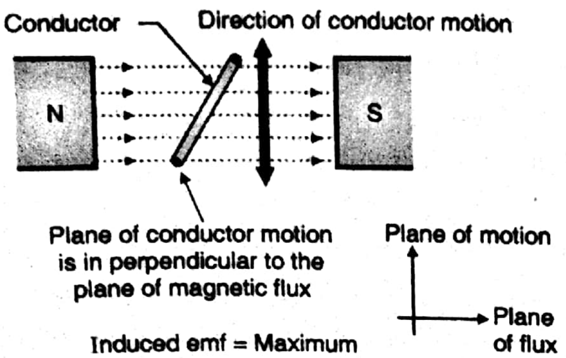
is due to the physical movement of either the coil or the magnet as discussed in the Faraday's two experiments (Section 1.14.1).

1.16.1 Magnitude of Dynamically Induced E.M.F. :

- As discussed earlier the induced emf is dependent on the rate of change of flux linkage taking place with the conductor.
- Now consider a conductor of length " l " placed in the magnetic field produced by a permanent magnet as shown in Fig. 1.16.1(a).
- In Fig. 1.16.1(a) the conductor moves in a plane which is parallel to the plane of the magnetic flux. Therefore it does not cut any magnetic flux. Hence the induced emf is zero.



(a) Direction of conductor movement parallel to the plane of magnetic flux



(b) Direction of conductor movement perpendicular to the plane of magnetic flux

(A-486) **Fig. 1.16.1 : Dynamically induced EMF**

- Now refer to Fig. 1.16.1(b), the plane of direction of motion of the conductor is perpendicular to the plane of magnetic flux. Therefore the cutting of magnetic flux is maximum and the induced emf in the conductor is maximum.

Conclusion :

The induced emf is zero when the plane of conductor motion is parallel to the plane of magnetic flux whereas it is maximum when the plane of conductor motion is perpendicular to the plane of flux.

Expression for the magnitude :

- When the plane of motion of the conductor is exactly perpendicular to the plane of flux, the induced emf is given by,

$$e = B \times l \times v \text{ Volts} \qquad ...(1.16.1)$$

where B = Flux density,

l = Conductor length,

v = Velocity

- But if the plane of motion of the conductor is not exactly perpendicular to the plane of flux, then the expression for the induced emf is given by,

$$e = B \times l \times v \sin\theta \qquad ...(1.16.2)$$

where θ = The angle between plane of flux and direction of conductor movement

1.16.2 Direction of Dynamically Induced EMF :

The direction of the dynamically induced emf can be obtained by using either Fleming's right hand rule or Lenz's law.

1.16.3 Applications :

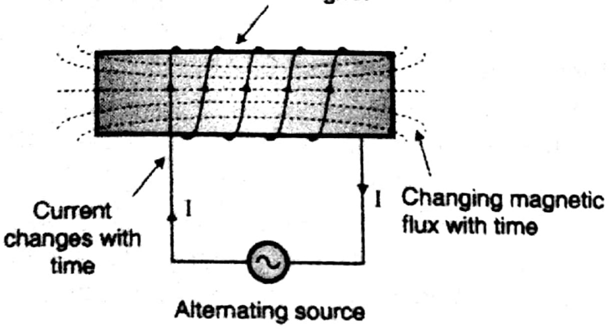
- The applications of dynamically induced emf are as follows :
  1. DC generator
  2. Back emf of dc motor.
  3. Induction motor.

1.17 Statically Induced E.M.F. :

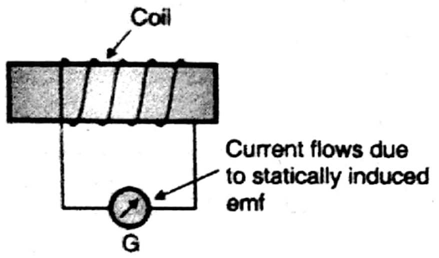
- This is another technique of generating an e.m.f. But in this technique neither the conductor nor the magnetic field are physically moved for e.m.f. generation. Both of them are stationary.

Principle :

- The flux linkage taking place with the conductor is changed by changing the magnitude of the current that produces the magnetic field. This is illustrated in Fig. 1.17.1.



(a)



(b)

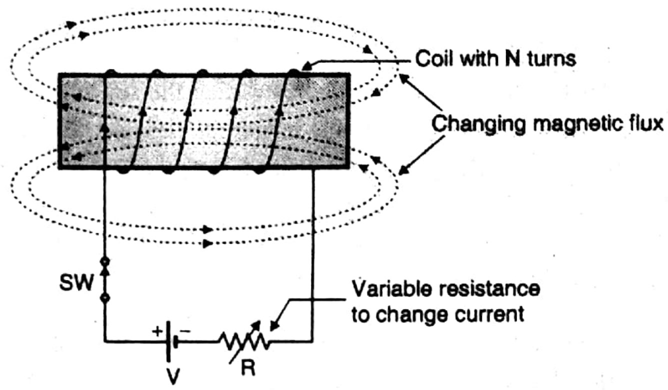
(A-489) **Fig. 1.17.1 : Statically induced e.m.f.**

Implementation :

- To produce e.m.f. statically, it is necessary to use an electromagnet. The source of excitation should be alternating (ac).
- Due to alternating source, there is a change in coil current with respect to time.
- This change in current will result into alternating flux. Hence there will be change in flux with respect to time ($d\phi / dt$). This $d\phi / dt$ gets linked with the coil which is placed near the electromagnet.
- This $d\phi / dt$ will induce an e.m.f. in this coil which will be called as the statically induced e.m.f. The best example of statically induced e.m.f. is the induced in the secondary voltage of a transformer, due to flow of current in the primary winding.
- There are two different types of the statically induced e.m.f. :
  1. Self induced e.m.f.
  2. Mutually induced e.m.f.

1.17.1 Self Induced E.M.F. :

- To understand the concept of self induced emf refer to Fig. 1.17.2. The set up consists of a coil (with N turns) wound on a magnetic material core.
- A battery alongwith a variable resistance R is used to adjust the current I flowing through the coil.
- As we close the switch SW, current I starts flowing through the coil, and due to this current, magnetic flux lines are produced as shown in Fig. 1.17.2.



(A-490) **Fig. 1.17.2 : Setup to understand the concept of self induction**

- The flux lines which form complete loops as shown in Fig. 1.17.2 are said to be linked with the coil. If the flux linked with the coil is ϕ-Wb then the flux linkage with the coil is given by,

  Flux linkage with coil = $N \times \phi$

- If we change the value of R, then current I will change. Hence ϕ will change, therefore the flux linkage $N\phi$ will also change.
- Due to change in flux linkage with the coil, an e.m.f. is induced into the coil as per the Faraday's law. This emf is called as the **self induced emf or emf due to self induction** and this phenomenon is called as the **self induction.**
- The phenomenon of self induction is used in the following a.c. applications :
  1. The action of choke used with the fluorescent tube.
  2. Filter choke used in the rectifier circuits.
- The self induced emf will last only till the current through the coil is changing with time. As soon as the current stops changing, the self induced emf will reduce to zero.

1.17.2 Self Inductance :

- As per the Lenz's law, the self induced emf opposes any current change taking place.
- This property of the coil to oppose any change in current flowing through it is known as the **self inductance** or **inductance.**
- As per the Faraday's law of electromagnetic induction, the magnitude of the self induced emf in a coil (refer Fig. 1.17.2) due to change in current flowing through it is given by,

$$e = -N\frac{d\phi}{dt} \text{ Volts} \quad ...(1.17.1)$$

where the negative sign indicates that the self induced Voltage opposes the change in current through the coil.

- If the current through the coil (I) produces a flux (ϕ) Webers then the self inductance is given by,

$$\therefore \text{ Inductance (L)} = \frac{N \times \phi}{I} \quad ...(1.17.2)$$

- Thus self inductance (L) is defined as the ratio of the flux linkage Wb meter ($N \times \phi$) to the current I. The units of inductance is Wb Turn / Ampere or Henry.
- Substituting $\phi = \frac{L \times I}{N}$ into Equation (1.17.1) we get,

$$e = -L\left[\frac{dI}{dt}\right] \text{ Volts} \quad ...(1.17.3)$$

1.17.3 Expression for the Coefficient of Self Inductance (L) :

- We have defined the co-efficient of self inductance (L) as,

$$L = \frac{N \times \phi}{I} \text{ Henry}$$

But $$\phi = \frac{\text{m.m.f.}}{\text{Reluctance}} = \frac{N \times I}{S}$$

$$\therefore L = \frac{N}{I}\left[\frac{N \times I}{S}\right] = \frac{N^2}{S} \text{ Henry} \quad ...(1.17.4)$$

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

$$\therefore L = \frac{N^2 \times \mu_0 \mu_r a}{l} \text{ Henry} \quad ...(1.17.5)$$

Where l = Length of the magnetic circuit ,

μ_r = Relative permeability ,

a = Cross sectional area of magnetic circuit.

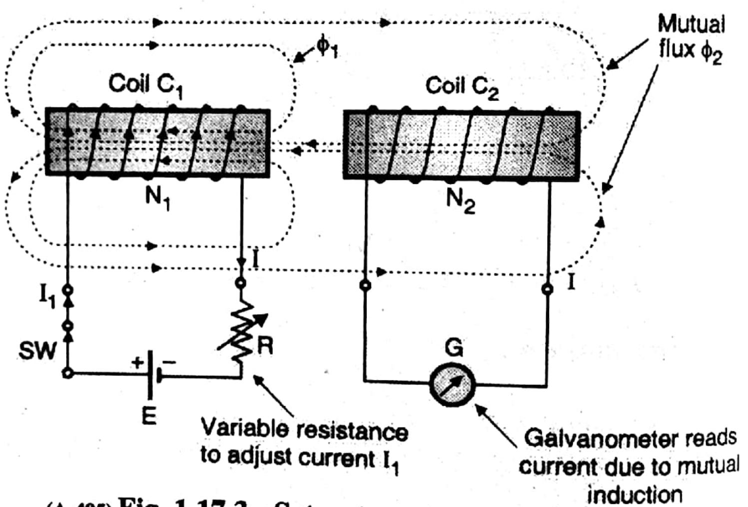
N = Number of turns.

1.17.4 Mutually Induced E.M.F. :

- In the last section we have discussed about the self induced e.m.f. The mutually induced emf is the other type of statically induced emf.
- Only one coil is involved in the self induced e.m.f. But in the mutually induced emf, two or more coils are involved.

Setup for mutually induced E.M.F. :

- The setup to understand the concept of mutually induced e.m.f is as shown in Fig. 1.17.3. Two coils C_1 and C_2 are placed near each other.
- Coil C_1 consists of N_1 turns and coil C_2 consists of N_2 number of turns. A switch, battery and a variable resistance R are connected in the circuit consisting of coil C_1.
- Whereas a galvanometer is connected to coil C_2. This galvanometer is connected to sense the current induced in coil C_2.



(A-495) **Fig. 1.17.3 : Setup to understand the mutual induction**

Description :

- Due to the battery a current I_1 starts flowing through coil C_1. This current can be changed by changing the value of resistance R.
- Due to current I_1 flowing through coil C_1, flux is produced, which is denoted by ϕ_1. A part of this flux completes its path through coil C_2 as shown in Fig. 1.17.3. This flux ϕ_2 is called as the **mutual flux.**
- If we change current I_1 through coil C_1 by changing R, then flux ϕ_1 will change. This will change the mutual flux ϕ_2. According to the Faraday's laws there will be induced e.m.f. in coil C_2.
- Due to this emf, current I_2 will start flowing through coil C_2 which is indicated by the galvanometer "G".

- Thus if the flux produced by one coil gets linked with another coil, and due to the change in this flux produced by the coil C_1 if there is induced emf in the second coil then such an emf is known as **mutually induced emf.**
- The mutually induced emf in coil C_2 will exist as long as the value of current through coil C_1 i.e. I_1 is changing with respect to time.

1.17.5 Mutual Inductance (M) :

- The two magnetically coupled coils C_1 and C_2 in Fig. 1.17.3, are said to have **mutual inductance.**
- It is defined as the property due to which the change in current through one coil produces an emf in the other coil placed nearby, by induction. It is denoted by M and measured in Henry.
- The expression for mutual inductance is,

$$M = \frac{N_2 \phi_2}{I_1} \quad \text{Or} \quad M = \frac{N_1 \times \phi_1}{I_2} \qquad ...(1.17.6)$$

Where N_1 and N_2 are the number of turns of coils C_1 and C_2. I_1 and I_2 are the currents flowing through them. ϕ_1 is the flux produced by I_1 in C_1 and ϕ_2 is the flux produced by I_2 in C_2.

1.17.6 Alternate Way of Defining the Mutual Inductance :

There are many different ways of defining the mutual inductance (M). We can define it as follows :

- The mutual inductance (M) is defined as the emf induced in the second coil when a uniform current change of 1 Amp/sec. takes place in the first coil.
- The mutual inductance (M) can also be defined as the flux linkage of the second coil per ampere current flowing in the first coil.

1.17.7 Expression for Mutual Inductance :

$$M = \frac{N_1 N_2 \mu_0 \mu_{r1} a_1}{l_1} \qquad ...(1.17.7)$$

$$\text{or} \quad M = \frac{N_1 N_2 \mu_0 \mu_{r2} a_2}{l_2} \qquad ...(1.17.8)$$

where N_1, N_2 = Number of turns of coils C_1 and C_2.

a_1, a_2 = Cross sectional areas.

l_1, l_2 = Lengths of the coils.

1.17.8 Coefficient of Coupling (K) :

- The two expressions for the mutual inductance are,

$$M = \frac{N_2 K_1 \phi_1}{I_1} \qquad ...(1.17.9)$$

$$\text{and} \quad M = \frac{N_1 K_2 \phi_2}{I_2} \qquad ...(1.17.10)$$

- Multiply Equations (1.17.9) and (1.17.10) to get,

$$M^2 = \frac{N_1 N_2 K_1 K_2 \phi_1 \phi_2}{I_1 I_2}$$

- Rearrange this expression as follows :

$$M^2 = K_1 K_2 \cdot \left[\frac{N_1 \phi_1}{I_1}\right]\left[\frac{N_2 \phi_2}{I_2}\right] \qquad ...(1.17.11)$$

- But $\left[\frac{N_1 \phi_1}{I_1}\right] = L_1$ i.e. self inductance of coil C_1.

And $\left[\frac{N_2 \phi_2}{I_2}\right] = L_2$ i.e. the self inductance of coil C_2.

- Substituting these values into Equation (1.17.11) we get,

$$M^2 = K_1 \cdot K_2 \cdot L_1 \cdot L_2$$

$$\therefore M = \sqrt{K_1 K_2}\sqrt{L_1 L_2} \qquad ...(1.17.12)$$

$$\therefore M = K\sqrt{L_1 L_2} \qquad ...(1.17.13)$$

$$\text{Where} \quad K = \sqrt{K_1 K_2}$$

and K is called as the coefficient of coupling.

- Mathematical expression for coefficient of coupling is :

$$K = \frac{M}{\sqrt{L_1 L_2}} \qquad ...(1.17.14)$$

- From this expression we can define the coefficient of coupling K as the ratio of actual mutual inductance (M) present between the coils C_1 and C_2 to the maximum value of M. Because

$$M_{max} = \sqrt{L_1 L_2}$$

$$\therefore K = \frac{M}{M_{max}} \qquad ...(1.17.15)$$

- The maximum value of K is 1 which represents the coupling of all the flux produced by one with the other one.
- Corresponding to K = 1 the value of the mutual inductance will be maximum and it is given by,

$$M_{max} = \sqrt{L_1 L_2} \quad \text{...(corresponding to } K = 1) \qquad ...(1.17.16)$$

Tight coupling and loose coupling :

- The coupling between the two coils is said to be a **tight coupling** if K = 1 and the coupling is called as the **loose coupling** if K is less than one.
- The coefficient of coupling is also called as **Magnetic Coupling Coefficient.**

Thus the coefficient of mutual inductance is defined as the property which is responsible for the induced emf in one coil due to change in current flowing through some other coil placed nearby. It is also called as the mutual inductance (M) and it is measured in Henry.

1.17.9 Comparison of Statically and Dynamically Induced E.M.F. :

Table 1.17.1

Sr. No.	Characteristics	Dynamically induced emf	Statically induced emf
1.	Movement of coil or magnet.	Either coil moves or magnet moves.	Neither coil nor magnet moves.
2.	Current through electromagnet.	Can remain constant.	Must vary with respect to time.
3.	Expression for induced Voltage.	$e = B \times l \times v \sin\theta$	$e = -L\, di/dt$. or $N\, d\phi/dt$
4.	Applications	DC generators, Back emf in DC motors, Induction motors.	Transformer.
5.	Example	emf induced in a generator	Emf induced in a transformer winding

Ex. 1.17.1 : A conductor of 1.5 m length moves at right angles to a uniform magnetic field of flux density 1 Tesla with a velocity of 100 m/s. Calculate the emf induced in it. Find also the value of induced emf when the conductor moves at an angle of 30° to the direction of field.

Soln. :

Part I

Given : $l = 1.5$ m, B = 1 T, v = 100 m/s

Conductor moves at right angles to the field.

$\therefore$ Induced emf e $= B \times l \times v = 1 \times 1.5 \times 100$

$\therefore$ e $= 150$ Volts ...Ans.

Part II

Given : $\theta = 30°$

$\therefore$ Induced emf e $= B\, l\, v \sin\theta = 150 \sin 30°$

$= 75$ Volts ...Ans.

Ex. 1.17.2 : A conductor of length one meter moves at right angle to a uniform magnetic field of flux density 1.5 tesla with a velocity of 80 m/s. Calculate the induced e.m.f. in a conductor. What will be the value of induced emf, if conductor moves at an angle of 30° with the direction of the field ?

Soln. :

Given : B = 1.5 T, v = 80 m/s, $l = 1$ meter, $\theta = 30°$

To find : Induced emf

Part I : Conductor moves at right angles to the field

Induced emf $= B \times l \times v$

$= 1.5 \times 1 \times 80$

$\therefore$ e $= 120$ Volts ...Ans.

Part II : Conductor moves at an angle θ = 30°

Induced emf $= B\, l\, v \sin\theta$

e $= 120 \sin 30 = 60$ Volts ...Ans.

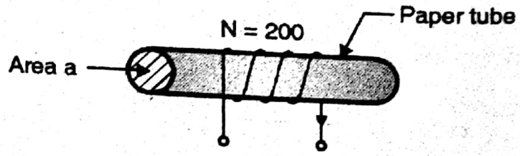
Ex. 1.17.3 : What is the inductance of a coil of 200 turns wound and a paper tube 25 cm long and 5 cm radius ?

Soln. :

Given : N = 200, $l = 25$ cm = 0.25 m, r = 5 cm = 0.05 m

To find : Inductance (L)

Step 1 : Calculate reluctances S :



(A-491) **Fig. P. 1.17.3**

Cross sectional area of the tube is,

$$a = \pi r^2 = \pi \times (0.05)^2$$

$$\therefore \; a = 7.854 \times 10^{-3}\ m^2$$

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

$$= \frac{0.25}{4\pi \times 10^{-7} \times 1 \times 7.854 \times 10^{-3}}$$

$$\therefore \; S = 25.33 \times 10^6 \text{ AT/Wb}$$

Step 2 : Calculate inductance :

$$L = \frac{N^2}{S} = \frac{(200)^2}{25.33 \times 10^6}$$

$$\therefore \; L = 1.579 \times 10^{-3} \text{ H or } 1.579 \text{ mH} \quad \text{...Ans.}$$

Ex. 1.17.4 : An air cored circular coil has 500 turns and a mean diameter of 20 cm and cross-sectional area 5 cm^2. Find :

1. The inductance of the coil.
2. Average value of emf induced in the coil if a current of 4 A is reversed in 0.1 seconds.

Soln. :

Part I : Inductance

Given : $N = 500$, air core $\therefore \mu_r = 1$, $d = 20\text{ cm} = 0.2\text{ m}$

$a = 5\text{ cm}^2 = 5 \times 10^{-4}\ m^2$

$$\text{Inductance of coil} = \frac{N^2}{S}$$

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

$$\therefore \; L = \frac{N^2 \mu_0 \mu_r a}{l}$$

$$= \frac{(500)^2 \times 4\pi \times 10^{-7} \times 1 \times 5 \times 10^{-4}}{\pi \times d}$$

$$\therefore \; L = \frac{1.57 \times 10^{-4}}{\pi \times 0.2}$$

$$= 2.5 \times 10^{-4} \text{ H or } 250\ \mu\text{H} \quad \text{...Ans.}$$

Part II : Induced emf

Given : $dI = 8$ Amp., $dt = 0.1$ sec

$$\therefore \; e = L\, dI / dt = 2.5 \times 10^{-4} \times \frac{8}{0.1}$$

$$\therefore \; e = 0.02 \text{ Volts} \quad \text{...Ans.}$$

Ex. 1.17.5 : A coil of 100 turns is linked by a flux of 20 mWb. If this flux is reversed in a time of 2 msec. Calculate the average e.m.f. induced in the coil.

Soln. :

Given : $N = 100$, $\phi = 20$ mWb, $dt = 2$ mS

To find : emf e

$$e = N \frac{d\phi}{dt}$$

$$d\phi = 20 \times 2 = 40 \text{ mWb} \text{ ...as the flux is reversed}$$

$$dt = 2 \text{ mS} = 2 \times 10^{-3} \text{ sec}$$

$$\therefore \; e = 100 \times \frac{40 \times 10^{-3}}{2 \times 10^{-3}} = 2000 \text{ Volts} \quad \text{...Ans.}$$

Ex. 1.17.6 : A short coil of 200 turns surrounds the middle of the bar magnet. If the magnet sets up a flux of 80 μWb. Calculate the average value of E.M.F. induced in the coil. When the magnet is taken away from the coil in 0.05 seconds.

Soln. :

Given : $N = 200$, $d\phi = 80\ \mu\text{Wb} = 80 \times 10^{-6}$ Wb,

$dt = 0.05$ sec

To find : Induced emf e

$$\text{Average induced emf } e = \frac{N d\phi}{dt} = \frac{200 \times 80 \times 10^{-6}}{0.05}$$

$$= 0.32 \text{ Volts} \quad \text{...Ans.}$$

Ex. 1.17.7 : A coil wound on an iron core of relative permeability 500 has 200 turns and a cross-sectional area of 4 cm^2. Calculate the induction of the coil. Given that a steady current of 5 A produces a magnetic field of 10 mWb, when air is present as the medium.

Soln. :

Given : $\mu_r = 500$, $N = 200$, $a = 4\text{ cm}^2 = 4 \times 10^{-4}\ m^2$,

$I = 5$ A, $\phi = 10$ mWb

To find : Inductance L

$$L = \frac{N \times \phi}{I} = \frac{200 \times 10 \times 10^{-3}}{5}$$

$$\therefore \; L = 0.4 \text{ H} \quad \text{...Ans.}$$

Ex. 1.17.8 : An air cored coil has mean diameter of 5 cm and a length of 50 cm. It has 500 turns of wire. Find the inductance of coil and hence the e.m.f induced when current of 10 Amp is reversed in 10 msec.

Soln. :

Given : $d = 5\text{ cm} = 0.05$ m, $l = 50\text{ cm} = 0.5$ m,

$dt = 10\text{ msec} = 10 \times 10^{-3}$ sec,

$N = 500$, $I = 10$ Amp.

To find :

1. Inductance 2. Induced emf

1. Inductance :

$$H = \frac{NI}{l} = \frac{500 \times 10}{0.5} = 10000$$

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

But $\mu_r = 1$ and $a = \pi r^2 = \pi (d/2)^2 = \left(\dfrac{0.05}{2}\right)^2 \pi$

$$a = 0.00196 \text{ m}^2$$

$$\therefore \quad S = \frac{0.5}{4\pi \times 10^{-7} \times 0.00196 \times 1}$$

$$S = 20.31 \times 10^{-7} \text{ AT/Wb}$$

Inductance $L = \dfrac{N^2}{S} = \dfrac{(500)^2}{20.31 \times 10^7} = 0.0012$

$$L = 0.0012 \text{ H}$$

...Ans.

2. Induced emf :

$$e = L\frac{di}{dt} = \frac{0.0012 \times 20}{10 \times 10^{-3}}$$

$$\therefore e = 2.4 \text{ Volts}$$

...Ans.

Ex. 1.17.9 : A wooden ring of mean diameter 400 mm and cross sectional area 350 mm^2 is uniformly wound with a coil of 900 turns which carries a current of 3.5 A. Determine the self inductance of the coil.

Soln. :

Given :

$d = 400$ mm $= 0.4$ m, $a = 350 \text{ mm}^2 = 350 \times 10^{-6} \text{ m}^2$,

$N = 900$, $I = 3.5$ A

To find : Self inductance L.

Step 1 : Find ϕ :

Length of the magnetic circuit,

$$l = \pi d = \pi \times 0.4 = 1.2566 \text{ m}$$

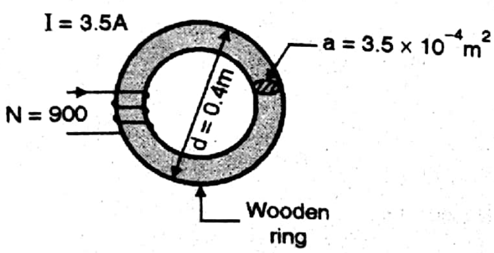
$$\therefore \quad \text{Reluctance } S = \frac{l}{\mu_0 \mu_r a}$$

For a wooden ring, $\mu_r = 1$.

$$\therefore \quad S = \frac{1.2566}{4\pi \times 10^{-7} \times 3.5 \times 10^{-4}}$$

$$\therefore \quad S = 2857.14 \times 10^6 \text{ AT/Wb}$$

Total mmf, $F = N \times I = 900 \times 3.5 = 3150$ AT



(A-2917) **Fig. P. 1.17.9**

$$\therefore \quad \phi = \frac{F}{S} = \frac{3150}{2857.14 \times 10^6} = 1.1025 \ \mu\text{Wb} \quad ...(1)$$

Step 2 : Find L :

$$\text{Self inductance } L = \frac{N \times \phi}{I} = \frac{900 \times 1.1025 \times 10^{-6}}{3.5}$$

$$\therefore \quad L = 0.2835 \text{ mH}$$

...Ans.

Ex. 1.17.10 : A coil of 200 turns of wire is wound on a magnetic circuit of reluctance 2000 AT/Wb. If a current of 1 A flowing in the coil is reversed in 10 mS, find the average emf induced in the coil.

Soln. :

Given : $S = 2000$ AT/Wb, $N = 200$, $I = 1$ A,

Current reversed in 10 mS, $\therefore$ $dt = 10 \times 10^{-3}$ sec.

To find : Average induced emf e.

Step 1 : Find self inductance L :

$$L = \frac{N^2}{S} = \frac{(200)^2}{2000} = 20 \text{ H}$$

Step 2 : Find e :

$$di = 1\text{ A} - (-1\text{A}) = 2 \text{ Amp}$$

$$dt = 10 \times 10^{-3}$$

$$\therefore \quad e = L\frac{di}{dt} = 20 \times \frac{2}{10 \times 10^{-3}}$$

$$= 4000 \text{ Volts}$$

...Ans.

Ex. 1.17.11 : Two identical coils with L = 0.03 H have a coupling coefficient of 0.8 calculate the mutual inductance.

Soln. :

Given : $L_1 = L_2 = 0.03$ H, $K = 0.8$

To find : M

$$\text{Mutual inductance } M = K\sqrt{L_1 L_2}$$

$$= 0.8\sqrt{0.03 \times 0.03}$$

$$\therefore \quad M = 0.024 \text{ H}$$

...Ans.

Ex. 1.17.12 : If a coil of 150 turns is linked with a flux of 0.01 Wb when carrying a current of 10 A. Calculate the inductance of the coil. If this current is uniformly reversed in 0.01 seconds. Calculate the induced emf. If second coil of 100 turns is uniformly wound over first coil, find mutual inductance between the two coils.

Soln. :

Part I : Inductance of coil

Given : $N = 150$ turns, $\phi = 0.01$ Wb, $I = 10$ A

$$L = \frac{N \times \phi}{I} = \frac{150 \times 0.01}{10}$$

$$= 0.15 \text{ H}$$

...Ans.

Part II : Induced emf

Given : $dI = 20$ A, $dt = 0.01$ sec

$$\therefore \text{ Induced emf } e = L\frac{dI}{dt} = 0.15 \times \frac{20}{0.01}$$

$$\therefore e = 300 \text{ Volts} \quad \text{...Ans.}$$

Part III : Mutual inductance

Given : $N_2 = 100$

$$M = N_2\frac{\phi}{I_1} = \frac{100 \times 0.01}{10}$$

$$= 0.1 \text{ H} \quad \text{...Ans.}$$

Ex. 1.17.13 : Two coils A and B are wound side by side on a paper tube former. An e.m.f. of 0.25 V is induced in coil A when the flux linking it changes at the rate of 10^{-3} Wb/s. A current of 2 A in coil B causes a flux of 10^{-5} Wb to link coil A. What is the mutual inductance between the coils ?

Soln. :

Given : $\mu_r = 1$, $e_A = 0.25$ V, $\frac{d\phi_A}{dt} = 10^{-3}$ Wb/s

$I_B = 2$ A, $\phi_A = 10^{-5}$ Wb

To find : M

Step 1 : Calculate N_A :

$$e_A = N_A\frac{d\phi_A}{dt}$$

$$\therefore 0.25 = N_A \times 10^{-3}$$

$$\therefore N_A = \frac{0.25}{10^{-3}} = 250 \text{ turns}$$

Step 2 : Calculate M :

$$M = \frac{N_A \phi_A}{I_B}$$

$$\therefore M = \frac{250 \times 10^{-5}}{2}$$

$$= 1.25 \times 10^{-3} \text{ H or } 1.25 \text{ mH} \quad \text{...Ans.}$$

Ex. 1.17.14 : Coils A and B in a magnetic circuit have 600 and 500 turns respectively. A current of 8 A in coil A produces a flux of 0.04 wb. If the co-efficient of coupling is 0.2 calculate :

1. Self-inductance of coil A when B is open circuit.
2. Flux linkage with coil B.

Soln. :

Given : $N_A = 600$, $N_B = 500$, $I_A = 8$ A, $\phi = 0.04$ Wb, $K = 0.2$

To find :
1. L_A
2. Flux linkage with coil B

1. Self inductance of coil A :

$$L_A = \frac{N_A \phi}{I_A}$$

$$= \frac{600 \times 0.04}{8} = 3 \text{ Amp.} \quad \text{...Ans.}$$

2. Calculate flux linkage with coil B :

$$\phi_2 = K\phi = 0.2 \times 0.04$$

$$\therefore \phi_2 = 8 \text{ mWb} \quad \text{...Ans.}$$

Ex. 1.17.15 : Two coils A and B have the turns 1000 and 2000 respectively. They lie in parallel to each other. Current of 1 amp. through coil A produces flux of 0.1 milliweber. Find mutual inductance between the coils.

Soln. :

Given : $N_A = 1000$, $N_B = 2000$, $I_A = 1$ A,

$\phi_B = 0.1 \text{ mWb} = 0.1 \times 10^{-3} = 1 \times 10^{-4}$ Wb

To find : M

$$M = \frac{N_B \phi_B}{I_A}$$

$$M = \frac{2000 \times 1 \times 10^{-4}}{1} = 0.2 \text{ H} \quad \text{...Ans.}$$

Review Questions

Q. 1 Define magnetic field.

Q. 2 Define magnetic flux (ϕ) and magnetic flux density (B).

Q. 3 State Lenz's law.

Q. 4 Define self induced emf and state expression.

Q. 5 Define mutually induced emf and state its expression.

Q. 6 Define self inductance.

Q. 7 Define mutual inductance.

Q. 8 Define coefficient of coupling.

Q. 9 Define the term electromagnetic induction.

Q. 10 What are the factors affecting the value of self inductance L ?

Q. 11 Define mutually induced emf.

Q. 12 What is the difference between self induced emf and mutually induced emf ?

Q. 13 State Faraday's laws of electromagnetic induction and derive the expression for the induced emf.

Q. 14 State and explain Fleming's right hand rule.

Q. 15 State and explain Lenz's law.

Q. 16 What is the difference between dynamically induced and statically induced emf ?

Q. 17 Explain the concept of self induced emf.

Q. 18 What is the relation between mmf, flux and reluctance of a magnetic circuit.

Q. 19 Why does hysteresis occur ?

Q. 20 What is the practical importance of hysteresis loop ?

Q. 21 What are the factors affecting the hysteresis loop ?

Q. 22 State the applications of electromagnets.

Q. 23 Draw the hysteresis loops for the nonmagnetic material.

Q. 24 What does the area under a hysteresis loop indicate ?

Q. 25 Define permeability and define the following terms :

1. Absolute permeability
2. Relative permeability
3. Permeability of free space.

Q. 26 For a series magnetic circuit, derive the expression for the total reluctance.

Q. 27 For a series magnetic circuit derive the expression for total m.m.f.

Q. 28 Compare the magnetic and electrical circuits based on their similarities and dissimilarities.

1.18 I-Scheme Questions and Answers :

Winter 2018 [Total Marks - 14]

Q. 1 Define permeability. **(Section 1.8)** **(2 Marks)**

Q. 2 Define MMF. **(Section 1.9.1)** **(2 Marks)**

Q. 3 Draw and explain B-H curve.

(Section 1.13) **(4 Marks)**

Q. 4 State and explain Faraday's laws of electromagnetic induction. **(Section 1.14.1)** **(6 Marks)**

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