1. Magnetic Circuits(10 Marks)

Q: What is magnet ? what is magnetism?

A substance that attracts piece of iron and steel is called **magnet.** This property of the material is called **magnetism.**

What are the types of magnet?

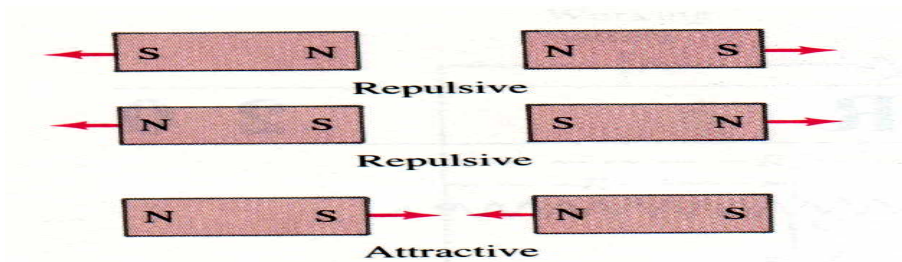
There are mainly two types of magnet. One in **natural magnet** and other is **artificial magnet**. Natural magnets are those collected from the earth. These are generally weak in strength hence are not used commercially. Commercially used magnets are mainly artificial magnets.

The most usual way of making an Artificial magnets is passing current through a wire wound over an iron or steel bar .Depending upon the ability to retain magnetism, artificial magnets are classified as **temporary magnet** and **permanent magnet.** Hardened steel, certain alloys of nickel and cobalt, when magnetised, retain their magnetism and unaltered for a long time after removal of magnetising force. Such substances are said to have high retentivity and after becoming magnet these are called permanent magnet. On the other hand the substance is like soft iron are easily and strongly be magnetised but lose most of their strength when the magnetising force is removed. Such substances are said to have low retentivity and after becoming magnet these are called temporary magnet.

What are the natures of magnetism?

A magnet has two opposite kinds of poles. These two types of poles are known as the North Pole and South Pole respectively. Experimentally this can be found that, 1. Similar kinds of poles repel each other and two opposite kinds of poles attract each other. 2. The attraction or repulsion force between two magnetic poles is directly proportional to the product of the strength of these poles and inversely proportional to the square of the distance between these two poles. 3. If a magnet is divided into different pieces, each of the pieces will become a complete magnet with its own north pole and south pole. 4. If any non-magnetised soft iron piece is brought nearer to a magnetic pole, the opposite pole is induced in the nearer portion of the soft iron piece and hence the piece will be attracted by the magnetic pole.

Opposites Attract / Likes Repel



With magnetic fields, opposite poles attract and like poles repel

Direction of Field: North South

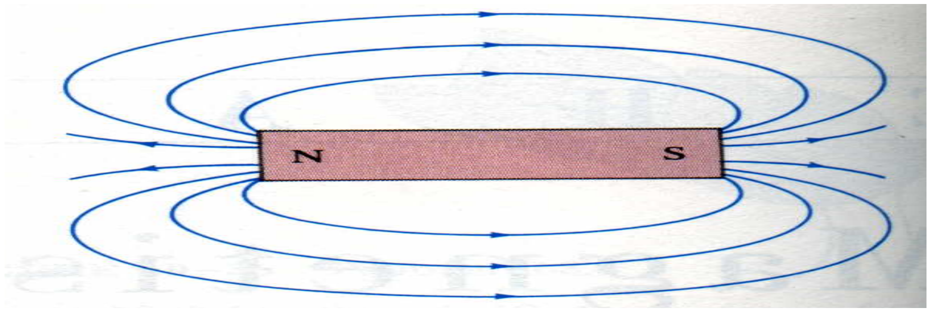
Magnetic Circuit Terminology:

Q: Define Magnetic field.

Magnetic field: The space (or field) in which a magnetic pole experiences a force is called a magnetic **field**.

Q: Define Magnetic lines of force.

Magnetic lines of force: The magnetic field around a magnet is represented by imaginary lines called **magnetic lines of force.**



A magnetic line of force can be drawn so that the field lines emanate from the North pole and go toward the South pole of the magnet.

Q: Write Properties of Magnetic lines of force.

Properties of Magnetic lines of force:

1.Each magnetic line of force forms a closed loop i.e. outside the magnet, the direction of a magnetic lines of force from north pole to south pole and if continuous through the body of the magnet to form a closed loop.

2. No two magnetic lines of force can intersect each other. If two magnetic lines of force intersects , there would be two directions of magnetic field at that point which is not possible.

3. The field is stronger where the field lines are more dense , so the field is stronger at the poles and weaker farther away from the poles.

Q: Define Magnetic flux.

Magnetic flux: It is defined as the amount of magnetic field produced by a magnetic source. In other words it is the number of lines of force produced by Magnetic source. The symbol for magnetic flux is Φ.

The unit of magnetic flux is **weber (Wb).**

Q: Define Magnetic flux density.

Magnetic flux density: It is the amount of flux passing through a defined area that is perpendicular to the direction of the flux.

Magnetic flux density = (magnetic flux) / (area)

$B = \Phi / A$

The symbol for magnetic flux density is B.

The unit of magnetic flux density is the Tesla (T)

$1\ T = 1 Wb/m^2$

Q: Define Poles of magnet.

poles of magnet: The ends of the bar magnet are apparently points of the magnetic effects are called as the poles of the magnets.

Q: Define poles of unit strength.

pole of unit strength: suppose two equal point poles placed 1 m apart in air extent a force of 62800 Newtons i.e.

A pole of unit strength is that pole which when placed in air 1m from an identical pole , repels it with a force of 62800 Newtons.

Q: Define MagnetoMotive Force (m.m.f.)

MagnetoMotive Force (m.m.f.): It is the cause of the presence of a magnetic flux in a magnetic circuit.

Q: Define Reluctance S (or R_M) .

Reluctance S (or R_M) : It is the magnetic resistance of a magnetic circuit to the presence of magnetic flux(Φ).

The unit of reluctance is **AT/Wb** .

Q: Define Permeability.

Permeability: (μ) Permeability of a material means its conductivity for magnetic flux. The greater is the Permeability of a material, greater is its conductivity for magnetic flux and vice versa.

$\mu 0$ = absolute permeability of air or vaccum = $4\pi \times 10$^-7 H/m

μr = Relative permeability of a material.

$$\mathbf{\mu 0.\mu r = \mu}$$

Q: Define Electromagnetism.

Electromagnetism: The branch of engg. Which deals with the magnetic effect electric current is called electromagnetism.

Permanent magnets produce a good and sometimes very strong static magnetic field in some applications the strength of this field is still too weak or we need to be able to control the amount of magnetic flux that is present.

So in order to obtain a much stronger and more controllable magnetic field we need to use electricity. By using coils of wire wrapped or wound around a soft magnetic material such as an iron core we can produce very strong electromagnets for use in may different applications. This then produces a relationship between Electricity and Magnetism that gives us another form of magnetism called **Electromagnetism**.

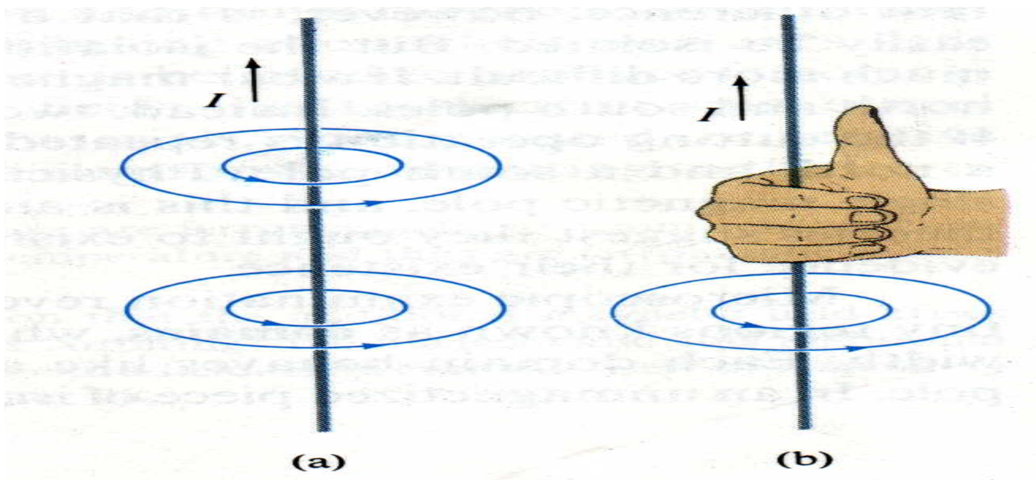
Electromagnetism **is** produced when an electrical current flows through a simple conductor such as a piece of wire or cable. A small magnetic field is created around the conductor with the direction of this magnetic field with regards to its “North” and “South” poles being determined by the direction of the current flowing through the conductor.

Therefore, it is necessary to establish a relationship between current flowing in the conductor and the resultant magnetic field produced by this current flow and thereby defining the definite relationship that exists between **Electricity** and **Magnetism** in the form of **Electromagnetism**.

When an electrical current flows through a conductor a circular electromagnetic field is generated around it. The direction of rotation of this magnetic field is governed by the direction of the current flowing through the conductor with the corresponding magnetic field produced being stronger near to the centre of the current carrying conductor and weaker farther away from it as shown below.

 # Right Hand Rule # 1

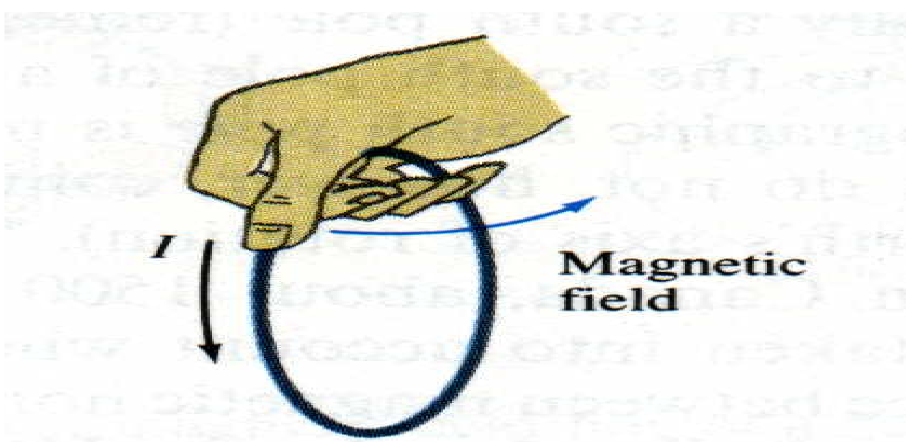
Electric Currents Magnetism!



Current running through a wire creates a magnetic field. This version of the "right hand rule" shows the thumb running in the direction of the current, and the magnetic field curves around the wire in the direction that the fingers curl.

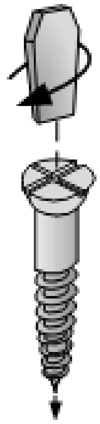
 # Right Hand Rule # 1

Electric Currents Magnetism!



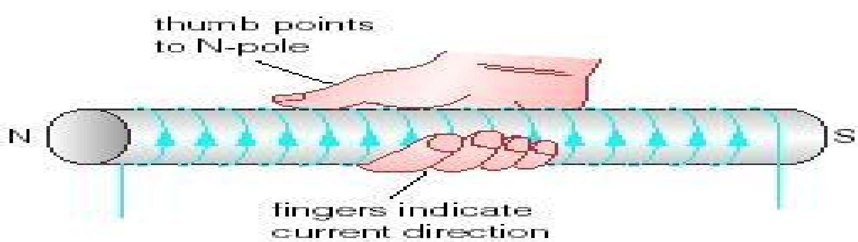
In the case of a circular loop of current, the thumb goes in the direction of the current loop, and the fingers curl inward in the direction of the magnetic field.

Right Hand Screw Action.



Hold the corkscrew in your right hand and move it in such a way that it advances in the direction of current .Then, the direction in which the fingers move is the direction of lines of force around the conductor.. This concept is known generally as the Right Hand Screw Action.

Right Hand Rule for coil:



Place your right hand over the coil, with your fingers wrapped in the direction of current flow through the coil. Your thumb will then point to the magnetic north of your electromagnet.

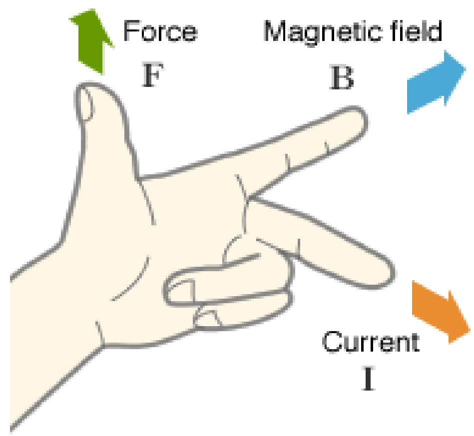
Q: Explain Fleming's Left Hand Rule.

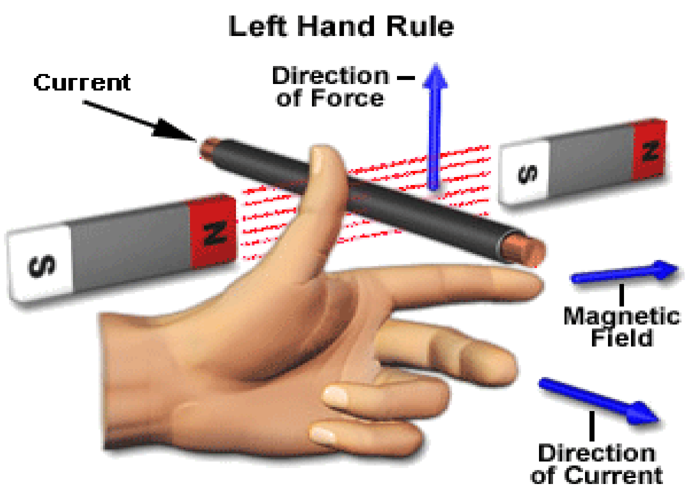
Fleming's Left Hand Rule:

When a current carrying conductor is placed at right angles to a magnetic field , it experiences a force which acts in the direction perpendicular to both the field and the current.

$$F=B.I.L \text{ Newtons}$$

Stretch out the first finger, second finger and thumb of your left hand so that they are at right angles to one another. If the first finger points in the direction of magnetic field (north to south) and the second finger (i.e. middle finger) points towards the direction of current then the thumb will point in the motion of the conductor.





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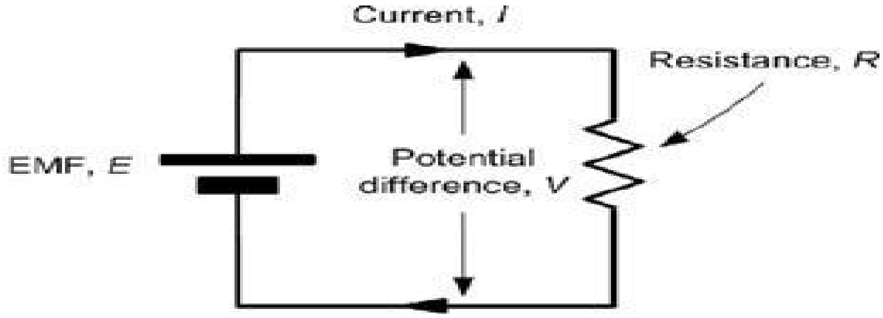
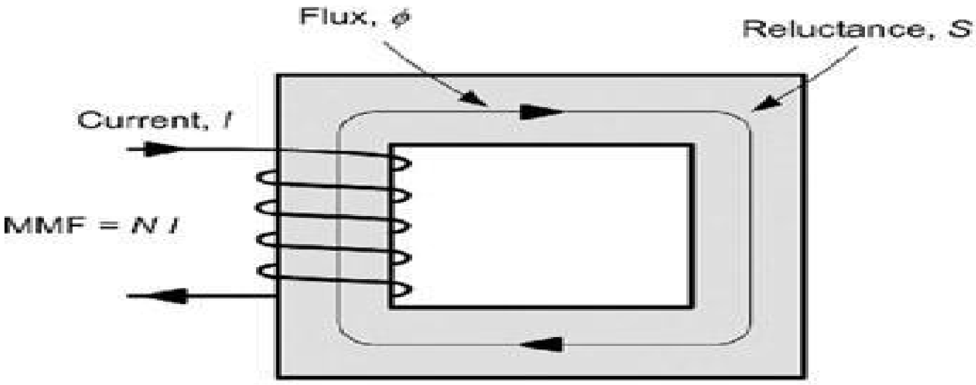
Q: Compare Magnetic Circuits and Electric Circuits.

Magnetic Circuits and Electric Circuits:



A An electric circuit



B A magnetic circuit

There are few dissimilarities between the two circuits which are listed below:

Electric Circuit	**Magnetic Circuit**
In the electric circuit, the current is actually flows. ie there is movement of electrons.	Due to mmf flux gets established and does not flow in the sense in which current flows.
There are many materials which can be used as insulators (air, PVC, synthetic resins etc) which current can not pass	There is no magnetic insulator as flux can pass through all the materials, even through the air as well.
Energy must be supplied to the electric circuit to maintain the flow of current.	Energy is required to create the magnetic flux, but is not required to maintain it.
The resistance and conductivity are independent of current density under constant temperature. But may change due to the temperature.	The reluctance, permanence and permeability are dependent on the flux density.
Electric lines of flux are not closed. They start from positive charge and end on negative charge.	Magnetic lines of flux are closed lines. They flow from N pole to S pole externally while S pole to N pole internally.

There is continuous consumption of electrical energy.	Energy is required to create the magnetic flux and not to maintain it.

Comparison between electrical and magnetic quantities

Electric Circuit	**Magnetic Circuit**
e.m.f. E (V)	m.m.f. F_m (A)
current I (A)	flux Φ (Wb).
resistance R (Ω)	reluctance S (H^{-1}) (AT/Wb)
R= (ρl) / A	**S = l/ $\mu_0\mu_r$A**
I = E / R	**Φ = mmf / S**

Similarities between electrical and magnetic circuits are given below

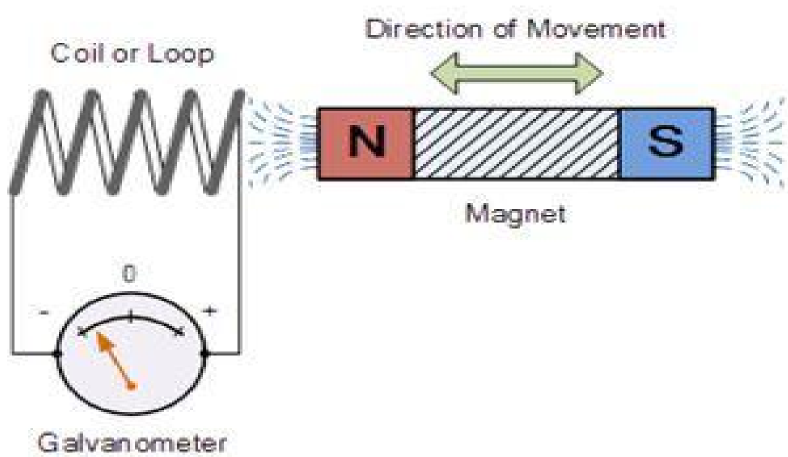
Electric Circuit	**Magnetic Circuit**
Path traced by the current is known as electric current.	Path traced by the magnetic flux is called as magnetic circuit.
EMF is the driving force in the electric circuit. The unit is Volts.	MMF is the driving force in the magnetic circuit. The unit is ampere turns.
There is a current I in the electric circuit which is measured in amperes.	There is flux φ in the magnetic circuit which is measured in the weber.
The flow of electrons decides the current in conductor.	The number of magnetic lines of force decides the flux.
Resistance (R) oppose the flow of the current. The unit is Ohm	Reluctance (S) is opposed by magnetic path to the flux. The Unit is ampere turn/weber.
R = ρ. l/a. Directly proportional to l. Inversely proportional to a. Depends on nature of material.	S = l/ ($\mu_0\mu_r$a). Directly proportional to l. Inversely proportional to a
The current I = EMF/ Resistance	The Flux = MMF/ Reluctance
The current density	The flux density
Kirchhoff current law and voltage law is applicable to the electric circuit.	Kirchhoff mmf law and flux law is applicable to the magnetic flux.

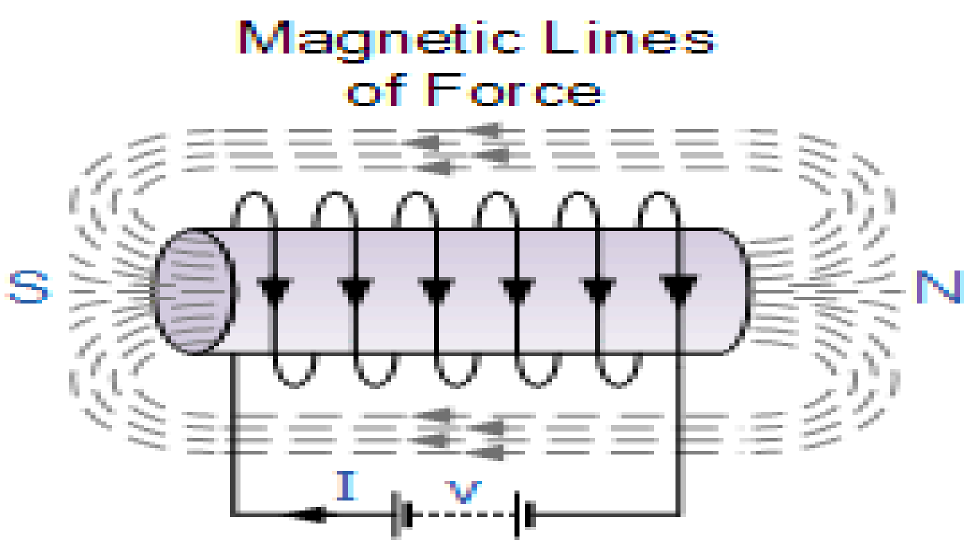
Q: What is Electromagnetic Induction.

Electromagnetic Induction:

When a magnetic flux linking a conductor changes, an E.M.F. is induced in the conductor . This phenomenon is known as **Electromagnetic Induction.**

The basic requirement of electromagnetic induction is the change of magnetic flux linking the conductor (or coil). Secondly, the E.M.F. and hence the current in this conductor (or coil) will persist so long as this change is taking place.





To demonstrate the phenomenon of electromagnetic Induction , consider a coil C of several turns connected to a centre zero galvanometer G as shown in figure, If a permanent magnet is moved towards the coil, it will be observed that the galvanometer shows deflection in one direction. If the magnet is moved away from the coil, the galvanometer again shows deflection but in the opposite direction. In either case, the deflection will persist so long as the magnet is in motion (towards or away from the coil), there amount of magnetic flux linking the coil changes-the basic requirement for inducing e.m.f. in the coil. If the movement of the magnet is stopped, though the magnetic flux linking the coil, there is no change in magnetic flux and hence no e.m.f. is induced in the coil. consequently, the deflection of the galvanometer reduces to zero.

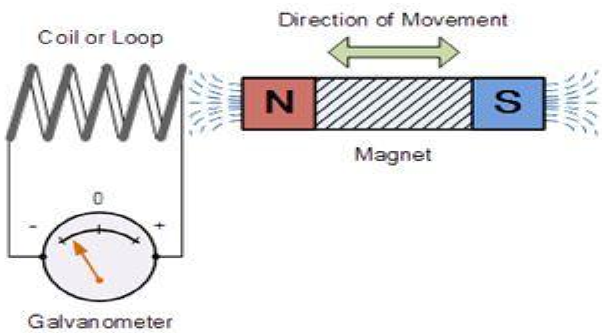
It is emphasized here that the basic requirement for inducing e.m.f. in the coil is not the magnetic flux linking the coil but the change in magnetic flux linking the coil. No change in magnetic flux, no e.m.f. is induced in the coil.

Q: Explain FARADAY'S laws of electromagnetic Induction.

FARADAY"S laws of electromagnetic Induction:

First law: It states that …When the magnetic flux linking a conductor or coil changes, an e.m. f. is induced in it.

Second Law: It states that….The magnitude of induced e. m.f. in a coil is equal to the rate of change of magnetic flux linkages.



Suppose a coil has N turns and magnetic flux linking the coil increases from $\Phi 1$ Wb to $\Phi 2$ Wb in t seconds. Now magnetic flux linkages means the product of magnetic flux and no. of turns.

Initial magnetic flux linkage = $N. \Phi 1$

final magnetic flux linkage = $N. \Phi 2$

e = rate of change of magnetic flux linkages

$= N. \Phi 2 - N. \Phi 1 / t$

$= N (\Phi 2- \Phi 1) / t$

In differential form, we have,

$$\mathbf{e = N\, d\, \Phi / dt \quad volts}$$

it is a usual practice to give a minus sign to right hand side expression. The minus sign comes from **Lenz"s law** and indicates that the voltage is induced in a direction opposite to the change in flux that produced it.

$e = - N\, d\Phi / dt$ volts

So how much voltage (emf) can be induced into the coil using just magnetism. Well this is determined by the following 3 different factors.

- 1). Increasing the number of turns of wire in the coil.
- 2). Increasing the speed of the relative motion between the coil and the magnet.
- 3). Increasing the strength of the magnetic field.

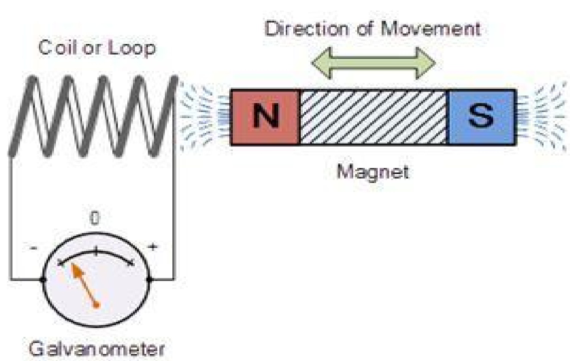
Q: Explain **RELATIONSHIP BETWEEN INDUCED EMF AND FLUX.**

RELATIONSHIP BETWEEN INDUCED EMF AND FLUX

In this experiment, Faraday takes a magnet and a coil and connects a galvanometer across the coil. Galvanometer is basically a very sensitive centre zero'ed moving-coil ammeter,At starting, the magnet is at rest, so there is no deflection in the galvanometer i.e needle of galvanometer is at the center or zero position. When the magnet is moved towards the coil, the needle of galvanometer deflects in one direction. When the magnet is held stationary at that position, the needle of galvanometer returns back to zero position. Now when the magnet is moved away from the coil, there is some deflection in the needle but in opposite direction and again when the magnet becomes stationary, at that point with respect to coil, the needle of the galvanometer returns back to the zero position. Similarly, if magnet is held stationary and the coil is moved away and towards the magnet, the galvanometer shows deflection in similar manner. It is also seen that, the faster the change in the magnetic field, the greater will be the induced emf or voltage in the coil.

When the magnet shown below is moved "towards" the coil, the pointer or needle of the galvanometer will deflect away from its centre position in one direction only. When the magnet stops moving and is held stationary with regards to the coil the needle of the galvanometer returns back to zero as there is no physical movement of the magnetic field.

Likewise, when the magnet is moved "away" from the coil in the other direction, the needle of the galvanometer deflects in the opposite direction with regards to the first indicating a change in polarity. Then by moving the magnet back and forth towards the coil the needle of the galvanometer will deflect left or right, positive or negative, relative to the directional motion of the magnet.



Q:Explain Applications of Faraday Law.

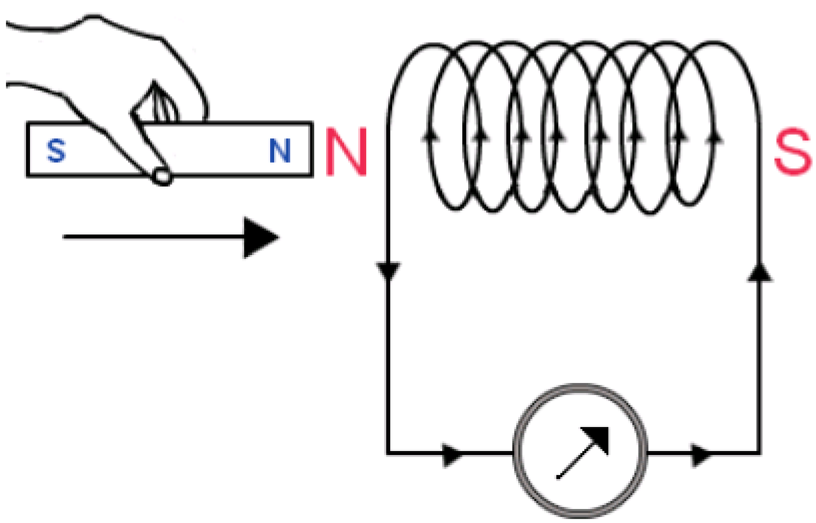
Applications of Faraday Law:
• **Electrical Transformers** It is a static ac device which is used to either step up or step down voltage or current. It is used in generating station, transmission and distribution systems. The transformer works on Faraday's law.
• **Electrical Generators** The basic working principle of electrical generators is Faraday's law of mutual induction. Electric generator is used to convert mechanical energy into electrical energy.

• **Induction Cookers** The Induction cooker is the fastest way of cooking. It also works on the principle of mutual induction. When current flows through the coil of copper wire placed below a cooking container, it produces a changing magnetic field. This alternating or changing magnetic field induces an emf and hence the current in the conductive container, and we know that flow of current always produces heat in it.
• **Electromagnetic Flow Meters** It is used to measure velocity of blood and certain fluids. When a magnetic field is applied to electrically insulated pipe in which conducting fluids are flowing, then according to Faraday's law, an electromotive force is induced in it. This induced emf is proportional to velocity of fluid flowing ..
• **Musical Instruments** It is also used in musical instruments like electric guitar, electric violin etc.

Q: Explain how to find out Direction of induced E. M. F. and current.

Direction of induced E. M. F. and current: The direction of induced e.m.f. and hence current in a conductor or coil can be determined by one of the following two methods:

1. **Lenz's law: An induced current will flow in such a direction so as to oppose the cause that produces it.**

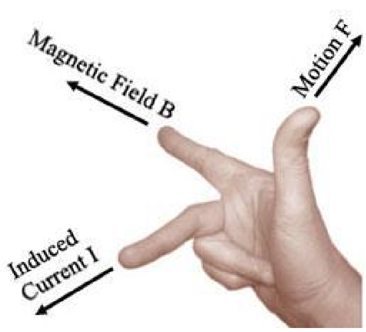


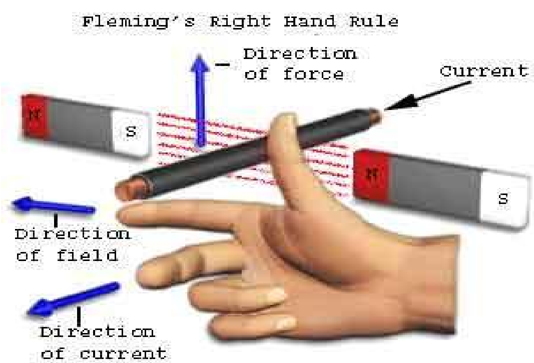
2. **Fleming's Right Hand Rule:**

This rule is particularly suitable to find the direction of induced e.m.f. nd hence current when the conductor moves at right angles to a stationary magnetic field. It may be stated as under:

Stretch out the forefinger, middle finger and thumb of your right hand so that they are at right angles one another. If the forefinger points in the direction of magnetic field, thumb in the direction of motion of the conductor, then the middle finger will point in the direction of induced current.

Consider a conductor AB moving upwords at right angles to uniform magnetic field. Applying Fleming's right hand rule , it is clear that the direction of induced current is from B to A. If the motion of the conductor is downwards, keeping the direction of magnetic field unchanged then the direction of induced current will be from A to B.





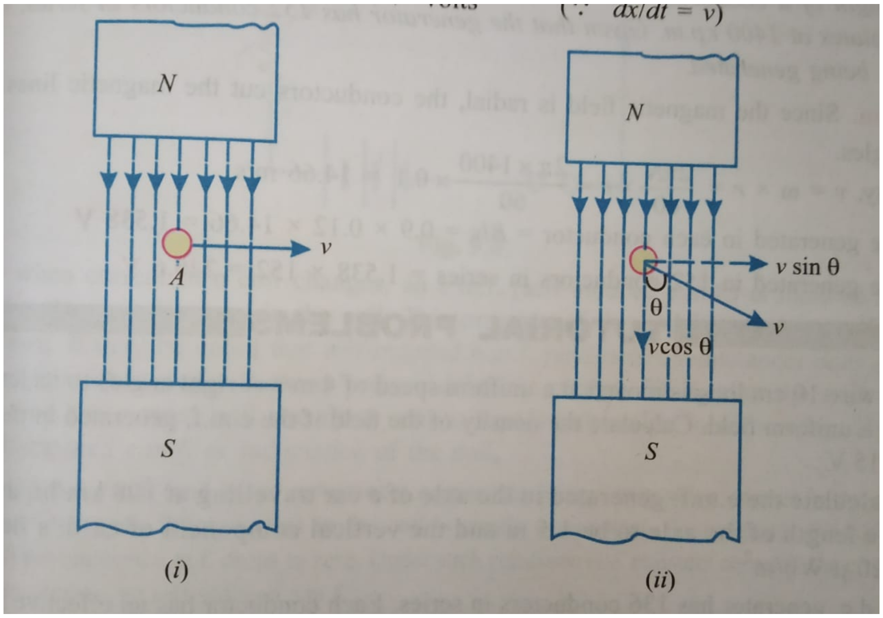
Q:Explain Induced E.M.F. and its types.

Induced E.M.F.

When magnetic flux linking a conductor or coil changes ,an e.m.f. is induced in it. This change in magnetic flux linkages can be brought about in the following ways.

1. The conductor is moved in a stationary magnetic field in such a way that the magnetic flux linking it changes in magnitude. The e.m.f. induced in this way is called dynamically induced e.m.f. . It is so called because e.m.f. is induced in the conductor which is in motion.
2. The conductor is stationary and the magnetic field is moving or changing. The e.m.f. induced in such a way is called statically induced e.m.f.. It is so called because e.m.f. induced in a conductor which is stationary.

1. **Dynamically induced E.M.F.:**



Consider a single conductor of length l meters moving at right angles to a uniform magnetic field of B Wb/ m^2 with a velocity of v m/s . suppose the conductor moves the small distance dx in dt seconds. Then area swept by the conductor is = l×dx

Therefore, magnetic flux cut , dΦ = flux density × area swept

= B l dx Wb

According to Faraday's law of Electromagnetic Induction, e.m.f. e induced in the conductor is given by,

$$e = N\, d\Phi/dt$$

$$e = N.\ B\, l\, dx/dt$$

as N=1 and dx/dt = v

$$e = B.l.v \text{ volts}$$

if the conductor moves at right angles θ to the magnetic field, then the velocity at which the conductor moves across the field is = v sin θ

therefore…$e = B\, l\, v \sin\theta$

the direction of induced e.m.f. can be determined by Fleming's Right hand rule.

2. **Statically induced E.M.F.**

When the conductor is stationary and the field is moving or charging, the e.m.f. induced in the conductor is called statically induced e.m.f. A statically induced e.m.f. can be further sub divided into:

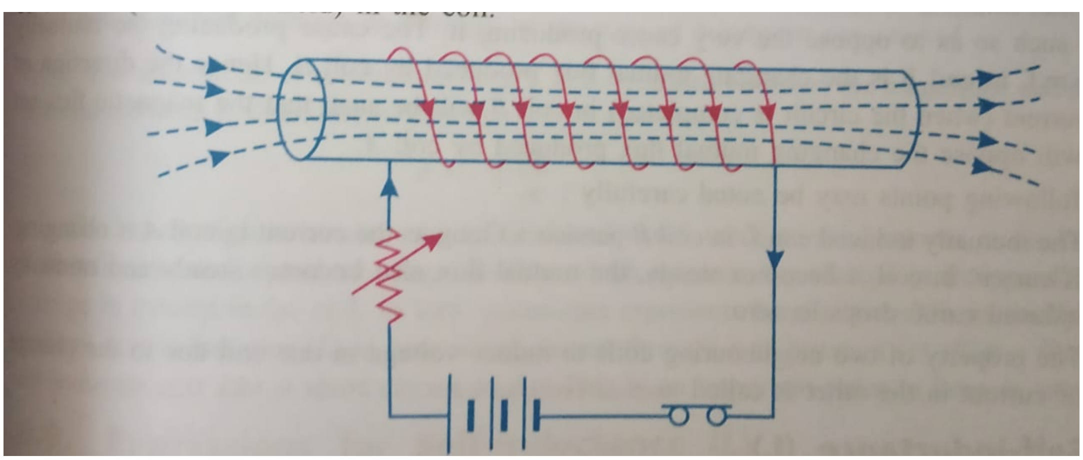
1. **Self induced e.m.f.**
2. **Mutually induced e.m.f.**

Self induced E.M.F.

The e.m.f induced in a coil due to the change of its own magnetic flux linked with it is called self induced e.m.f.

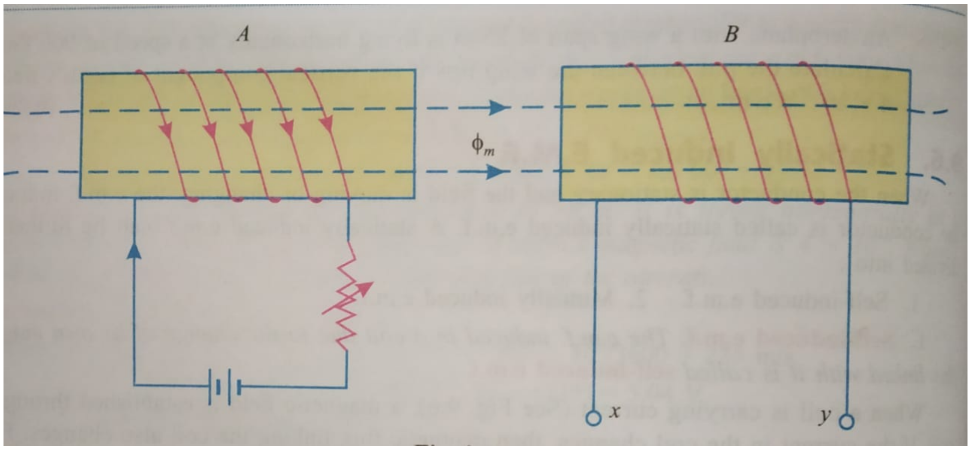
When a coil is carrying current, a magnetic field is established through the coil, if the current in the coil changes, then magnetic flux linking the coil also changes. Hence by Faraday's laws, an e.m.f. will be induced in the coil. This is known as self induced e.m.f. The magnitude of this induced e.m.f. $= N\ d\Phi/dt$. The direction of induced e.m.f. (by Lenz law) is always such so as to oppose the cause responsible for inducing the e.m.f. namely change of current (and hence field) in the coil.

Thus when current in the coil changes, an e.m.f.(self induced e,m,f,)is induced in it which opposes the change of current in the coil. This property of the coil is called its self inductance or inductance. It may be noted that self induced e.m.f. does not prevent the current from changing:nit serves only to delay the change . thus after the switch is closed ,the current will rise from zero to final steady value in some time. This dely is due to self induced e.m.f.



Mutually induced e.m.f:

The e.m.f. induced in a coil due to the changing current in the neighbouring coil is called mutually induced e.m.f.



Consider two coils A and B placed adjacent to each other as shown in figure. A part of the magnetic flux produced by coil A Passes through or links with coil B. This magnetic flux which is common to both the coils A and B is called mutual flux(Φm). If current in the coil A is varied, the mutual flux also varies and hence, e.m.f. is induced in both coils. The e.m.f. induced in coil A is called self induced e.m.f. The e.m.f. induced in coil B is known as mutually induced e.m.f. The magnitude of mutually induced e.m.f. is given by Faraday's laws i.e.

$$Em = N B \, d\Phi m/dt$$

where , N is the no. of turns in coil

$d\Phi m/dt$ is the rate of change of mutual flux i.e. magnetic flux common to both the coils

The direction of mutually induced e.m.f. (by lenz law) is always such so as to oppose the very cause producing it. The cause producing the mutually inducing e.m.f. in coil B is the changing flux produced by coil A. Hence the deflection of induced current (when the circuit is completed) in coil B will be such that the magnetic flux set up by it will oppose the changing mutual flux produced by coil.

1. The mutually induced e.m.f. in the coil B persists so long as the current in the coil is changing. If current in the coil becomes steady, the mutual flux also becomes steady and mutually induced e.m.f. will drop to zero.
2. The property of two neighbouring coils to induce voltage in one coil due to the change of current in the other is called mutual inductance

Q: Define Self Inductance.

Self Inductance(L):

The property of a coil that opposes any change in the amount of current flowing through it is called its self inductance or Inductance.

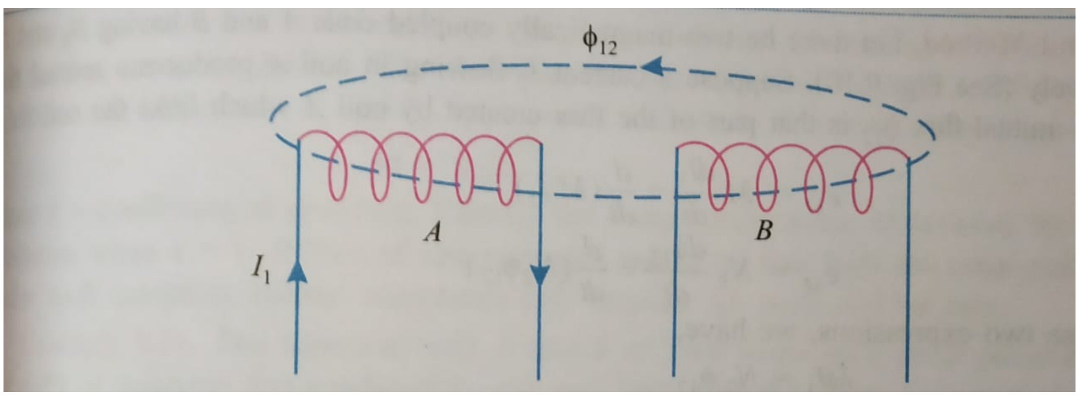
This property is due to the self induced e.m.f. in the coil itself by the changing current. If the current inn the coil is increasing , the self induced e.m.f. is set up in such a direction so as to rise of current i.e. direction of self induced e.m.f. is opposite to that of the applied voltage.similarly, If the current inn the coil is decreasing , the self induced e.m.f. is set up in such a direction so as to decrease of current i.e. direction of self induced e.m.f. is same to that of the applied voltage.

The greater the self induced e.m.f., the greater the self inductance of the coil and hence larger is the opposition to the changing current. Hence inductance of the coil depends upon following factors:

1. Shape and no. of turns
2. μr of the material surrounding the coil
3. the speed with which the magnetic field changes.

Coefficient of coupling: The coefficient of coupling (k) between two coils is defined as the fraction of magnetic flux produced by the current in one coil that links the other.

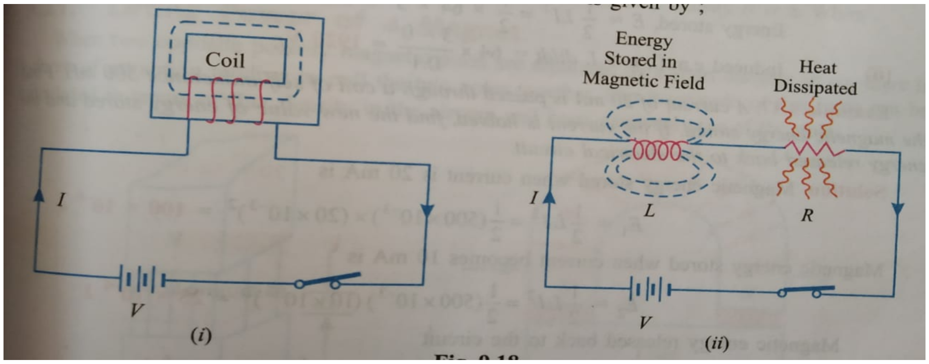
Mutual Inductance (M): The two coils so arranged that a change of current in one coil causes an e.m.f. to be induced in the other are said to have mutual inductance.



Q: Explain Energy stored in a magnetic field.

Energy stored in an magnetic field: In order to establish a magnetic field around the coil, energy is required, though no energy is needed to maintain it. This energy is stored in a magnetic field and is not used up. When current is decreased, the magnetic flux surrounding the coil is decreased, causing the stored energy to return to the circuit .Consider an inductor connected to the dc source as shown in figure. The inductor is equivalent to inductance L in series with a small resistance R as shown in figure. The energy supplied to the circuit is spent in two ways:

1. A part of supplied energy is spent to meet $I^2 R$ looses and cannot be recovered
2. The remaining part is spent to create a magnetic flux around the coil (or inductor) and is stored in the magnetic field . When the field collapses, this stored energy is returned to the circuit.



Suppose at any instant the current in the coil is i and is increasing at the rate of di/dt . then magnitude of e.m.f. e across L is given by:

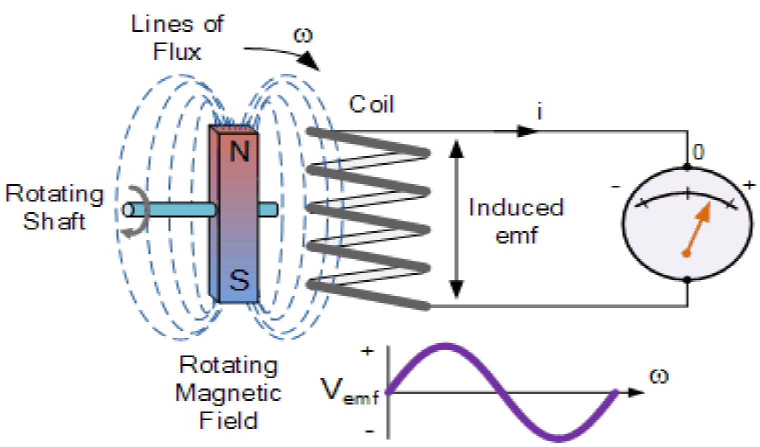
$$e = L.\, di/dt$$

energy stored in magnetic field

$$E = \frac{1}{2} L.I^2 \text{ Joules}$$

Q: Explain Simple Generator using Magnetic Induction.

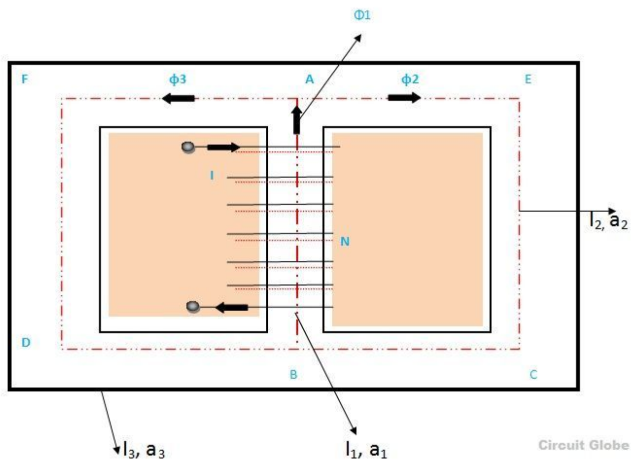
Simple Generator using Magnetic Induction.



The simple dynamo type generator above consists of a permanent magnet which rotates around a central shaft with a coil of wire placed next to this rotating magnetic field. As the magnet spins, the magnetic field around the top and bottom of the coil constantly changes between a north and a south pole. This rotational movement of the magnetic field results in an alternating emf being induced into the coil as defined by Faraday's law of electromagnetic induction.

Q:Explain Series and parallel magnetic circuits.

Parallel Magnetic Circuit: Definition: A magnetic circuit having two or more than two paths for the magnetic flux is called a **parallel magnetic circuit**. Its behaviour can be compared to the parallel electric circuit. The parallel magnetic circuit contains different dimensional areas and materials having various numbers of paths.



The above figure shows a parallel magnetic circuit. In this circuit, a current-carrying coil is wound on the central limb AB. This coil sets up the magnetic flux φ1 in the central limb of the circuit. The flux φ1 which is in the upward direction is further divided into two paths namely ADCB and AFEB. The path ADCB carries flux φ2, and the path AFEB carries flux φ3. It is clearly seen fro the above circuit that

φ1 = φ2 + φ3

The two magnetic paths ADCB and AFEB form the parallel magnetic circuit, thus, the ampere-turns (ATs) required for this parallel circuit are equal to the ampere-turns (ATs) required for any one of the paths.

As we know, reluctance is

$$S = \frac{l}{a_1 \mu_0 \mu_{r1}}$$

If S1 = reluctance of path BA will be

$$S_1 = \frac{l_1}{a_1 \mu_0 \mu_{r1}}$$

S2 =reluctance of path ADCB will be

$$S_2 = \frac{l_2}{a_2 \mu_0 \mu_{r2}}$$

S3 = reluctance of the path AFEB will be

$$S_3 = \frac{l_3}{a_3 \mu_0 \mu_{r3}}$$

Therefore, the total MMF or the total Ampere turns required in the parallel magnetic circuit will be the sum of all the individual parallel paths.

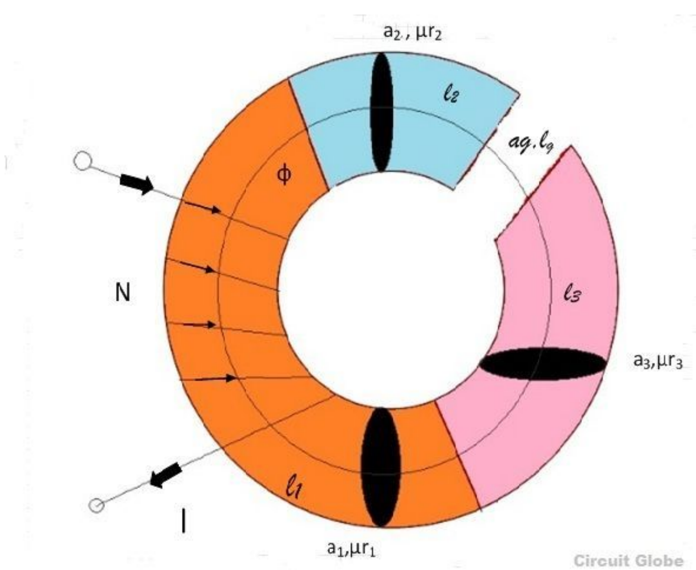
Total mmf required = mmf required for the path BA +mmf required for the path ADCB + mmf required for the path AFEB

$$\text{Total mmf or Ampere turns} = \varphi_1 S_1 + \varphi_2 S_2 + \varphi_3 S_3$$

Where φ1. Φ2, φ3 is the flux and S1, S2, S3 are the reluctances of the parallel path BA, ADCB and AFEB respectively.

Series Magnetic Circuit:

Definition: The **Series Magnetic Circuit** is defined as the magnetic circuit having a number of parts of different dimensions and materials carrying the same magnetic field. Consider a circular coil or solenoid having different dimensions as shown in the figure below:



Current I is passed through the solenoid having N number of turns wound on the one section of the circular coil. Φ is the flux, set up in the core of the coil.

a1, a2, a3 are the cross-sectional area of the solenoid.

l1, l2, l3 are the length of the three different coils having different dimension joined together in series.

µr1, µr2, µr3 are the relative permeability of the material of the circular coil.

ag and are the area and the length of the air gap.

The total reluctance (S) of the magnetic circuit is

$$S = S_1 + S_2 + S_3 + S_g$$

$$S = \frac{l_1}{a_1 \mu_0 \mu_{r1}} + \frac{l_2}{a_2 \mu_0 \mu_{r2}} + \frac{l_3}{a_3 \mu_0 \mu_{r3}} + \frac{l_g}{a_g \mu_0}$$

Total MMF = φ x S ……..…. (1)

Putting the value of S in equation (1) we get,

$$\text{Total mmf} = \varphi \ x \ \frac{l_1}{a_1 \mu_0 \mu_{r1}} + \frac{l_2}{a_2 \mu_0 \mu_{r2}} + \frac{l_3}{a_3 \mu_0 \mu_{r3}} + \frac{l_g}{a_g \mu_0} \ldots\ldots\ldots (2)$$

(As B = φ/a) putting the valve of B in the equation (2) we obtain the following equation for the total MMF

$$\text{Total mmf} = \frac{B_1 l_1}{\mu_0 \mu_{r1}} + \frac{B_2 l_2}{\mu_0 \mu_{r2}} + \frac{B_3 l_3}{\mu_0 \mu_{r3}} + \frac{B_g l_g}{\mu_0}$$

$$(\text{As } H = B/\mu_0 \mu_r)$$

$$\text{Total mmf} = H_1 l_1 + H_2 l_2 + H_3 l_3 + H_g l_g$$

Magnetic Permeability:

Definition: The magnetic permeability is defined as the property of the material to allow the magnetic line of force to pass through it. In other words, the magnetic material can support the development of the magnetic field.

Magnetic Circuit:

The closed path followed by magnetic lines of forces is called the **magnetic circuit**. In the **magnetic circuit**, magnetic flux or magnetic lines of force starts from a point and ends at the same point after completing its path.

Flux is generated by magnets, it can be a permanent magnet or electromagnets.

A **magnetic circuit** is made up of magnetic materials having high permeability such as iron, soft steel, etc. **Magnetic circuits** are used in various devices like electric motor, transformers, relays, generators galvanometer, etc.

Permeance

Definition: It is the measure of the ease with which flux can be set up in a material. In other words, it measures the magnitude of the flux for the number of turns in an electric circuit. The permeance is analogous to the conductance in an electrical circuit.

It is denoted by **P** and measured in **Weber per ampere turns (Wb/AT) or Henry (H).** The permeance of the magnetic circuit is expressed as:

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

Where a – cross-sectional area

l – magnetic path length

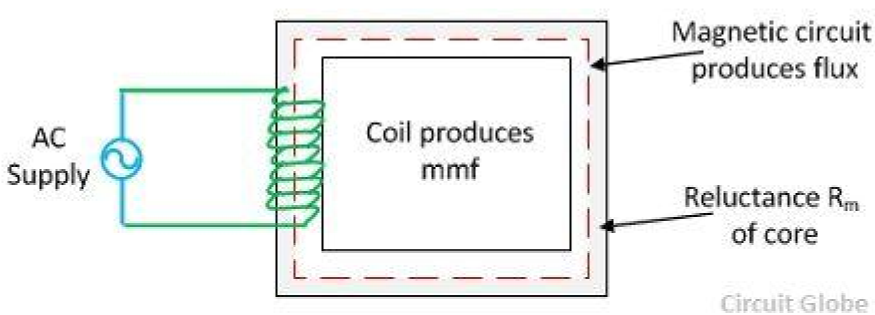
μ_o – permeability of vacuum

μ_r – permeability of air

Magnetic Reluctance:

Definition: The obstruction offered by a magnetic circuit to the magnetic flux is known as **reluctance.** As in electric circuit, there is resistance similarly in the magnetic circuit, there is a reluctance, but resistance in an electrical circuit dissipates the electric energy and the reluctance in magnetic circuit stores the magnetic energy.

Also in an electric circuit, the electric field provides the least resistance path to the electric current. Similarly, the magnetic field causes the least reluctance path for the magnetic flux. It is denoted by S.



$$Reluctance\ (S) = \frac{l}{\mu_0 \mu_r A}$$

Where, l – the length of the conductor

μo – permeability of vacuum which is equal to 4π X107 Henry/metre.

μr – relative permeability of the material.

A – cross-section area of the conductor.

Its SI unit is **AT / Wb (ampere-turns / Weber).** The reluctance of the magnetic circuit is directly proportional to the length of the conductor and inversely proportional to the cross-section area of the conductor.

The reciprocal of the magnetic reluctance is known as the magnetic **permeance**. It is given by the expression $$Permeance\ (P) = \frac{1}{Reluctance} = \frac{1}{R}$$

The reluctance in the DC field is defined as the ratio of the magnetic motive force and to the magnetic flux of the same circuit. The reluctance in the DC field is expressed as

$$Reluctance\ (S) = \frac{m.m.f}{flux} = \frac{F}{\emptyset}$$

Where, S – reluctance in ampere-turns per weber.

F – magnetic motive force

Φ – magnetic flux

The non-uniform magnetic circuit is made by adding the uniform sections having the different value of a length, cross-section area, and permeability of the magnetic circuit.

The reluctance of the non-uniform circuit is calculated by adding the reluctance of the uniform section of the magnetic circuit. The calculation of the non-uniform magnetic field is more complex as compared to the uniform magnetic field.

In most of the transformer, an air gap is created for reducing the effects of the saturation. The air gap increases the reluctance of the circuit and hence stores more magnetic energy before the saturation.

Magnetic Hysteresis:

Magnetic Hysteresis When a magnetic material is subjected to a cycle of magnetisation (i.e. it is magnetised first in one direction and then in the other), it is found that flux density B in the material lags behind the applied magnetising force H. This phenomenon is known as **hysteresis.**

The phenomenon of lagging of flux density (B) behind the magnetising force (H) in a magnetic material subjected to cycles of magnetisation is known as **magnetic hysteresis.**

The term **'hysteresis'** is derived from the Greek word hysterein meaning to lag behind. If a piece of magnetic material is subjected to *one cycle of magnetisation, the resultant B-H curve is a closed loop abcdefa called hysteresis loop [See Fig. 8.36 (ii)]. Note that B always lags behind H. Thus at point 'b', H is zero but flux density B has a positive finite value ob. Similarly at point 'e', H is zero, but flux density has a finite negative value oe. This tendency of flux density B to lag behind magnetising force H is known as **magnetic hysteresis**.

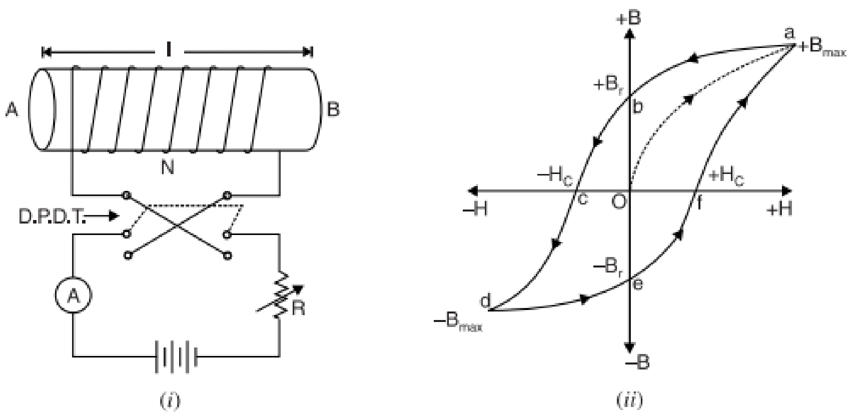
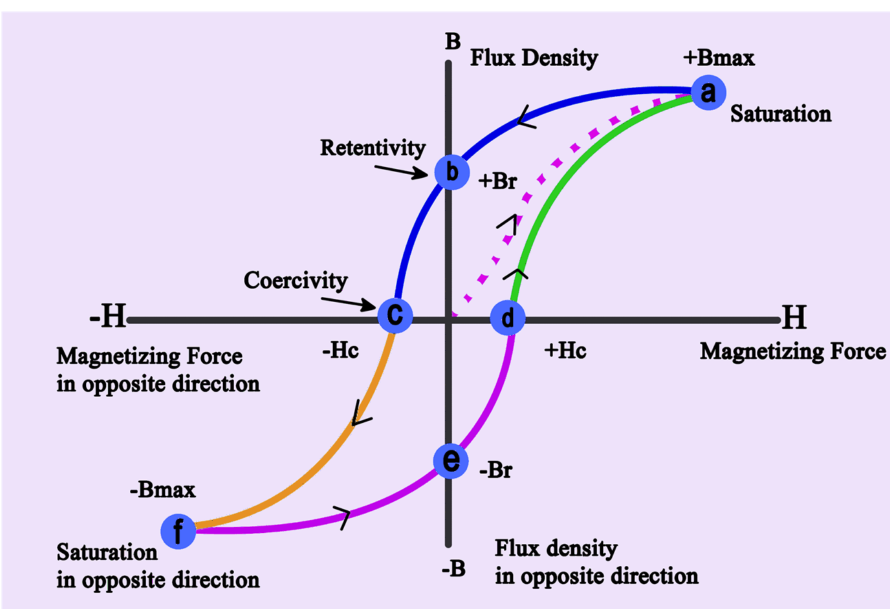


Fig. 8.36



Hysteresis Loop

Consider an unmagnetised iron bar AB wound with N turns as shown in Fig. 8.36 (i). The magnetising force H (= NI/l) produced by this solenoid can be changed by varying the current through the coil.

The double-pole, double-throw switch (DPDT) is used to reverse the direction of current through the coil. We shall see that when the iron piece is subjected to a cycle of magnetisation, the resultant B-H curve traces a loop abcdefa called **hysteresis loop. (**

i) We start with unmagnetised solenoid AB. When the current in the solenoid is zero, H = 0 and hence B in the iron piece is 0. As H is increased (by increasing solenoid current), the flux density (+ B) also increases until the point of maximum flux density (+ Bmax) is reached. The material is saturated and beyond this point, the flux density will not increase regardless of any increase in current or magnetising force. Note that B-H curve of the iron follows the path oa.

(ii) If now H is gradually reduced (by reducing solenoid current), it is found that the flux density B does not decrease along the same line by which it had increased but follows the path ab. At point b, the magnetising force H is zero but flux density in the material has a finite value + Br (= ob) called r**esidual flux density.** It means that after the removal of H, the iron piece still retains some magnetism (i.e. + Br). In other words, B lags behind H. The greater the lag, the greater is the **residual magnetism** (i.e. ordinate ob) retained by the iron piece. The power of retaining residual magnetism is called **retentivity** of the material. The hysteresis effect (i.e. lagging of B behind H) in a magnetic material is due to the opposition offered by the magnetic domains (or molecular magnets) to the turning effect of magnetising force. Once arranged in an orderly position by the magnetising force, the magnetic domains do not return exactly to the original positions. In other words, the material retains some magnetism even after the removal of magnetising force. This results in the lagging of B behind H.

(iii) To demagnetise the iron piece (i.e. to remove the residual magnetism ob), the magnetising force H is reversed by reversing the current through the coil. When H is graudally increased in the reverse direction, the B-H curve follows the path bc so that when H = oc, the residual magnetism is zero. The value of H (= oc) required to wipe out residual magnetism is known as coercive force (Hc).

(iv) If H is further increased in the reverse direction, the flux density increases in the reverse direction (− B). This process continues (curve cd) till the material is saturated in the reverse direction (−Bmax point) and can hold no more flux.

(v) If H is now gradually decreased to zero, the flux density also decreases and the curve follows the path de. At point e, the magnetising force is zero but flux density has a finite value −Br (= oe) — the residual magnetism.

(vi) In order to neutralise the residual magnetism oe, magnetising force is applied in the positive direction (i.e. original direction) so that when H = of (coercive force Hc), the flux density in the iron piece is zero. Note that the curve follows the path ef. If H is further increased in the positive direction, the curve follows the path fa to complete the loop abcdefa. Thus when a magnetic material is subjected to one cycle of magnetisation, B always lags behind H so that the resultant B-H curve forms a closed loop, called hysteresis loop. For the second cycle of magnetisation, a *similar loop abcdefa is formed. If a magnetic material is located within a coil through which alternating current (50 Hz frequency) flows, 50 loops will be formed every second. This hysteresis effect is present in all those electrical machines where the iron parts are subjected to cycles of magnetisation e.g. armature of a d.c. machine rotating in a stationary magnetic field, transformer core subjected to alternating flux etc.

Hysteresis Loss

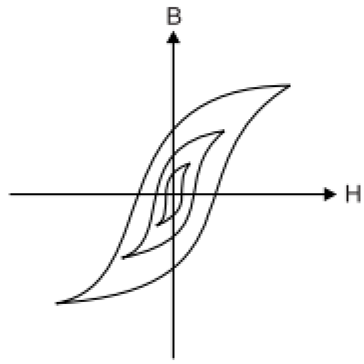
When a magnetic material is subjected to a cycle of magnetisation (i.e. it is magnetised first in one direction and then in the other), an energy loss takes place due to the *molecular friction in the material. That is, the domains (or molecular magnets) of the material resist being turned first in one direction and then in the other. Energy is thus expended in the material in overcoming this opposition. This loss is in the form of heat and is called **hysteresis loss.**

Hysteresis loss is present in all those electrical machines whose iron parts are subjected to cycles of magnetisation. The obvious effect of hysteresis loss is the rise of temperature of the machine. (i) Transformers and most electric motors operate on alternating current. In such devices, the flux in the iron changes continuously, both in value and direction. Hence hysteresis loss occurs in such machines.

(ii) Hysteresis loss also occurs when an iron part rotates in a constant magnetic field e.g. d.c. machines

Factors Affecting the Shape and Size of Hysteresis Loop

There are three factors that affect the shape and size of hysteresis loop. (i) The material. The shape and size of the hysteresis loop largely depends upon the nature of the material. If the material is easily magnetised, the loop will be narrow. On the other hand, if the material does not get magnetised easily, the loop will be wide. Further, different materials will saturate at different values of magnetic flux density thus affecting the height of the loop. (ii) The maximum flux density. The loop area also depends upon the maximum flux density that is established in the material. This is illustrated in Fig. 8.38. It is clear that the loop area increases as the alternating magnetic field has progressively greater peak values.



Variation of peak flux density

Fig. 8.38

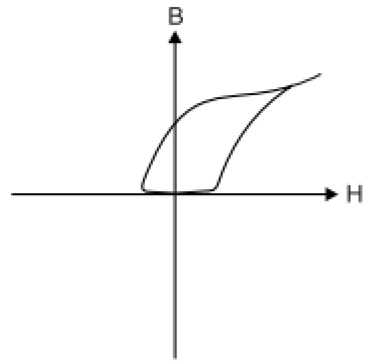
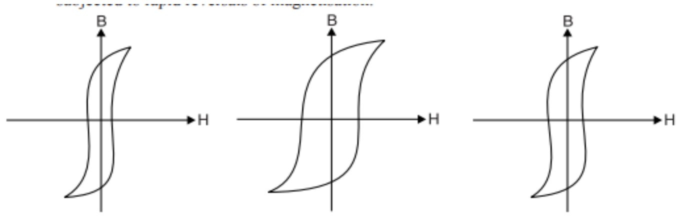


Fig. 8.39

Importance of Hysteresis Loop

The shape and size of the hysteresis loop *largely depends upon the nature of the material. The choice of a magnetic material for a particular application often depends upon the shape and size of the hysteresis loop. A few cases are discussed below by way of illustration. (i) The smaller the hysteresis loop area of a magnetic material, the less is the hysteresis loss. The hysteresis loop for silicon steel has a very small area [See Fig. 8.40 (i)]. For this reason, silicon steel is widely used for making transformer cores and rotating machines which are subjected to rapid reversals of magnetisation.



Silicon steel (*i*) Hard steel (*ii*) Wrought iron (*iii*)

Fig. 8.40

Applications of Ferromagnetic Materials

Ferromagnetic materials (e.g. iron, steel, nickel, cobalt etc.) are widely used in a number of applications. The choice of a ferromagnetic material for a particular application depends upon its magnetic properties such as retentivity, coercivity and area of the hysteresis loop. Ferromagnetic materials are classified as being either soft (soft iron) and hard (steel). Fig. 8.41 shows the hysteresis loop for soft and hard ferromagnetic materials. The table below gives the magnetic properties of hard and soft ferromagnetic materials.

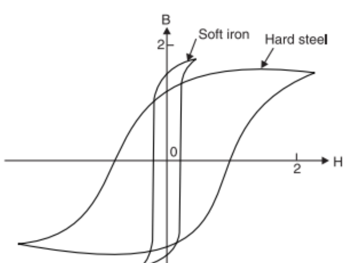


Fig. 8.41

Magnetic property Soft Iron Hard Steel Hysteresis loop narrow large area Retentivity high high Coercivity low high Saturation flux density high good.

(i) The permanent magnets are made from hard ferromagnetic materials (steel, cobalt steel, carbon steel etc). Since these materials have high retentivity, the magnet is quite strong. Due to their high coercivity, they are unlikely to be demagnetised by stray magnetic fields.

(ii) The electromagnets or temporary magnets are made from soft ferromagnetic materials (e.g. soft iron). Since these materials have low coercivity, they can be easily demagnetised. Due to high saturation flux density, they make strong magnets.

(iii) The transformer cores are made from soft ferromagnetic materials. When a transformer is in use, its core is taken through many cycles of magnetisation. Energy is dissipated in the core in the form of heat during each cycle. The energy dissipated is known as hysteresis loss and is proportional to the area of hysteresis loop. Since the soft ferromagnetic materials have narrow hysteresis loop (i.e. smaller hysteresis loop area), they are used for making transformer core.

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