Unit 1 : Electromagnetism

Review: Resistance, EMF, Current, Potential, Potential difference and Ohm's law

Resistance

Definition: The **opposition** offered by a substance to the flow of electric current is called its resistance.

Unit of resistance: Ohm and is represented by the symbol Ω.

Ohm: A wire is said to have a resistance of 1 ohm if a p.d. of 1 volt across its ends causes 1 ampere to flow through it

Electromotive Force (emf)

Electromotive force (emf) is a **measurement of the energy** that causes current to flow through a circuit.

It can also be defined as the **potential difference in charge** between two points in a circuit.

Electromotive force is also known as voltage, and it is measured in volts.

Electric Current

Definition: The **directed flow of free electrons** (or charge) is called electric current.

The flow of electric current can be explained by referring to the adjoining figure.

The **copper strip** has a large number of **free electrons**.

When **electric pressure or voltage** is applied, then free electrons, being negatively charged, will start **moving towards the positive terminal** around the circuit as shown in figure.

This directed flow of electrons is called electric current.

Electric Potential

Definition: The **capacity of a charged body to do work** is called its electric potential.

Electric potential, V = Work done per Charge = W/Q

S.I unit of electric potential: joules/coulomb or volt(V)

Potential Difference

Definition: The **difference in the potentials** of two charged bodies is called potential difference.

If two bodies have different electric potentials, a potential difference exists between the bodies. Consider two bodies A and B having potentials of 5 volts and 3 volts respectively as shown in adjoining figure. Each coulomb of charge on body A has an energy of 5 joules while each coulomb of charge on body B has an energy of 3 joules. Clearly, body A is at higher potential than the body B.

If the two bodies are joined through a conductor [See Fig. (ii)], then electrons will flow from body B to body A. When the two bodies attain the same potential, the flow of current stops. Therefore, we arrive at a very important conclusion that current will flow in a circuit if potential difference exists. No potential difference, no current flow.

Unit: Since the unit of electric potential is volt, one can expect that unit of potential difference will also be volt.

OHM's Law

The **ratio** of **potential difference (V)** between the ends of a conductor to the **current (I)** flowing between them is constant, provided the physical conditions (e.g. temperature etc.) do not change

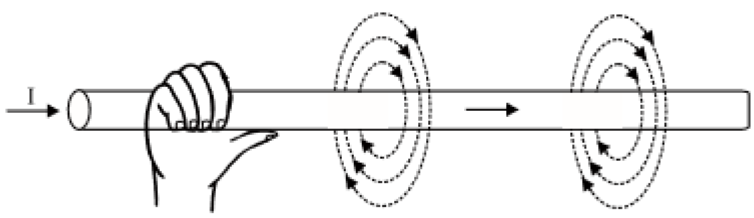
i.e. V=I∗R, where **R is the resistance** of the conductor between the two points considered.

Magnetic Effect of Electric Current

When an electric current flows through a conductor, magnetic field is set up all along the length of the conductor.

Fig. shows the magnetic field produced by the current flowing in a straight wire. The magnetic lines of force are in the form of concentric circles around the conductor. The direction of lines of force depends upon the direction of current and may be determined by right-hand rule.

Hold the conductor in the right-hand with the thumb pointing in the direction of current (See Fig. 7.12). Then the fingers will point in the direction of magnetic field around the conductor.



Applying this rule to Fig., it is clear that when viewed from left-hand side, the direction of magnetic lines of force will be clockwise.

The following points may be noted about the magnetic effect of electric current :
(i) The greater the current through the conductor, the stronger the magnetic field and vice-versa.
(ii) The magnetic field near the conductor is stronger and becomes weaker and weaker as we move away from the conductor.
(iii) The magnetic lines of force around the conductor will be either clockwise or anticlockwise, depending upon the direction of current. One may use right-hand rule to determine the direction of magnetic field around the conductor.
(iv) The shape of the magnetic field depends upon the shape of the conductor.

Cross and Dot convention

They represent the direction of current perpendicular to the two dimensional surface it has been represented upon (board, paper, screen etc.)

Perpendicular to the surface, there can be two possible directions a vector can take.

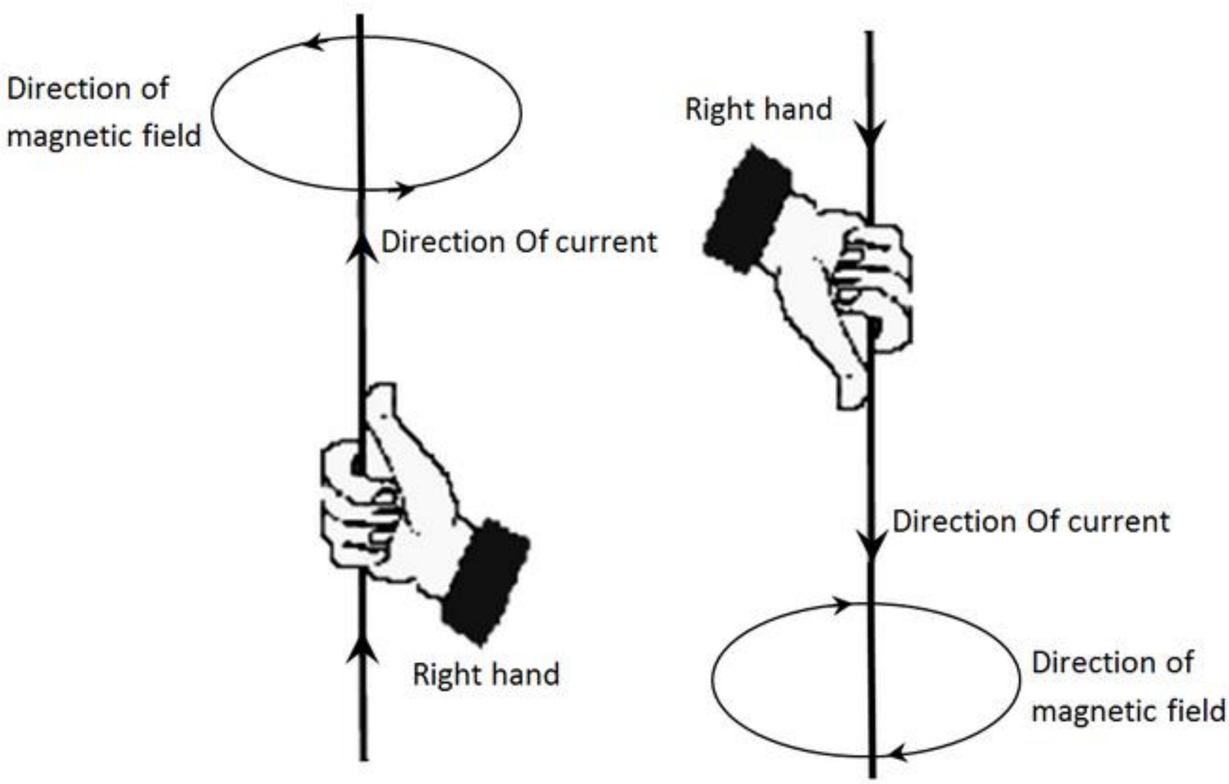
It can either come out of the surface towards the observer and is denoted by the dot (.).

Or it can go away from the observer into the surface, denoted by the cross (x).

Right Hand Thumb Rule

Right hand thumb rule was given by Maxwell. So this rule is also known as Maxwell's right hand thumb rule.

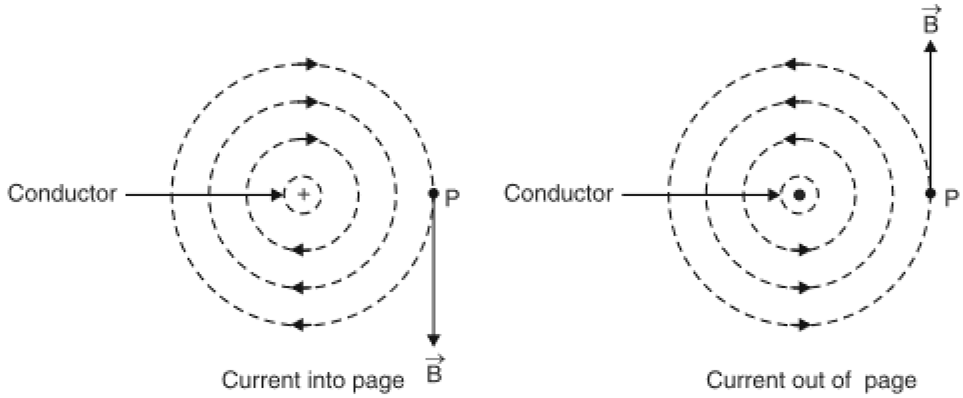
According to this rule, imagine that you are holding a current carrying wire in your right hand so that the thumb points in the direction of the current, then the direction in which the fingers wrap the wire will represent the direction of magnetic lines of force.



Nature of Magnetic Field of a Long Straight Conductor

For a long straight conductor carrying current, the magnetic lines of force are concentric circles with conductor at the centre

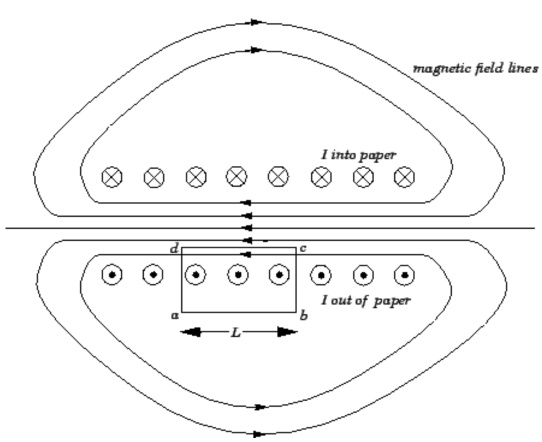
The direction of magnetic lines of force can be found by right-hand grip rule. The direction of **B** at any point is along the tangent to field line at that point as shown in Fig.



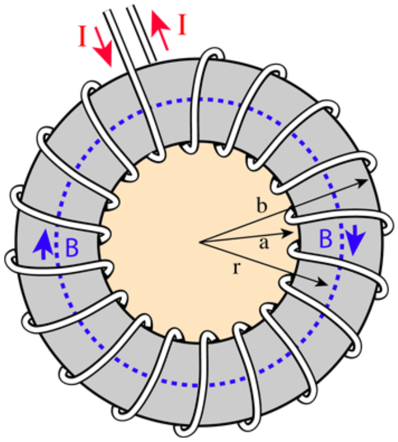
Nature of Magnetic Field of a Solenoid

A solenoid is a tightly wound helical coil of wire whose diameter is small compared to its length. The magnetic field generated in the centre, or core, of a current carrying solenoid is essentially uniform, and is directed along the axis of the solenoid. Outside the solenoid, the magnetic field is far weaker.

The magnetic field in the core of a solenoid is directly proportional to the product of the current flowing around the solenoid and the number of turns per unit length of the solenoid. This, result is exact in the limit in which the length of the solenoid is very much greater than its diameter.



Nature of Magnetic Field of Toroid



Toroid is a solenoid whose ends are connected to each other

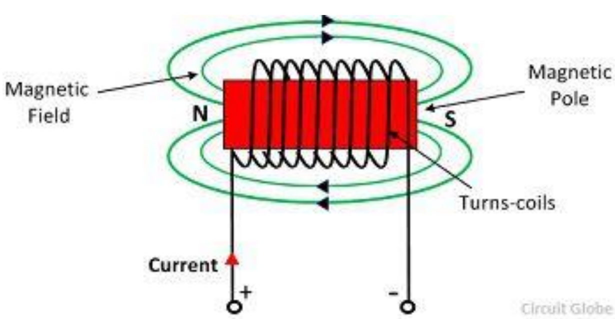
The magnetic field exists only in the tubular area bound by the coil and it does not exist in the area inside and outside the toroid. i.e. B is zero at centre and outside the toroid.

Concept of mmf, flux, flux density, reluctance, permeability and field strength, their units and relationships

MMF:-

It stands for Magnetomotive force (mmf).

The current flowing in an electric circuit is due to the existence of electromotive force similarly **magnetomotive force** (**MMF**) is required to drive the magnetic flux in the magnetic circuit. The magnetic pressure, which sets up the magnetic flux in a magnetic circuit is called **Magnetomotive Force**.



It is denoted by F. F = NI ampere-turns (At),

where N = number of conductors (or turns) and

I = current in amperes. Since 'turns' has no units,

the SI unit of mmf is the ampere(A), but to avoid any possible confusion 'ampere-turns', (A t)

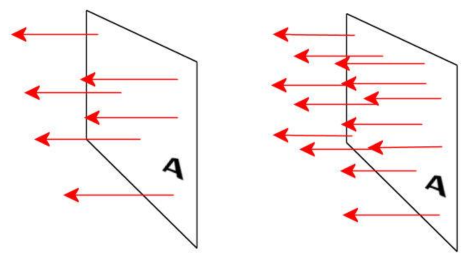
FLUX:-

Flux is defined as the number of field lines passing through a given closed surface.

It gives the measurement of the total field that passes through a given surface area.

It is denoted by Φ.

S.I unit is weber (Wb).



FLUX DENSITY:-

The flux density is the number of magnetic lines of flux that pass through a certain point on a surface.

Flux density is the amount of flux per unit area perpendicular to the field.

The SI unit is T (tesla), which is weber per square metre (Wb/m^2) and the unit in the CGS system is G (gauss).

RELUCTANCE:-

It is defined as the ratio of magnetomotive force to magnetic flux. It represents the opposition to magnetic flux, and depends on the geometry and composition of an object.

$$R = F/\Phi$$

where,

R is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry
F is the magnetomotive force (MMF) in ampere-turns
Φ is the magnetic flux in webers
S.I unit is henry.

PERMEABILITY:-

The magnetic permeability is defined as the property of the material to allow the magnetic line of force to pass through it.

The magnetic permeability of the material is directly proportional to the number of lines passing through it.

It is denoted by μ.

SI unit is Henry per meter (H/M). The permeability of the air or vacuum is represented by μ_0 which is equal to $4\pi\times17^{-7}$ H/m.

It is expressed by the formula shown below.

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

Where, B – magnetic flux density
H – magnetic field intensity

SI unit is Henry per meter (H/M or Hm^2) or newton per ampere square ($N\text{-}A^2$).

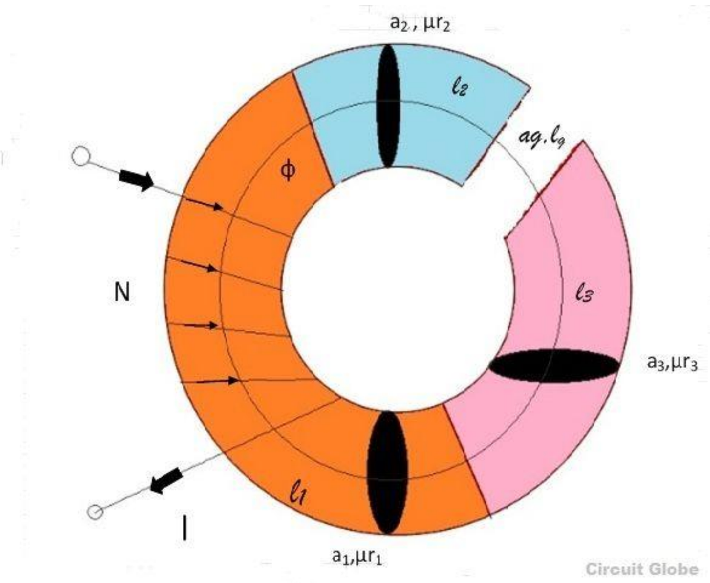
FIELD STRENGTH:-

Field strength means the magnitude of a vector-valued field (e.g., in volts per meter, V/m, for an electric field E).

For example, an electromagnetic field results in both electric field strength and magnetic field strength. Field strength corresponds to the density of the field lines.

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, sets up in the core of the coil.

a_1, a_2, a_3 are the cross-sectional area of the solenoid.

l_1, l_2, l_3 are the length of the three different coils having different dimension joined together in series.

μr_1, μr_2, μr_3 are the relative permeability of the material of the circular coil.

a_g 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

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

Putting the valve of B in the equation (2) we obtain the following equation for the total MMF

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

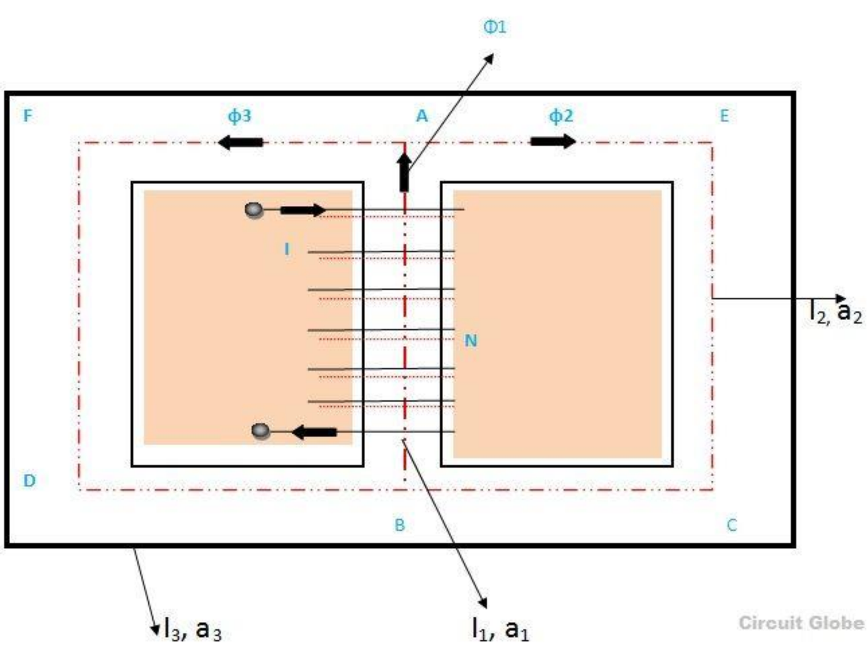
$(\text{As } H = B/\mu_0\mu_r)$

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

Parallel Magnetic Circuit

A magnetic circuit having two or more than two paths for the magnetic flux is called a parallel magnetic circuit.

The parallel magnetic circuit contains.different dimensional areas and materials having various numbers of paths.



The above figure shows parallel magnetic circuit.

In this circuit, a current carrying coil is wound on the central limb AB. This coil sets up the magnetic flux φ_1 in the central limb of the circuit. The flux φ_1 which is in the upward direction is further divided into two paths namely ADCB and AFEB. The path ADCB carries flux φ_2, and the path AFEB carries flux φ_3. It is clearly seen from the above circuit that

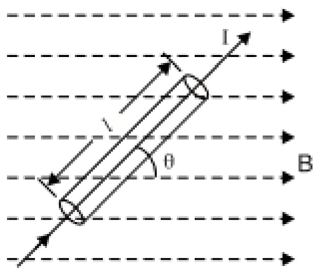
$\varphi_1 = \varphi_2 + \varphi_3$

Comparison Between Electric and Magnetic Circuit

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.
$R = \rho.\ l/a$. 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 $\mu = \mu_0\mu_r$. 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.

Force acting on a current carrying conductor placed in a magnetic field

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



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Consider a straight current-carrying conductor placed in a uniform magnetic field as shown in Fig.

Let,

B = magnetic flux density in Wb/(m^2)
I = current through the conductor in amperes
l = effective length of the conductor in metres i.e. the length of the conductor lying in the magnetic field
θ = angle which the conductor makes with the direction of the magnetic field.

It has been found experimentally that the magnitude of force (F) acting on the conductor is directly proportional to the magnitudes of flux density (B), current (I), length (l) and sin θ i.e.,

$$F \propto BIl \sin\theta \text{ newtons}$$

$$\Rightarrow F = k\, BIl \sin\theta$$

where,
k is a constant of proportionality.

Now SI unit of B is so defined that value of k becomes unity.

$\therefore F = BIl \sin\theta$

By experiment, it is found that the direction of the force is always perpendicular to the plane containing the conductor and the magnetic field. Both magnitude and direction of the force will be given by the following vector equation :

Special Cases.

$F = BIl \sin \theta$

(i) When $\theta = 0°$ or $180°$; $\sin \theta = 0$

$F = BIl \times 0 = 0$

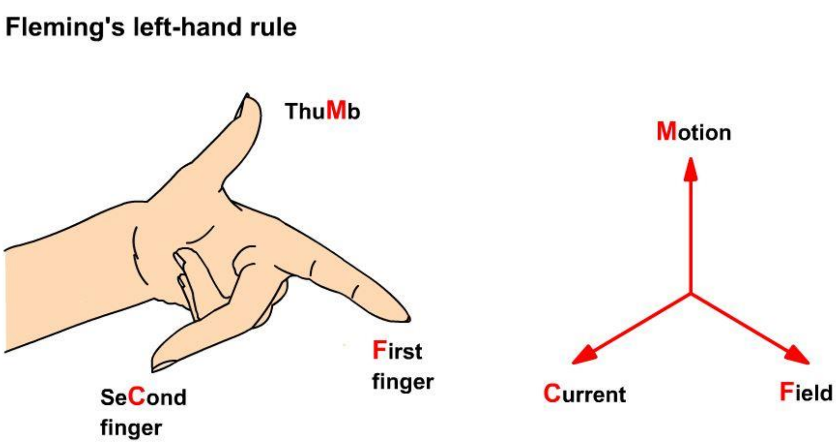
Therefore, if a current-carrying conductor is placed parallel to the direction of magnetic field, the conductor will experience no force.

(ii) When $\theta = 90°$; $\sin \theta = 1$

$F = BIl$ ...maximum value

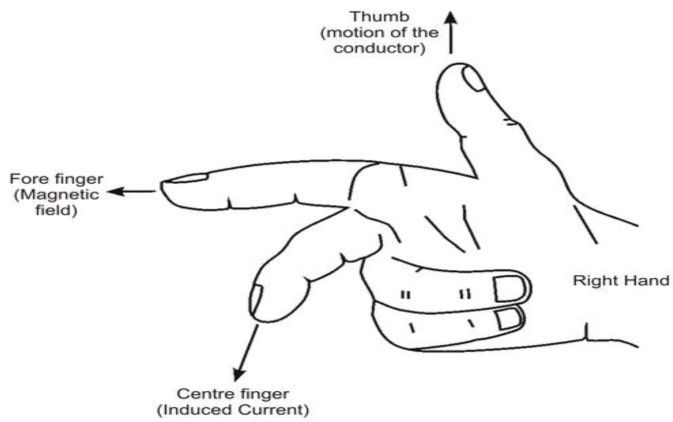
Therefore, a current-carrying conductor will experience a maximum force when it is placed at right angles to the direction of the magnetic field.

Fleming's left hand rule, Fleming's right hand rule



Fleming's left-hand rule is used for electric motors.

Fleming's left hand rule states that if the thumb, forefinger and the middle finger are stretched mutually perpendicular to each other then the thumb represents the direction of force, the forefinger represents the the direction of magnetic field and the middle finger represents the motion or direction of the induced current.



Fleming's Right-hand Rule (for generators)

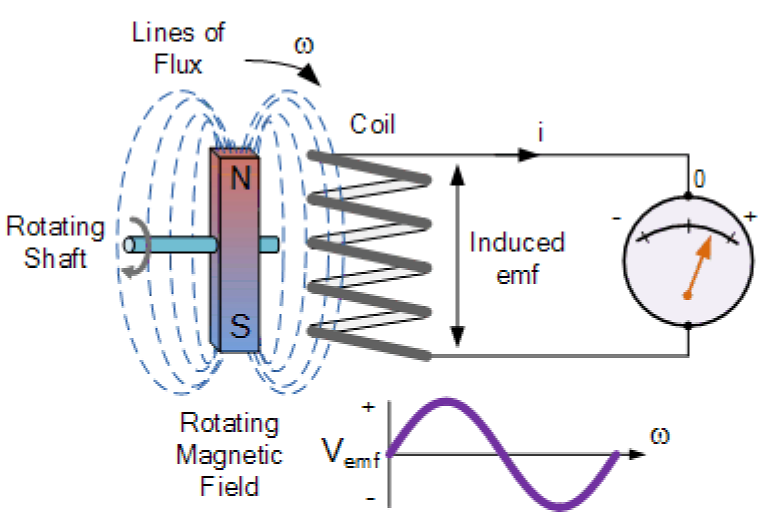
It shows the direction of induced current when a conductor attached to a circuit moves in a magnetic field. It can be used to determine the direction of current in a generator's windings.

The thumb is pointed in the direction of the motion of the conductor relative to the magnetic field.

The first finger is pointed in the direction of the magnetic field. (north to south)

Then the second finger represents the direction of the induced or generated current within the conductor

Faradays Laws of Electromagnetic Induction



FARADAY'S FIRST LAW OF ELECTROMAGNETIC INDUCTION:-

When a conductor links with a changing magnetic flux there is a voltage induced in it.

FARADAY'S SECOND LAW OF ELECTROMAGNETIC INDUCTION:-

Magnitude of induced emf in a conductor is directly proportional to the rate of change of flux linkage with respect to time.

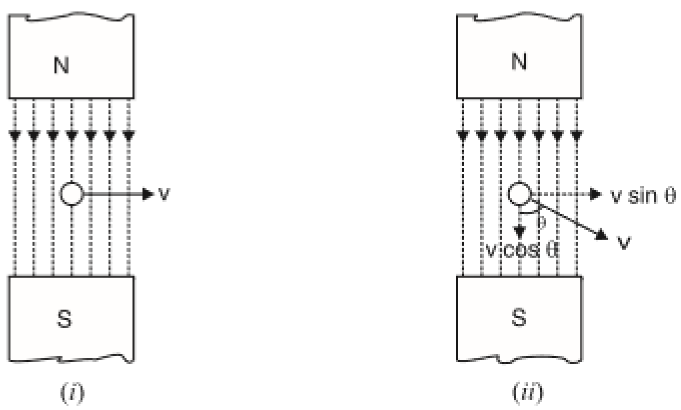
Rate of change of flux linkage with respect to time increases induced voltage increases.

Statically and Dynamically induced e.m.f

Dynamically induced EMF

In dynamically induced emf the magnetic field system is kept stationary, and the conductor is moving, or the magnetic field system is moving, and the conductor is stationary thus by following either of the two process the conductor cuts across the magnetic field and the emf is induced in the coil.

This phenomenon takes place in electric generators and back emf of motors and also in transformers.



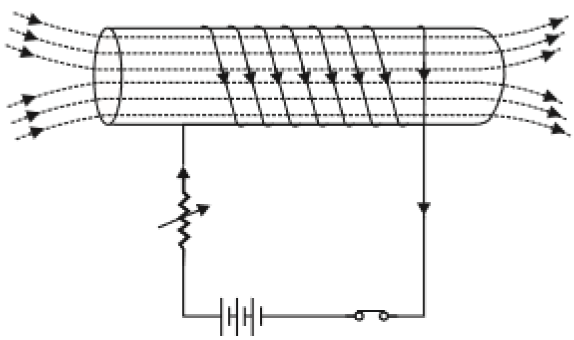
Statically Induced Emf

This type of EMF is generated by keeping the coil and the magnetic field system, both of them stationary at the same time; that means the change in flux linking with the coil takes place without either moving the conductor (coil) or the field system.

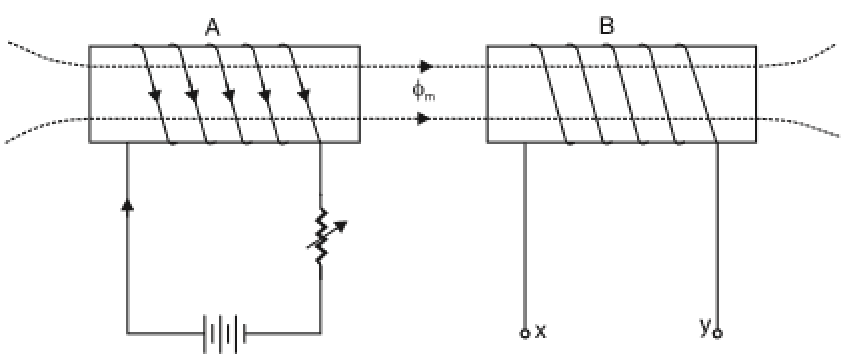
This change of flux produced by the field system linking with the coil is obtained by changing the electric current in the field system.

It is further divided in two ways:-

(1-> Self-induced emf (emf which is induced in the coil due to the change of flux produced by it linking with its own turns.)



(2-> Mutually induced emf (emf which is induced in the coil due to the change of flux produced by another coil, linking with it.)



self and mutual 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. Self-inductance does not prevent the current from changing, it serves only to delay the change.

The magnitude of self-induced e.m.f. is

e=L(dI/dt).

However, the magnitude and direction of self-induced e.m.f should be written as :

e = – L(dI/dt).

The minus sign is because the self
induced e.m.f. tends to send current in the coil in such a direction so as to
produce magnetic flux which opposes the change in flux produced by the ch ange in current in the coil. In fact, minus sign represents Lenz’s law mat hematically.

Mutual-inductance(M):-

Two coils placed near each other, the first coil will make turns and carry the current which results in the magnetic field. As both the coils nearly close to each other, the magnetic field through one coil will all pass through the other coil. So one coil causes the change in magnetic flux because of which current is induced in the other coil.This type of induction mainly depends upon the number of turns, size, and shape of the coil and medium between the two coils. The magnitude and direction of mutual-induced e.m.f should be written as :

eM = M (dI/dt)

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.

When the entire flux of one coil links the other, coefficient of coupling is 1 (i.e., 100%).

If only half the flux set up in one coil links the other, then coefficient of coupling is 0·5 (or 50%).

If two coils have self-inductances L1 annd L2, then mutual inductance M between them is given by ;

$$M = k\sqrt{L_1 L_2}$$

where k = coefficient of coupling.

Clearly, the mutual inductance M between the coils will be maximum when k=1.

If flux of one coil does not at all link with the other coil, then k = 0.

Under such condition, mutual inductance (M) between the coils will be zero.

Proof. Consider two magnetically coupled coils 1 and 2 having N1 and N2 turns respectively (See Fig. 9.14). The current I1 flowing in coil 1 produces a magnetic flux φ1. Suppose the coefficient of coupling between the two coils is k. It means that flux kφ1 links with coil 2. Then, by definition,

$$L_1 = \frac{N_1\phi_1}{I_1}$$

and $$M_{12} = \frac{k\phi_1 N_2}{I_1}$$

where M12 represents mutual inductance of coil 1 to coil 2.
The current I2 flowing in coil 2 will produce flux φ2. Since the coefficient of coupling between the coils is k, it means that flux kφ2 will link with coil 1. Then,

$$L_2 = \frac{\phi_2 N_2}{I_2}$$

and $$M_{21} = \frac{k\phi_2 N_1}{I_2} \qquad ...(ii)$$

where
M21 represents mutual inductance of coil 2 to coil 1. Mutual inductance between the two coils is exactly the same i.e., M12 = M21 = M.

$$M_{12} \times M_{21} = \frac{(k\phi_1 N_2)}{I_1} \times \frac{(k\phi_2 N_1)}{I_2}$$

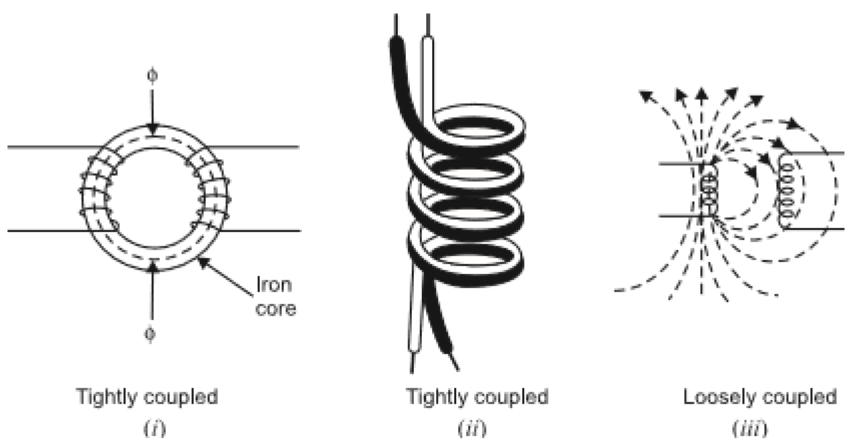
$$M^2 = k^2 \frac{\phi_1 N_1}{I_1} \times \frac{\phi_2 N_2}{I_2} = k^2 L_1 L_2$$

$$M = k\sqrt{L_1 L_2} \quad \text{...(iii)}$$

Expression (iii) gives the relation between the mutual inductance of the two coils and their self inductances. The reader may note that mutual inductance between the two coils will be maximum when k = 1. Obviously, the maximum value of mutual inductance between the two coils is $\sqrt{L_1 L_2}$.

$$\therefore \quad k = \frac{M}{\sqrt{L_1 L_2}} = \frac{\text{Actual mutual inductance}}{\text{Max. possible mutual inductance}}$$

Hence, coefficient of coupling can also be defined as the ratio of the actual mutual inductance (M) between the two coils to the maximum possible value is $\sqrt{L_1 L_2}$. When two coils are wound on a single ferromagnetic core as shown in Fig. (i), effectively all of the magnetic flux produced by one coil links with the other. The coils are then said to be tightly coupled. Another way to ensure tight coupling is shown in Fig. (ii) where each turn of the secondary winding is side by side with one turn of primary winding. Coils wound in this fashion are said to be bifilar and it is called bifilar winding.



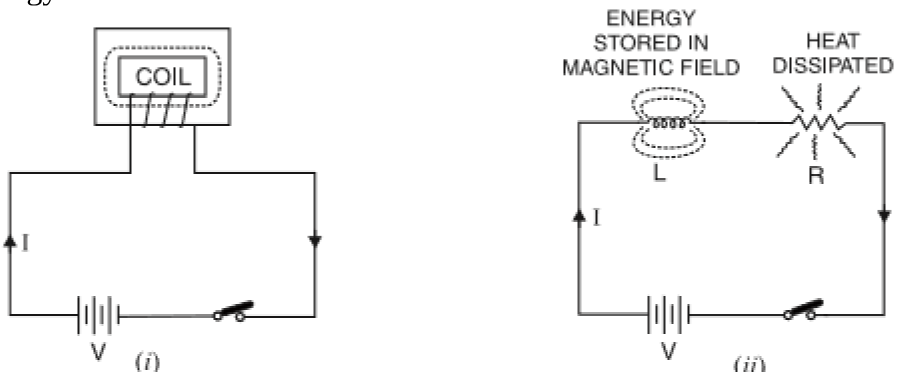
When the two coils are air-cored as shown in Fig. 9.15 (iii), then only a fraction of magnetic flux produced by one coil may link with the other coil. The coils are then said to be loosely coupled.

Energy stored in magnetic field.

Consider an inductor connected to a d.c. source as shown in Fig. (i)
The inductor is equivalent to inductance L in series with a small resistanc R as shown in Fig. 9.26 (ii).
The energy supplied to the circuit is spent in two ways :

(i) A part of supplied energy is spent to meet I2R losses and cannot be recovered.

(ii) The remaining part is spent to create flux around the coil (or inductor) and is stored in the magnetic field. When the field collapses, the stored energy is returned to the circuit.



Mathematical Expression. Suppose at any instant the current in the coil is i and is increasing at the rate of di/dt. The e.m.f. e across L is given by ;

$$e = L\frac{di}{dt}$$

$\therefore$ Instantaneous power, $p = ei = Li\frac{di}{dt}$

During a short interval of time dt, the energy dw put into the magnetic field is equal to power multiplied by time *i.e.*

$$dw = p.dt = \left(Li\frac{di}{dt}\right)dt = Li\,di$$

The total energy put into the magnetic field from the time current is zero until it has attained the final steady value I is given by ;

$$W = \int_0^I Li\,di = \frac{1}{2}LI^2$$

$\therefore$ Energy stored in magnetic field, $E = \frac{1}{2}LI^2$ joules

It is clear that energy stored in an inductor depends upon inductance and current through the inductor. For a given inductor, the amount of energy st ored is determined by the maximum current through the inductor. Note that energy stored will be in joules if inductance (L) and current (I) are in henry and amperes respectively.