[Unit-1]

Electromagnetism

Law of magnetisum [coloumb's law] / Law of Magnetic force :-

(i) When two isolated poles are placed near each other. They experience a force.

(ii) The force between two magnetic poles is directly proportional to the product of their poles in directly & inversely proportional to square of distance between their centers.

$\Rightarrow F \propto \frac{m_1 m_2}{d^2}$

$\Rightarrow F = K \frac{m_1 m_2}{d^2}$

$\Rightarrow$ Where, $K = \frac{\mu_0}{4\pi}$; $\mu_0 = 4\pi \times 10^{-7} H/m$

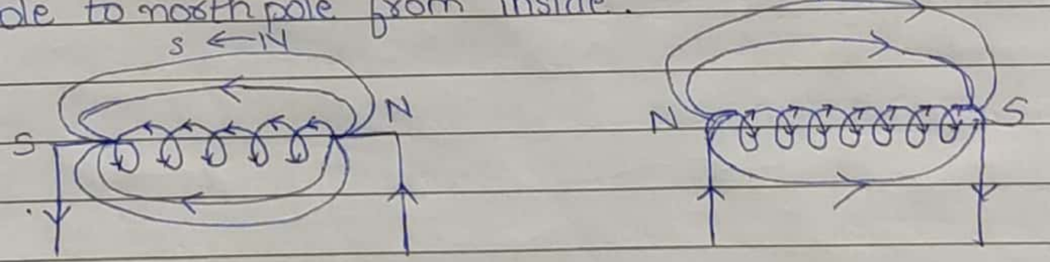
; μ_r = Relative permeability depends on material / media.

Magnetic Field lines:-

Magnetic field lines are imaginary lines drawn in region of "space-time" along which a "Free north pole" would move, if allowed.

Properties of Magnetic Field lines:-

(1) Magnetic field lines forms closed loop. It moves from north pole to south pole outside the magnet & moves from south pole to north pole from inside.



(2) No two magnetic lines of force intersect each other. If two magnetic lines of force intersect, there would be two direction of magnetic field lines at that points, which is not possible

~~(2)~~ (3) Pole Strength:-
Where the magnetic lines of force are close together, the magnetic field is strong & where they are well spaced out, the field is weak at that point.
(4) Magnetic lines of force contract longitudeinally and widen laterally.
~~(5)~~ (a) Contract longitudinally like a streched elastic string producing attraction between opposite charges.
(b) Repel each other laterally resulting in repulsion between similar charges and edge effect.
~~(c)~~ (5) Magnetic lines of force are always ready to pass through magnetic material like iron, in ~~per~~ preference to pass through non-magnetic like air.
(or)
Magnetic lines of force always prefer a path offering least opposition i.e low reluctance path.

* General Terms Related with Magnetism:-
(i) Magnetic flux (Ø):-
The total number of magnetic lines of force produced by a magnetic source called magnetic flux. Denoted by Ø (phi)
$\Rightarrow \phi = $ mWb
$\Rightarrow 1 Wb = 10^8$ lines of force.

(ii) Magnetic flux density (B):-
The magnetic flux passing normally per unit area.
$\Rightarrow B = \frac{\phi}{A}$; $\phi \longrightarrow$ flux in Wb
; $A \longrightarrow$ Area in m^3 normal to flux.
$\Rightarrow$ S.I unit is Wb/m^2

(a) when plane is perpendicular to the flux, then,
$\Rightarrow \phi = BA$ Wb

(b) When plane of coil is inclined at an angle θ to the flux direction
$\phi = BA\sin\theta$ Wb

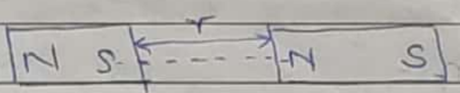
(c) when plane is parallel to flux direction $\theta = 0°$, then,
$\phi = BA\sin 0° = 0$

(iii) Magnetic Intensity (or) Magnetizing Force (or) Magnetic field Strength (H) :-

Magnetic intensity (or field strength) at a point in a magnetic field is the force acting on a unit N-pole (ie. N-pole of 1 Wb) placed at that point.

$$B = \frac{m \mu_0}{4\pi \times r^2} \text{ N/Wb (or A/m)}$$

$m \rightarrow$ pole strength
$r \rightarrow$ Distance
$\mu_0 \rightarrow 4\pi \times 10^{-7}$

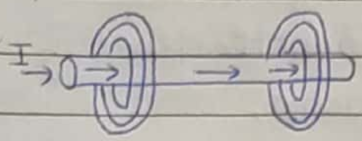


Magnetic effect of current :-

(1) When an electric current flows through a conductor, magnetic field is set-up all along the length of the conductor.
(2) The Magnetic lines of line of force are in the form of concentric circle around the conductor.
(3) Greater the current through the conductor, the stronger the magnetic field and vice-versa.
(4) The magnetic field near the conductor is stronger & becomes weaker & weaker as we move away from the conductor.
(5) The magnetic lines of force around the conductor will be either clockwise & Anti-clockwise depending upon the direction of current. Direction of Magnetic field may be formed by using right hand thumb rule.
(6) The slope of magnetic field depends upon the shape of the conductor.

(*) Right hand thumb rule:-

(i) The direction of lines of force depends upon the direction of current.



(ii) Using right hand thumb rule direction of lines of force can be determined.

(iii) Hold the conductor in the right-hand with the thumb pointing in the direction of current.

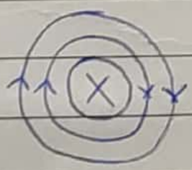
(iv) Then fingers will point in the direction of magnetic field around conductor.

(*) Cross & Dot conventions:-

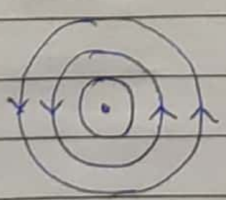
(i) When an electric current flows through a conductor, the magnetic field is set-up in conductor.

(ii) The direction of current and Magnetic field lines are shown by cross (⊗) & Dot (⊙) conventions.

(iii) The conductor is carrying current into the plane of paper, represented by a cross inside the cross-section of the conductor & that direction of magnetic lines of force will be clockwise.



(iv) The conductor carrying current out of the plane of paper, represented by a ~~dot~~ dot inside the cross-section of the conductor & the direction of magnetic lines of force will be anti-clockwise.



* Nature of Magnetic Field in straight conductor, solenoid & Toroid :-

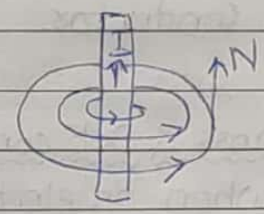
(i) Straight conductor:-

If a straight conductor is carrying current, the magnetic lines of force will be in concentric circles around the conductor.

(ii) Let the conductor carry 'I' current in upward direction. The magnetic field consist of circular lines of force in the clockwise direction. If current "I" is moving in downward direction, then the magnetic field lies of force are in anti-clockwise from the conductor.

let $r \rightarrow$ distance from the conductor

$H \rightarrow$ Field strength.



Now, using Ampere circuital law,

Total work done around conductor = Ampere current

$\Rightarrow$ m.m.f = force $\times$ distance = I $\Rightarrow H \times l = I$

$\Rightarrow H \times 2\pi r = I$ $\qquad l = 2\pi r$

$\Rightarrow H = \dfrac{I}{2\pi r}$

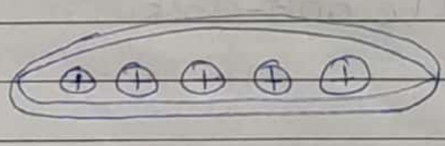
$\Rightarrow \therefore B = \mu_0 H$

$\Rightarrow B = \dfrac{\mu_0 I}{2\pi r}$ ---- in air

$\Rightarrow B = \dfrac{\mu_0 I \mu_r}{2\pi r}$ ---- in medium

(1) For single conductor, $B = \dfrac{\mu_0 I}{2\pi r}$

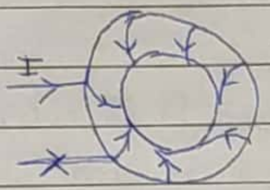
(2) For N number of conductor, $B = \dfrac{N \mu_0 I}{2\pi r}$

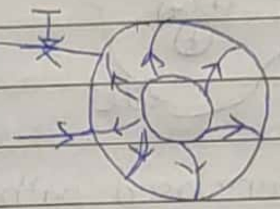


Toroid:-

It is a coil of insulated or enameled wire moved on a donut-shaped form/circular ring made of powdered iron.

(1) In toroid, corresponding to the direction of current, the flux set in the core is either anti-clockwise (or) clockwise.





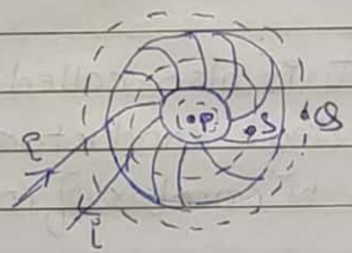
(2) In toriod all the magnetic flux is contained in the core material, because of the core has no ends forces which flux might leak off.

(3) This type of confinement of the flux present external magnetic field from effecting the behaviour of the toroid also prevents the magnetic field in the toroid from affecting other components is a circuits.

Magnetic field at point p (~~out~~inside) $\cdot B_p = 0$

Magnetic field at point ~~p~~Q (outside) $B_Q = 0$

Magnetic field at point 's'



$\Rightarrow Hl = NI$

$\Rightarrow H = \frac{NI}{l} = \frac{NI}{2\pi r}$

$\Rightarrow B = \mu_0 H = \frac{\mu_0 NI}{2\pi r}$ —— in air

$\Rightarrow B = \frac{\mu_0 \mu_r NI}{2\pi r}$ —— in medium.

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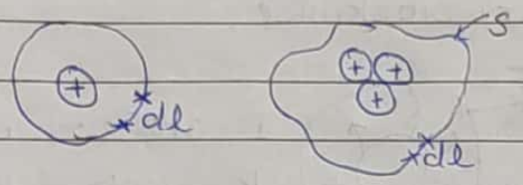
(*) Ampere's Work law (or) Ampere's Circuital law:-

The work done on (or) by a unit N-pole in moving once, around any complete path is equal to the current enclosed by the path.
(for particular $\oint \vec{H} \cdot d\vec{l} = I$ ampere's section)



for Total length of enclosed path
$\Rightarrow H \cdot l = I$
$\Rightarrow H = \frac{I}{l} = \frac{I}{2\pi r}$ - - - - - - - $[L = 2\pi r]$

(1) For single conductor $H = I/2\pi r$

(2) For N number of conductor $H = NI/2\pi r$

Here, I is also called as magneto motive force (m.m.f)
(1) for single conductor m.m.f = I
(2) for N number of conductor m.m.f = NI

(*) Magnetizing force [H] / Magnetic field strength produced by electric current:-

Magnetising Force [H] produced by an electric current is defined as the m.m.f set-up per unit length of the magnetic circuit.

Magnetising force $\Rightarrow H = \frac{NI}{l}$ AT/m

NI → m.m.f
l → length of magnetic circuit.

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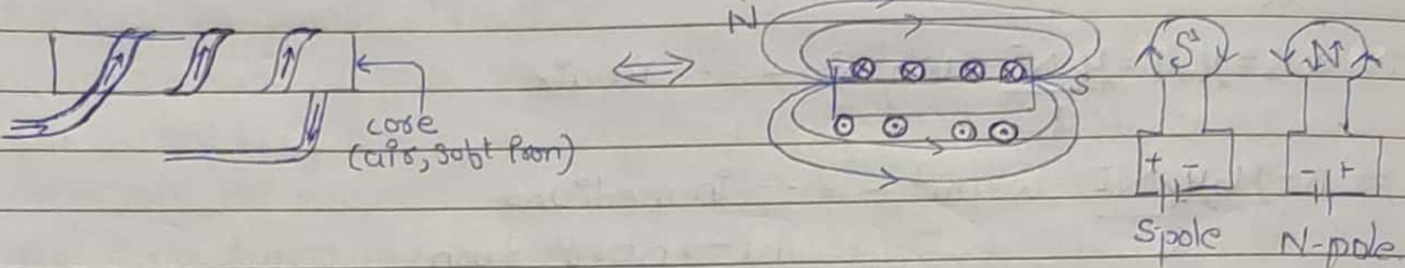
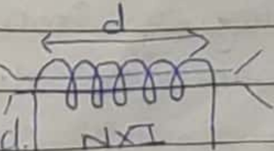
Solenoid:-



(i) A coil of several turns wound on hollow tube (or) iron bar, such arrangement is called solenoid.
(ii) The axial length of conductor is greater the diameter of core/turns
(iii) The part (or) element around which the conductor is wound is called core. Core may be air, steel (or) any other magnetic material.
(iv) When current pass through such conductor, then ~~it~~ it produces magnetic field, which act through the coil along the axis & around the solenoid & remains constant in axis.
(v) The strength of magnetic field produced by a current carrying solenoid depends on:-
(1) No. of turns → large the current, greater th magnetism.
(2) Strength of current → longer the current, greater is magnetism
(3) Nature of core used in solenoid → soft iron is an core for the solenoid produces strongest magnetism.

Let the magnetic field strength along ~~axis~~ air is 'H'
(1) ~~H~~ outside of solenoid is negligible
(2) H at inside the solenoid is uniform.
Let free worth pole is move around the magnetic lines of force of solenoid.
By using Ampere circuital law
⇒ Total work done around closed path = Amperes turns linked. $N \times I$



∴ There is negligible field strength (H) at outside ~~of~~ & the work done only in travelling length l within solenoid.

$\Rightarrow \therefore H \times l = NI$

$\Rightarrow H = \frac{NI}{l}$ AT/m (or) A/m

$\therefore \Rightarrow B = \mu_0 H = \frac{\mu_0 NI}{l}$ wb/m² ---- in air

$\Rightarrow B = \frac{\mu_0 \mu_r NI}{l}$ wb/m² ---- in medium

$N \rightarrow$ no. of turns

$l \rightarrow$ length of solenoid.

* Magnetic field strength in straight, coil & solenoid :-

(i) In straight conductor :-

$\Rightarrow H = \frac{I}{2\pi d}$ A/m

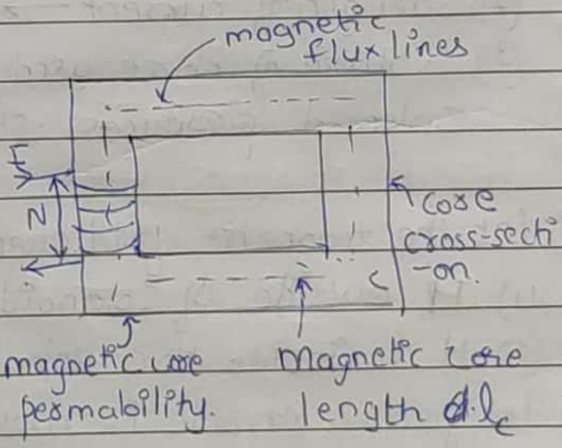
(ii) In coil :- $H = \frac{NI}{2\pi d}$

(iii) In long solenoid :- $H = \frac{NI}{l}$

* Magnetic Circuits *

(1) The closed path followed by magnetic flux is called magnetic circuit.

(2) In magnetic circuit, the magnetic flux leaves the N-pole, passes through entire circuit & ~~returns~~ returns to the starting point.



(3) A magnetic circuit usually consists of material having high permability eg:- iron, soft steel, etc.

(4) Usual way of producing flux consist of material having a passing electric current passing through a wire having no. of turns a wound over a magnetic material.

(5) When current "I" is passed through the coil, magnetic flux ϕ is set up in the core & the flux follows the closed path ABCD. Hence ABCD is magnetic circuit.

(6) The amount of flux set-up in the core depends upon the current (I) & number of turns (N), if the current (or) no. of turns increases the magnetic flux also increases & product of no. of the turns (N) & current (I) is also called magnetomotive force (mmf)

$$m.m.f = N \times I \text{ Ampere-turns (A-I)}$$

General terms related with magnetic circuits:-

(1) Permeance:-

It is a measure of the ease with which flux can pass through the material.

$$\Rightarrow \text{Permeanace} = \frac{a \mu_0 \mu_r}{l}$$

$\Rightarrow$ Unit $\rightarrow$ Wb/AT (or) Henery.

(2) Permability:-

Ability or ease with which the magnetic material forces the magnetic flux through a given medium.

For any material there are two permability.

(i) Absolute permability (μ)

(ii) Relative permability (μ_r)

(i) Absolute permability (μ_0):- The magnetic flux density in a a medium to the magnetic field strength which produces that flux density

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

B $\rightarrow$ Flux density

H $\rightarrow$ Field strength

Unit :- Heneries per meter (H/m)

(ii) ~~Permability in free space :- (μ_0) :-~~

(ii) Relative permability :-

The ratio of flux density produced in that material to the flux density produced in vaccume

$$\mu_r = \frac{B}{B_0} = \frac{\mu \cancel{H}}{\mu_0 \cancel{H}} = \frac{\mu}{\mu_0} \quad \therefore \mu_r = \frac{\mu}{\mu_0}$$

This is a unit less quantity

(3) Reluctance :- It is reciprocal of permeance & is a measure that oposition that the magnetic circuit offers to the magnetic flux

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

$\Rightarrow$ Unit :- AT/Wb

(4) Magnetomotive force :- The work done in moving a magnetic pole once assumed the magnetic circuit is called the m.m.f It is equal to the product of current & no. of turns of the coil.

m.m.f = NI ampere-turns (or) AT

(or)

The driving force required for the magnetic flux to be transfer in magnetic circuits

(*) Relations of m.m.f :-

(i) m.mf = ϕS

(ii) m.m.f = Hl

(iii) m.m.f = NI

(1) $\Rightarrow \boxed{m.m.f = \phi S}$ $\left[\because S = \frac{l}{a\mu_0\mu_r}\right]$

$\Rightarrow \quad = \frac{\phi l}{a\mu_0\mu_r}$

$= \frac{Bd}{\mu_0\mu_r}$ $\left[B = \frac{\phi}{a}\right]$

$= \frac{Bl}{\mu}$ $[\mu = \mu_0\mu_r]$

(2) $\boxed{m.m.f = Hl}$ $[H = B/\mu]$

(3) $m.m.f = \frac{NI}{l} \times l$ $\left[\because H = \frac{NI}{l}\right]$

$\Rightarrow \boxed{m.m.f = NI}$

(5) Ampere's turns:-

Magnetomotive force required for magnetization using a coil in terms of the product of the no. of coil turns & the current in amperes flowing through the coil.

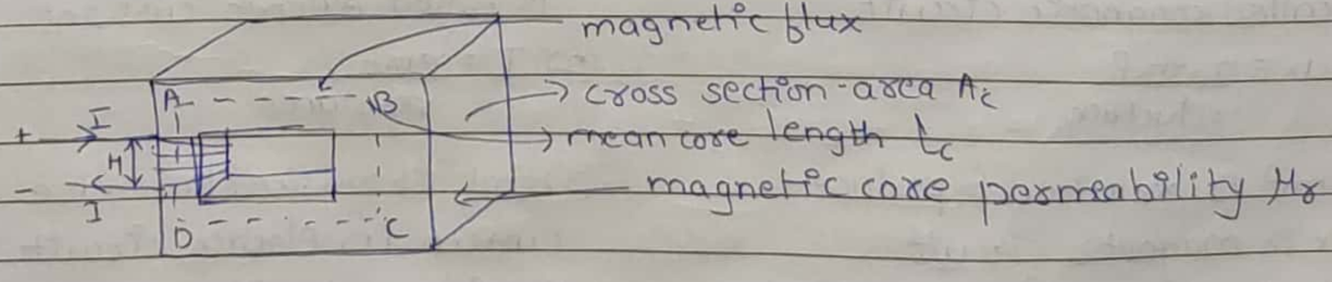
$\Rightarrow A.T = NI \Rightarrow A.T = m.m.f$

(or)

$\Rightarrow A.T = Hl$ $[\because m.m.f = Hl]$

$\Rightarrow$ A.T. required ~~for reg~~ in part = Field strength 'H' in that part $\times$ length of that part of magnetic circuit.

* Analysis of Magnetic circuit:-



ABCD → length of magnetic circuit = l

Cross-section area of core = $a\,m^2$

Relative permeability = μ_r

Flux density in material $B = \frac{\phi}{a}$ wb/m^2

Magnetising force in the material; $H = \frac{B}{\mu_0 \mu_r} = \frac{\phi}{a \mu_r \mu_0}$ AT/m

According to ampere circuital law (or) work law,
The work done in moving north pole around the magnetic circuit (ABCD) is equal to ampere turns ended by the magnetic circuit

$\Rightarrow H \times l = NI$

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

$\Rightarrow \phi = \frac{NI}{l / a \mu_0 \mu_r}$; where $N \times I \longrightarrow$ m.m.f

$\frac{l}{a \mu_0 \mu_r} \longrightarrow$ reluctance.

$\therefore$ Flux (ϕ) = $\frac{\text{m.m.f}}{\text{reluctance}}$ (ohm's law of magnetic circuit)

-: Similarities:-

Magnetic circuit.	Electric circuit
(1) Closed path for magnetic flux is called magnetic circuit.	(1) closed path for electric current is called electric current
(2) Flux = $\frac{\text{m.m.f}}{\text{reluctance}}$.	(2) $I = \frac{\text{emf}}{\text{resistance}}$
(3) m.m.f is required to produce flux in magnetic circuit	(3) Emf is required to cause current in electric circuit
(4) reluctance $S = \frac{l}{a \mu_0 \mu_r}$ (AT/wb)	(4) Resistance $R = \frac{\rho l}{a}$ (Ω)
(5) Flux density ; $B = \frac{\phi}{a}$ Wb/m^2	(5) ~~I~~ $J = I/a$ A/m^2
(6) mmf drop = ϕS (AT	(6) Voltage drop = IR (V)

(7) Magnetic intensity $H = \frac{NI}{l}$ | (7) Electric intensity $E = \frac{V}{d}$

(8) Permeance $= \frac{1}{S} = \frac{a \mu_0 \mu_r}{l}$ | (8) Conductance, $C = \frac{1}{R}$

(9) ~~Circu~~ Magnetic flux flow in circuit. | (9) Current flow in circuit.

Dis-similarities

Magnetic circuit	Electric circuit
1) Flux does not flow. It establish in a magnetic circuit.	1) Current flow in electric circuit
2) There does not exists magnetic insulator flux even in air	2) There are no. of electric insulators. Air is a very good insulator & current cannot pass through it.
3) Reluctance of a magnetic circuit depends on flux & changes with flux	3) Resistance of electric circuit is constant & is independent of the current as long as temperature is constant.
(4) Energy is required to create the magnetic flux but not required to maintain it.	(4) Energy must be supplied to maintain the flow of current.
(5) A magnetic circuit stores energy in its field	(5) An electric circuit dissipates its energy as heat.

Types of Magnetic Circuits :-

1) Series Magnetic circuit
2) Parallel Magnetic circuit.

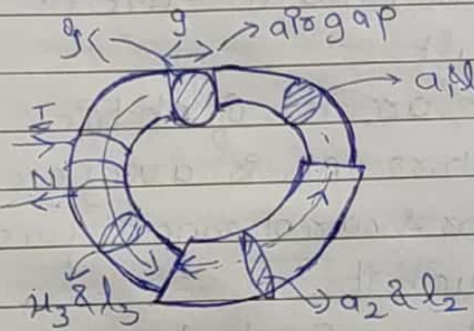
(1) Series magnetic circuits :-

(i) In a series magnetic circuit, the same flux ϕ flows through each part of the circuit like a series electric circuit which carries the same current throughout.

(ii) Let series magnetic circuit consist of three different magnetic material.

μ_{r_1}, μ_{r_2} & μ_{r_3} & $\mu_g \rightarrow$ Relative permeability along with air gap.

S_1, S_2, S_3 & $S_g \longrightarrow$ Reluctance along with air gap.



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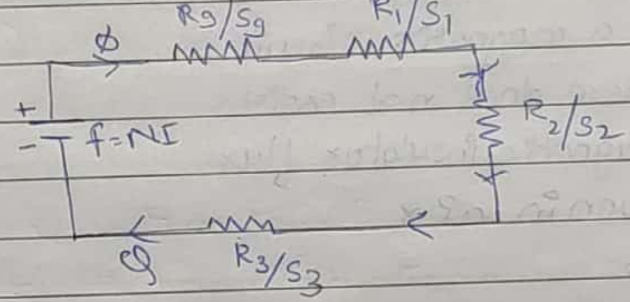


So total reluctance will be

$\Rightarrow S_T = S_1 + S_2 + S_3 + S_g$

$\Rightarrow S_T = \frac{l_1}{\mu_0 \mu_{r_1} a_1} + \frac{l_2}{\mu_0 \mu_{r_2} a_2} + \frac{l_3}{\mu_0 \mu_{r_3} a_3} + \frac{l_g}{\mu_0 a_g}$ $\quad \left[\therefore S = \frac{l}{\mu_0 \mu_r a} \right]$

$\Rightarrow$ flux $\phi = \frac{m.m.f}{S} \Rightarrow \phi = \frac{NI}{S} \Rightarrow NI = \phi S$

For complete magnetic circuit.

Total mmf/NI $= \phi S_T$

$= \phi(S_i) + \phi(S_g)$

$= \phi[S_1 + S_2 + S_3] + \phi S_g$

$= \phi\left[\frac{l_1}{\mu_0 \mu_{r_1} a_1} + \frac{l_2}{\mu_0 \mu_{r_2} a_2} + \frac{l_3}{\mu_0 \mu_{r_3} a_3}\right] + \phi\left[\frac{l_g}{\mu_g a_g}\right]$

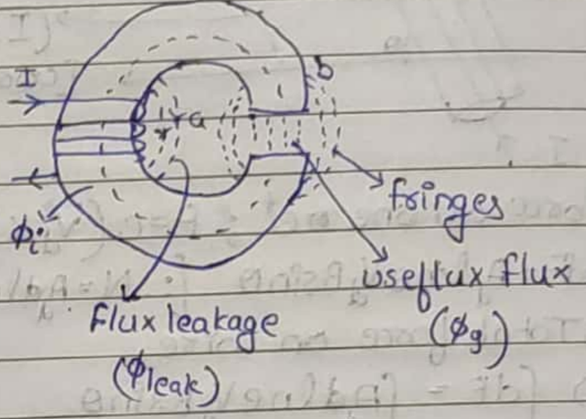
$\Rightarrow \frac{B_1 l_1}{\mu_0 \mu_{r_1}} + \frac{B_2 l_2}{\mu_0 \mu_{r_2}} + \frac{B_3 l_3}{\mu_0 \mu_{r_3}} + \frac{B_g l_g}{\mu_g}$ $\quad \left[\because B = \frac{\phi}{a} \right]$

$\boxed{\text{mmf} \Rightarrow H_1 l_1 + H_2 l_2 + H_3 l_3 + H_g l_g}$

⊛ Magnetic leakage:-

⇒ The flux that does not follow the desired path in a magnetic circuit is called flux leakage.

⇒ ϕ_t = Total flux produces,
i.e, flux in the core ring
ϕ_g = useful flux across the gap



⇒ ∴ leakage flux, $\phi_{leak} = \phi_i - \phi_g$

⇒ leakage coefficient,

⇒ $A = \dfrac{\text{Total flux}}{\text{useful flux}} = \dfrac{\phi_i}{\phi_g}$

⇒ The value of leakage coefficients for electrical machines is usually about 1.15 to 1.25

⇒ Flux leakage can be reduced by placing source of mmf near air gap.

⊛ Fringes:-

(1) when crossing air gap, magnetic field lines of force tend to budge out, such lines of forces repel each other when passing through non-magnetic material.

(2) Fringing is directly proportional to air gap. The longer the air gap, the greater is the fringing and vice-versa.

⊛ Force on a current carrying conductor placed in Magnetic field:-

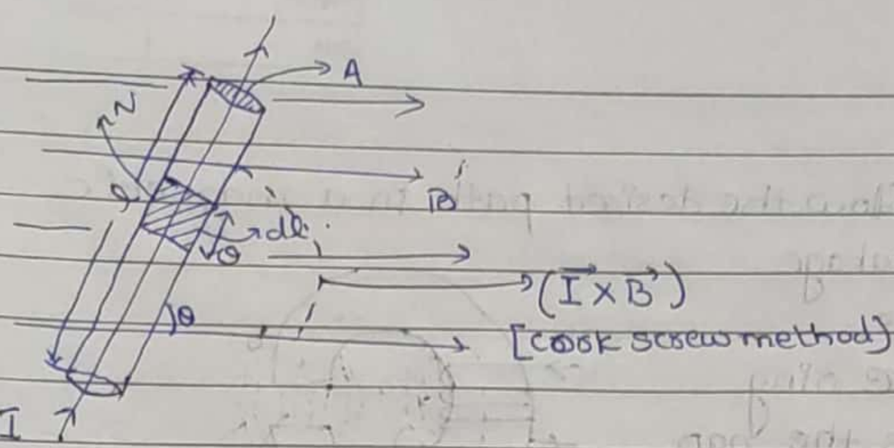
(1) when a current-carrying conductor is placed at right angles to the magnetic field, the conductor experiences a force which act in a direction perpendicular to direction of both the field and current. Let,

⇒ I = current through the conductor in Ampere

⇒ B = Magnetic flux density in Wb/m^2

⇒ l = length of conductor (m)

⇒ θ = Angle between conductor & magnetic field



Force on one e^+ ; $F = e(\vec{V_d} \times \vec{B}) = eV_d B\sin\theta$

$\Rightarrow dF = A\, dl\, n e V_d B\sin\theta$ $[\because N = A\,dl\,n]$

$\Rightarrow$ Total force on wire,

$\Rightarrow \int dF = \int A\,dl\,n e V_d B\sin\theta$

$\Rightarrow F = AV_d e n B\sin\theta \int dl$

$\Rightarrow F = AV_d e n B l\sin\theta$

$\Rightarrow F = V_d e n A B l\sin\theta$ $[\because I = V_d e n A]$

$\Rightarrow \boxed{F = IBl\sin\theta}$

Force acting on the conductor is directly proportional to the flux density (B), current (I), length (l) and angle (θ).
Direction of force is always perpendicular to the plane containing the conductor and magnetic field.

$\Rightarrow \boxed{\vec{F} = I(\vec{l} \times \vec{B})}$

In special case:-

(i) when $\theta = 0°$ (or) $180°$

$\Rightarrow F = BIl \times 0 = 0$ (minimum value)

conductor is place parallel to the direction of magnetic field, the conductor will experience no force.

(ii) When $\theta = 90°$ (or) $270°$; $\sin\theta = 1$,

$\Rightarrow F = BIl$ (maximum value)

conductor will experience force, when it is placed at right angle to the direction of magnetic fields.

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⊛ Electromagnetic Induction:-

The phenomenon of production of emf and current in a conductor (or) coil when the magnetic flux linking the conductor (or) coil changes.

⊛ flux linkage:-

The product of no. of turns (N) of the coil & the magnetic flux (ϕ) linking the coil.

$\Rightarrow$ $\boxed{\text{Flux linkage} = N\phi}$

⊛ Faraday's law:-

(i) I^{st} law:-

whenever, the magnetic flux linked with a circuit changes, emf is always induced in it, and when conductor forms a closed coil, an induced current flow through it.

(or)

whenever, there is a relative motion between coil & magnet, an emf is induced in coil conducting. If it is closed circuit, an induced current flows through it.

(ii) 2^{nd} law:-

The magnitude of the induced emf is equal to the rate of change of flux linkage.

According to Faraday's 2^{nd} law,

$\Rightarrow N\phi_1 \longrightarrow$ Initial Flux linkage

$\Rightarrow N\phi_2 \longrightarrow$ Final Flux linkage

$\Rightarrow$ Induced emf $= \dfrac{N\phi_1 - N\phi_2}{t} = \dfrac{N(\phi_1 - \phi_2)}{t}$

$\Rightarrow$ So, in the differential form, we have,

$\Rightarrow e_{inst} = N\left|\dfrac{d\phi}{dt}\right|$

$\Rightarrow e_{avg} = N\dfrac{\Delta\phi}{\Delta t}$

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⇒ General eqⁿ of induced emf will be

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

⊛ Direction of Induced emf & current:-

Direction of induced emf & current can be determined by one of the following any two method,

(i) Lenz's law & (ii) Fleming's Right-hand rule.

(i) Lenz's law:-

The induced current will flow in such a direction so as to the cause that produces it, i.e, the induced current will set-up magnetic-flux to oppose the change in flux.

$\Rightarrow \boxed{e = -N\frac{d\phi}{dt}}$

The negative sign reminds that the induced current opposes the changing magnetic field that caused the induced current.

(ii) Fleming's Right-hand Rule:-

ⓐ Streched out the fore finger, middle finger & thumb of right hand so that they are at right angle to each other.

ⓑ Fore-finger points in the direction of magnetic field.

ⓒ Middle finger points in the direction of of induced emf (or) current.

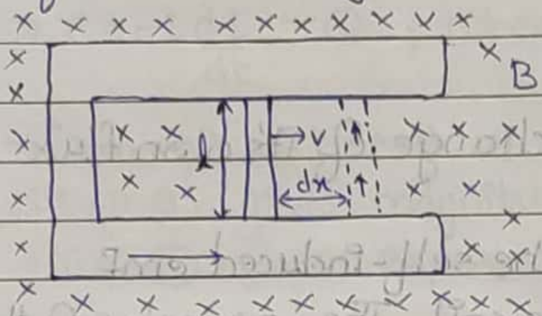
ⓓ Thumb will point in the direction of motion of the conductor.

⊛ Types of Induced emf:-

(1) Dynamically induced emf.

(2) Statistically induced emf.

(1) Dynamically induced emf:-
It is due to physical moment of conductor w.r.t flux (or) moment of flux (or) magnetic w.r.t conductor.



$l \rightarrow$ length of conductor
$B \rightarrow$ Magnetic flux density
$dx \rightarrow$ change in position w.r.t v

So, change in area of loop $dA = l\,dx$
So, change in magnetic flux will be,
$\Rightarrow d\phi = B\,dA$
$\Rightarrow \therefore d\phi = Bl\,dx$

$\Rightarrow$ Now, according to Faraday's 2nd law, $e = N\dfrac{d\phi}{dt}$;

$\Rightarrow e = \dfrac{d\phi}{dt}$

$\Rightarrow e = Bl\dfrac{dx}{dt}$ ---- $\left[\because \dfrac{dx}{dt} = v\right]$

$\Rightarrow \boxed{e = Blv}$

$\Rightarrow$ Now, if conductor moves at an angle 'θ' to the magnetic field, then emf induced will be,

$\Rightarrow \boxed{e = Bvl\sin\theta}$

(2) Statically induced emf:-
When the conductor is stationary and the field moving (or) changing, the emf induced in the conductor.

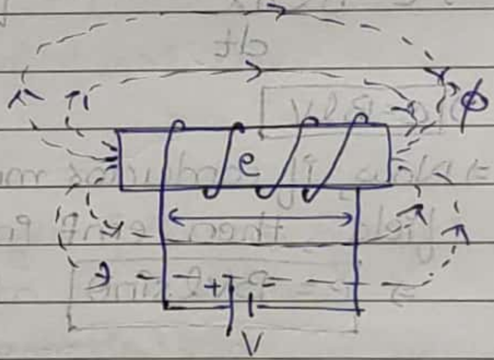
$\Rightarrow$ Types of statically induced emf:-
(i) Self induced emf (ii) Mutually induced emf.

(i) Self-induced emf:-
The emf induced in a coil due to the change of its own flux linked with it.

(ii) Mutually Induced emf:-
The emf induced in a coil due to the changing current in the neighbouring coil.

(i) Self-Induced emf:-
The emf induced in a coil due to the change of it's own flux linked with it.
→ when current in a coil changes, the self-induced emf opposes the change of current in the coil. The property of the coil is known as self-inductance (or) inductance.
→ The self induced emf will persist so long as the current in the coil is changing.
→ The self-induced emf (inductance) does not present the current from changing, it serves only in delay the change

⊛ Expression for self induced emf:-
⇒ As current 'I' is responsible to produce flux 'ϕ'



$\Rightarrow \therefore \phi \propto I$ —— ⓐ

$\Rightarrow \phi = KI$ - - - K → coefficient of coupling

$\Rightarrow K = \frac{\phi}{I}$ = constant.

⇒ Flux 'ϕ' can be written as, by multiplying & dividing by 'I'

$\Rightarrow \phi = \phi \times \frac{I}{I} = \frac{\phi}{I} \cdot I$ —— ①

⇒ differentiating $\frac{d\phi}{dt} = \frac{\phi}{I} \frac{dI}{dt}$ —— ②

Now,
⇒ When current 'I' in the coil changed emf induced in the coil & induced emf opposes the change in current.
⇒ by Lenz's law,

$\Rightarrow \therefore e = -N\frac{d\phi}{dt}$ —— ③

from eq^n ② & ③

$\Rightarrow e = -N \frac{dI}{dt}\left(\frac{\phi}{I}\right)$

$\Rightarrow e = -L\frac{dI}{dt}$ — ④ ; where $L = \frac{N\phi}{I}$ — ⑤

⇒ from eq^n $IL = N\phi \Rightarrow \phi \propto I$ equivalent to ⓐ

⇒ Eq^n ④ gives magnitude of induced emf.

⇒ Eq^n ⑤ gives expression for inductance.

✱ Self Inductance (L):-

⇒ The property of coil that opposes any change in the amount of current flowing through it.

⇒ Factors affecting the inductance,

(i) Shape & number of turns.

(ii) Relative permeability of the material surrounding the coil.

(iii) The speed with which the magnetic field changes,

from eq^{n}⑤

$\Rightarrow L = \frac{N\phi}{I}$

$\Rightarrow \therefore \phi = \frac{mmf}{reluctance} = \frac{NI}{S}$ — ⑥

substituting eq^n ⑥ in eq^n ⑤

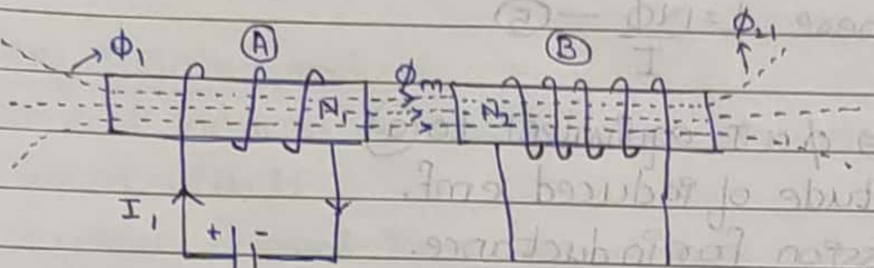
$\Rightarrow L = \frac{N}{\cancel{I}}\left(\frac{N\cancel{I}}{S}\right)$

$\Rightarrow L = \frac{N^2}{S} = \frac{N^2}{\frac{l}{\mu_0\mu_r A}} = \frac{N^2\mu_0\mu_r A}{l}$

$\Rightarrow \boxed{L = \frac{N^2\mu_0\mu_r A}{l}}$

⊛ Mutual Induced emf:-

(1) The emf induced in a coil due to the changing current in the neighbouring coil.



(2) when current coil 'A' is varied, the mutal flux also varies & hence emf is induced in both coils. Induced emf in coil 'A' is called self-induced emf & the emf induced in coil 'B' is called mutually induced emf.

(3) The mutually induced emf in coil 'B' persists as long as current in coil 'A' is changing. If current in coil 'A' becomes steady, the mutual flux also becomes steady & mutually induced emf drop to zero.

(4) The property of two neighbouring coil in induced voltage in one coil due to the change of current in the other is called mutual inductance.

⇒ Let $\phi_1 \rightarrow$ flux produced by 'I_1' again called self flux at coil 'A'

$\phi_{21} \rightarrow$ Part of ϕ_1 linking with coil 'B', again called as mutual flux.

$\Rightarrow$ As; $\phi_{21} \propto \phi_1$ &

$\Rightarrow \phi_1 \propto I_1$

$\Rightarrow \therefore \phi_{21} \propto I_1$

$\Rightarrow \phi_{21} = K I_1$

$\Rightarrow K = \dfrac{\phi_{21}}{I_1} =$ constant

⇒ flux ϕ_{21} can be written as, Multiplying & dividing by 'I_1',

$$\Rightarrow \phi_{21} = \frac{\phi_{21}}{I_1} \times I_1$$

$$\Rightarrow \frac{d\phi_{21}}{dt} = \frac{\phi_{21}}{I_1}\frac{dI_1}{dt} \quad \text{—(1)}$$

when ϕ_{21} link with coil 'B', according to Faraday's law a mutually induced emf e_{21} is induced in coil 'B' given by,

$\Rightarrow e_{21} = -N_2 \frac{d\phi_2}{dt}$

$\Rightarrow$ from eq^n ① $e_{21} = -\frac{N_2 \phi_{21}}{I_1} \frac{dI_1}{dt}$

$\Rightarrow \therefore \boxed{e_{21} = -M\frac{dI_1}{dt}}$; where, $M = \frac{N_2\phi_{21}}{I_1}$ (mutual inductance)

$\Rightarrow$ As 'ϕ_{21}' is part of 'ϕ_1' ; $\therefore \phi_{21} = K\phi_1$; K → Amount of flux linking with coil 'B'

$\Rightarrow M = \frac{N_2\phi_1 K}{I_1}$ —— ②

$\Rightarrow$ But ; $\phi_1 = \frac{m.m.f}{S_1} = \frac{N_1 I_1}{\frac{l_1}{\mu_0 \mu_{r_1} A_1}} = \frac{N_1 I_1 \mu_0 \mu_{r_1} A_1}{l_1}$ —— ③

$\Rightarrow$ Subs eq^n ③ in eq^n ②

$\Rightarrow$ Hence, $M = \frac{N_2 K}{\cancel{I_1}}\left(\frac{N_1 \cancel{I_1} \mu_0 \mu_{r_1} A_1}{l_1}\right)$

$\Rightarrow$ & for 100% flux linkage ; K = 1

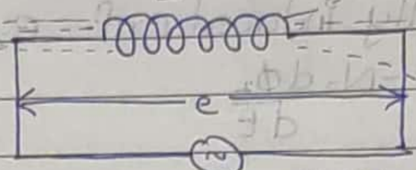
$\Rightarrow \therefore M = \frac{N_1 N_2 \mu_0 \mu_{r_1} A_1}{l_1}$

$\Rightarrow$ This expression for mutual inductance in terms of dimension. Similarly, if 'I_2' is current flowing through coil 'B'. Then mutual inductance & induced emf will be given by,

$\Rightarrow M = \frac{N_1 N_2 \mu_0 \mu_r A_2}{l_2}$

$\Rightarrow$ & $\boxed{e_{12} = -M\frac{dI_2}{dt}}$

* Energy stored in magnetic field:-



⇒ when the coil of inductance 'L', Henery, is connected across supply, the lines of forces are created.

Due to the lines of force linking of forces ~~are~~ to the coil, emf is induced in the coil. It is given as

⇒ $e = -L\frac{dI}{dt}$

⇒ But $e = -V$ (as induced emf is always opposed by the cause producting it as per Lenz's law)

⇒ $\therefore -V = -L\frac{dI}{dt}$

⇒ $V = L\frac{dI}{dt}$ —— (1)

⇒ Multiplying both side by "$I\,dt$" in eqn (1)

⇒ $VI\,dt = LI\,dI$

⇒ But $VI\,dt = E$ → the electrical energy supplied to the coil by source.

⇒ The total energy supplied by the source to the coil when current changes from I_1 to I_2

⇒ $E = \int VI\,dt = \int_{I_1}^{I_2} \cancel{VI\,dt}(LI\,dt)$

⇒ $E = L\left[\frac{I^2}{2}\right]_{I_1}^{I_2} = \frac{1}{2}L\left(I_2^2 - I_1^2\right)$

If the current in the coil varies from zero to final steady value 'I' ampere then, ⇒ $E = \frac{1}{2}L(I^2 - 0)$

⇒ $E = \frac{1}{2}LI^2$

Now, $L = \frac{N\phi}{I}$

⇒ $\therefore E = \frac{1}{2}\frac{N\phi}{\cancel{I}}LI^2$

⇒ $E = \frac{1}{2}N\phi LI$

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$\Rightarrow E = \frac{1}{2} N B a I$ ---- $[\therefore \phi = Ba]$

$\Rightarrow E = \frac{1}{2} B a H l$ ---- $[NI = Hl]$

$\Rightarrow E = \frac{1}{2} B a H l$

$\Rightarrow$ Now, $E = \frac{1}{2} B H V$ ---- [Volume, $V = al$]

$\Rightarrow \therefore \boxed{\frac{E}{V} = \frac{1}{2} BH}$

$\Rightarrow$ Energy stored per unit volume $= \frac{1}{2} BH$ Joules