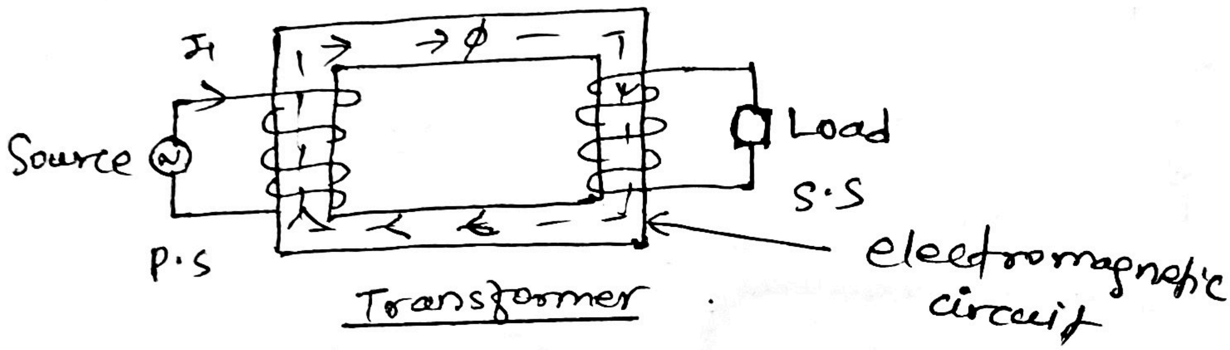
Chapter - 06

Magnetic circuit and Induction

Magnetic circuit → closed path

↳ closed path formed by magnetic material
⇓
which will pass flux

⇒ Magnetic circuit is a closed path which is followed by flux (ϕ).

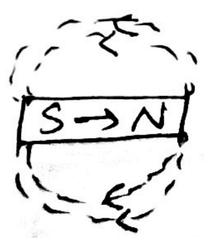


Transformer

Terms used in magnetic circuit

1) Magnetic flux (ϕ) -

⇒ number of magnetic field lines passing through a given closed surface.



outside N to S
Inside S to N

unit of flux (ϕ) is weber (wb).

$1\,Wb = 10^8$ magnetic lines of forces.

magnetic flux (ϕ) $\xrightarrow[\text{to}]{\text{analogous}}$ electric current (I)

2) Magnetic flux density (B) –

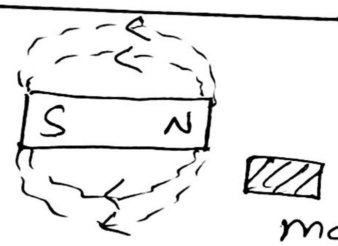
$$\boxed{B = \frac{\phi}{A}} \quad Wb/m^2 \quad \text{or Tesla (T)}$$

B $\xrightarrow{\text{analogous to}}$ J (current density)

$$J = I/A \quad A/m^2$$

⇒ Magnetic flux density is a measure of the quantity of magnetism, being the total number of magnetic lines of force passing through a specific area in a magnetic field.

3) magnetic field Intensity –



magnetic material

⇒ Suppose if we place magnetic material near unit North pole then how much force it will experience due to magnet is called magnetic field intensity (H).

Intensity ↑↑ attraction ↑↑

$$\boxed{H = \frac{NI}{l}} \ AT/m$$

where,

N = Number of turns of conductor winding

I = supply current

l = length of conductor

$H \xrightarrow{\text{analogous to}} E$ (electric field intensity)

$(E = F/q)$

4) Permeability -

⇒ ability to allow the magnetic flux passage.

⇒ measure of magnetisation that a material obtain in response to an applied magnetic field.

$$\boxed{\mu = \mu_0 \mu_r}$$

Greek letter

μ_0 = absolute permeability

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

μ_r = relative permeability of medium which will change according to medium having value equal to 1 for air or vacuum.

permeability $\xrightarrow{\text{analogous to}}$ conductivity

5) Reluctance -

⇒ opposes the magnetic lines of forces (flux)

$$\boxed{S \text{ or } R = \frac{l}{\mu A} = \frac{l}{\mu_0 \mu_r A}} \ AT/wb$$

Reluctance (S) $\xrightarrow{\text{analogous to}}$ Resistance (R) $[R = \rho \frac{l}{A}]$

6) Permeance -

→ reciprocal of reluctance

$$\boxed{\rho = \frac{1}{S} = \frac{\mu_0 \mu_r A}{l}} \quad wb/AT$$

Permeance $\xrightarrow{\text{analogous to}}$ Conductance

↳ reciprocal of resistance.

7) Magneto motive force (mmf) -

Magneto + motive + force

↓ Flux ↓ motion ↓ force required

$$\boxed{mmf = \phi S = Hl = NI} \quad (AT)$$

mmf $\xrightarrow{\text{analogous to}}$ Emf

Emf ⇒ electro + motive + force

↓ Charge ↓ motion ↓ force required

$$\boxed{E = V = IR}$$

Work law

→ work done in moving a unit magnetic pole area once around the magnetic circuit is equal to ampere turns (NI) enclosed by magnetic circuit.

Work done = Ampere-turns.

$$F \times d = NI$$

$$H \times l = NI$$

$$\boxed{H = NI/l} \quad AT/m$$

Ohm's law of magnetic circuit

we know,

$$B = \phi/A \quad \text{—} \ (1)$$

$$B = \mu H \quad \text{—} \ (2)$$

From work law,

$$H \cdot l = NI$$

$$\frac{B}{\mu} \cdot l = NI$$

$$\frac{\phi}{A} \times \frac{l}{\mu} = NI$$

$$NI = \phi * \frac{l}{\mu A}$$

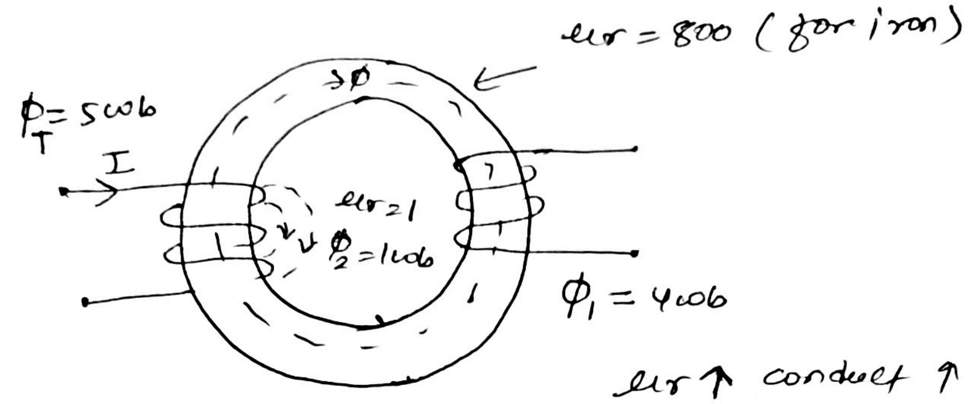
$$mmf = \phi S$$

$$\boxed{\therefore mmf = \phi S}$$

as $E = V = IR$

Magnetic leakage flux

→ any flux which will travel or move through any medium in undesirable condition.



$\mu_r \uparrow$ conduct $\uparrow$

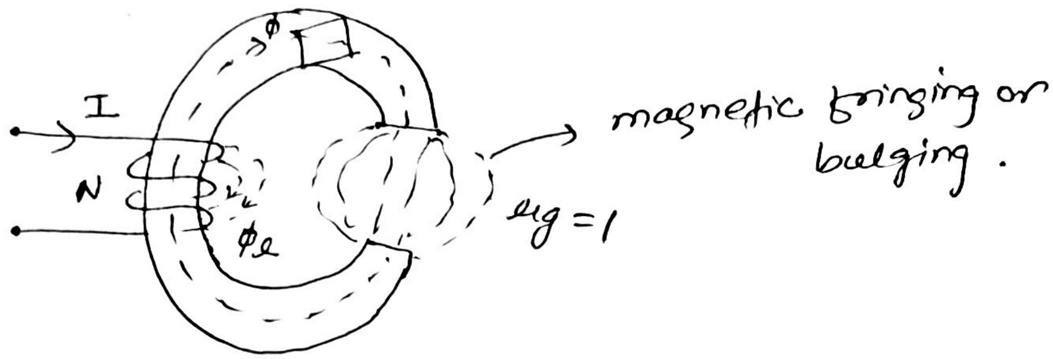
(means magnetic lines of forces will travel more)

$$\boxed{\phi_T = \underbrace{\phi_1}_{\text{useful flux}} + \underbrace{\phi_2}_{\text{leakage flux}}}$$

Magnetic fringing or Bulging

⇒ When the magnetic field lines pass through an air gap, they tend to bulge out. It is because the magnetic field lines repel each other when passing through the air (or non magnetic material). This effect is known as magnetic fringing or Bulging

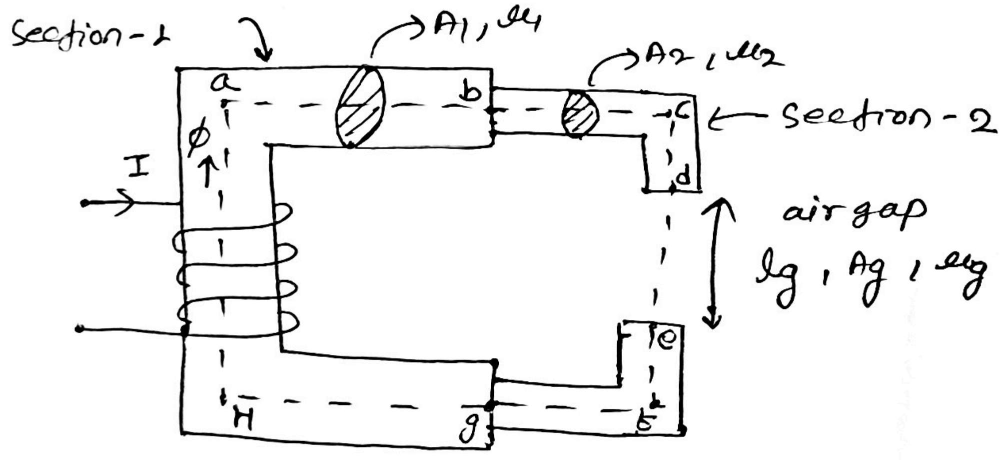
⇒ Due to magnetic fringing, the effective area of the air gap is increased and thus the magnetic flux density is decreased in the air gap. The longer the air gap, the higher is the fringing and viceversa.



Types of magnetic circuits

1) series magnetic circuit
2) parallel magnetic circuit

1) Series magnetic circuit –



⇒ If the magnetic flux doesn't divide and same flux passes through the different section of the core, then those section are said to be in series.

Section - 1

$L_1 = ba + aH + Hg$

Area $= A_1$

permeability $= \mu_1$

$$S_1 = \frac{L_1}{\mu_1 A_1}$$

Section - 2

$L_2 = bc + cd + ef + fg$

Area $= A_2$

permeability $= \mu_2$

$$S_2 = \frac{L_2}{\mu_2 A_2}$$

Air gap

length $= l_g$

Area $= A_g$

permeability $= \mu_g = \mu_0 \mu_r = \mu_0$

$$S_g = \frac{l_g}{\mu_0 A_g}$$

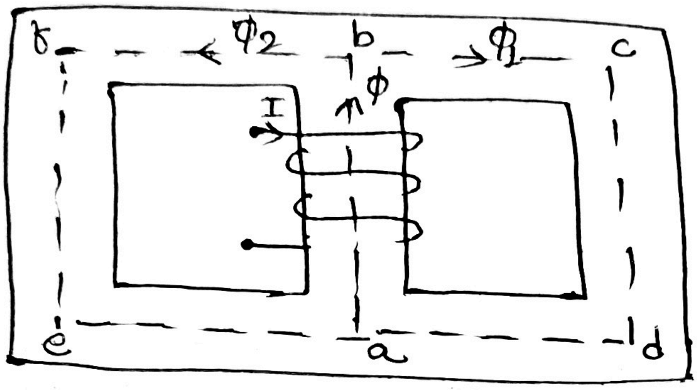
Total Reluctance is given by,

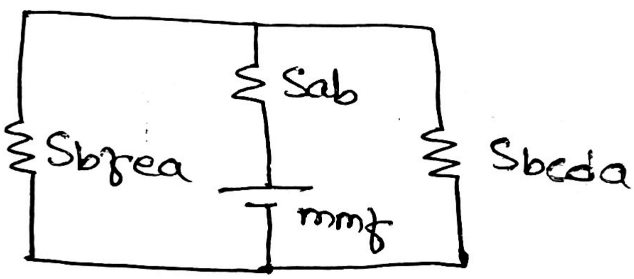
$$\boxed{S_T = S_1 + S_2 + S_g} \text{ AT/wb.}$$

$$\boxed{\phi = \frac{mmf}{S_T}} \text{ wb}$$

2) Parallel magnetic circuit -

⇒ If the magnetic flux divides into two or more parallel paths in some sections of the magnetic circuit in a core, then those section are said to be in parallel as shown in fig below:





$$S_{ab} = \frac{l_{ab}}{\mu A}$$

$$S_{bcda} = \frac{l_{bcda}}{\mu A}$$

$$S_{bfea} = \frac{l_{bfea}}{\mu A}$$

$$S_{eq} = S_T = S_{ab} + (S_{bcda} \parallel S_{bfea})$$

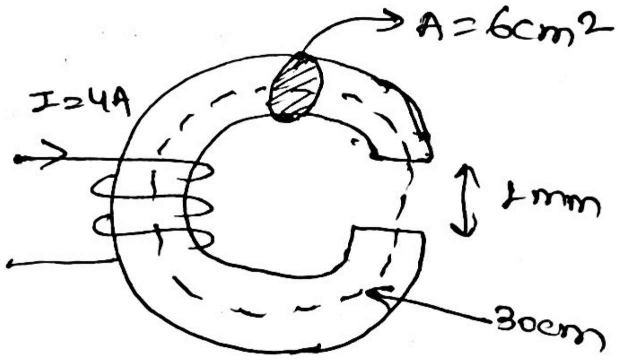
$$S_T = S_{eq} = S_{ab} + \frac{S_{bcda} \times S_{bfea}}{S_{bcda} + S_{bfea}}$$

$$\phi = \frac{mmf}{S_T} = \frac{NI}{S_{ab} + \frac{S_{bcda} \times S_{bfea}}{S_{bcda} + S_{bfea}}}$$

Q.1) A mild steel ring of 30cm mean circumference has a cross sectional area of $6cm^2$ and has a winding of 500 turns on it. The ring is cut through at a point so as to provide an gap of 1mm in the magnetic circuit. It is found that a current of 4A in the winding, provides density of 1T in the air gap. Find i) The relative permeability of steel

ii) Inductance of winding.

⇒ Soln-



we have,

$$A_1 = A_g = 6cm^2 = 6\times10^{-4} m^2$$

$$l_1 = 30 - 0.1 = 29.9 cm$$

Air gap flux density $(B_g) = 1T$

we know,

$$B_g = \frac{\phi_g}{A_g} = \frac{\phi_g}{6\times10^{-4}}$$

$$1 = \frac{\phi_g}{6\times10^{-4}}$$

$$\phi_g = 6\times10^{-4} = \phi_1$$

$$\therefore \phi_1 = \phi_g = 6\times10^{-4} wb$$

$$\text{Total mmf} = \phi_g (S_1 + S_g)$$

$$500\times4 = 6\times10^{-4}\left[\frac{0.299}{\mu_0\times\mu_{r1}\times6\times10^{-4}} + \frac{1\times10^{-3}}{\mu_0\times\mu_{rg}\times6\times10^{-4}}\right]$$

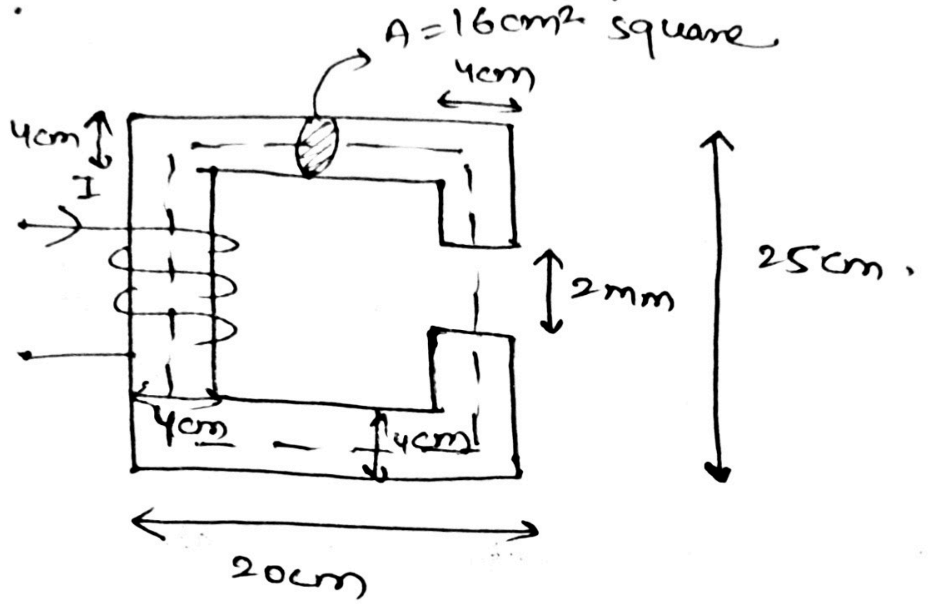
$$500\times4 = \frac{6\times10^{-4}}{6\times10^{-4}\times4\pi\times10^{-7}}\left[\frac{0.299}{\mu_{r1}} + \frac{1\times10^{-3}}{1}\right]$$

By Solving,

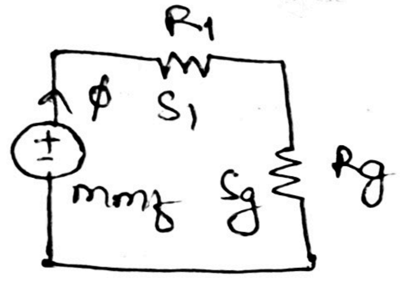
$\mu_{r1} = 198.$

ii) $L = \frac{N\phi}{I} = \frac{500\times6\times10^{-4}}{4}$

Q.2) A rectangular magnetic core shown in fig has a square section 16cm². An air gap of 2mm is cut across one of the limbs. Find the exciting current needed in the coil having 1000 turns wound on the core to create an air gap flux of 4mWb. The relative permeability of core is 2000.



⇒ Soln -



$A = 16cm^2$ (square)

$l = b = 4cm$

$N = 1000$ turns

$\phi g = 4mWb = 4\times10^{-3}$ Wb

$\mu r = 2000$

$lg = 2mm = 2\times10^{-3}m$

Magnetic flux density $(B) = \phi/A = \frac{4\times10^{-3}}{16\times10^{-4}} = 2.5T$

mean length of core $(l core) = (20-2-2)\times2 + (25-2-2) + (25-2-2 - 2\times10^{-2})$

$= 73.98cm$

$$\text{Total ampere-turn} = \frac{B}{\mu_0} l_g + \frac{B}{\mu_0 \mu_r} l_{core}$$

$$= \frac{2.5 \times 2 \times 10^{-3}}{4\pi \times 10^{-7}} + \frac{2.5 \times 0.738}{4\pi \times 10^{-7} \times 2000}$$

$$= 4713$$

$$NI = 4713$$

$$1000 \times I = 4713$$

$$\therefore \; I = 4713/1000$$

$$\therefore \; I = 4.713\,A$$

B-H relationship (magnetisation characteristics)

→ Graphical representation of magnetic flux density (B) and magnetic flux intensity (H).

$$B \propto H$$

$$\left[B = \phi/A \; T \quad \text{and} \quad H = NI/l \; AT/m \right]$$

$$B = \mu H$$

$$B = \mu_0 \mu_r H$$

$$B \uparrow \propto H \uparrow$$

$$H \uparrow \propto I \uparrow$$

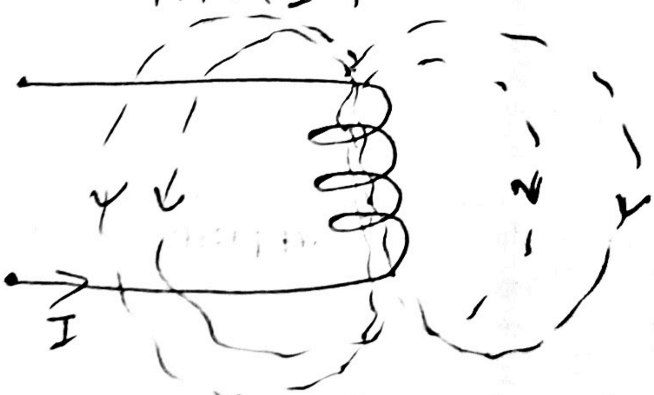


Fig coil without core

→ In freespace, the magnetic flux density (B) is directly proportional to magnetising force (H).

$$B \propto H$$
$$B = \mu_0 H$$

where,

μ_0 = permeability of free space
$= 4\pi \times 10^{-7}$

→ Here, the relationship between B and H is linear.

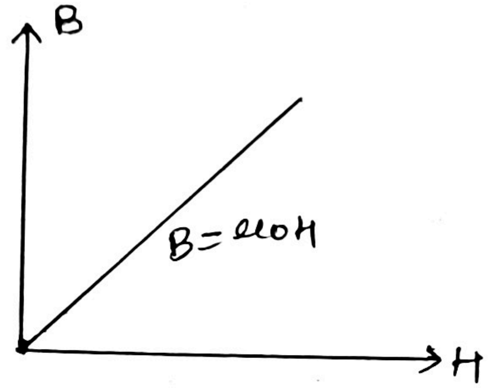


Fig. B-H characteristics curve without core

→ However, this is not the case in magnetic material used as core, as in electric machine. The relationship is strictly non linear. A typical B-H curve for a magnetic material is shown below -

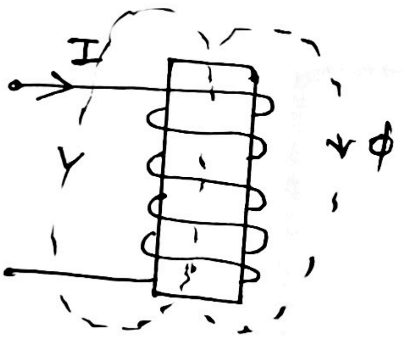


Fig. coil with ironcore

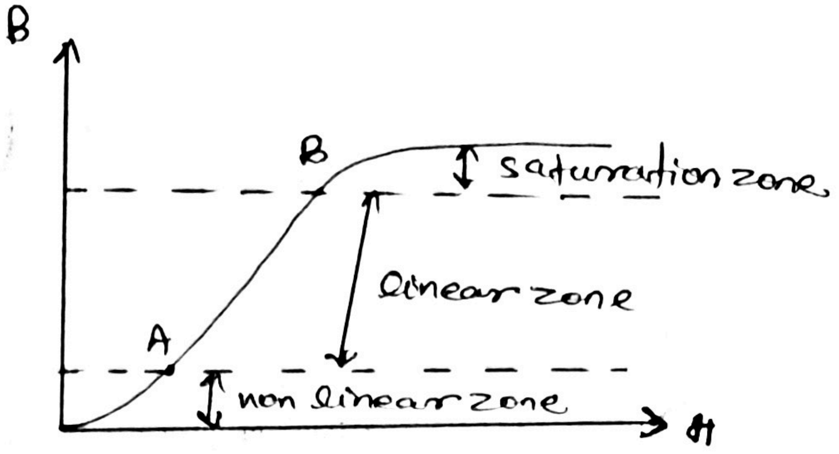
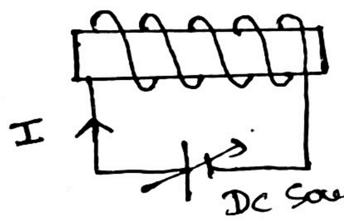


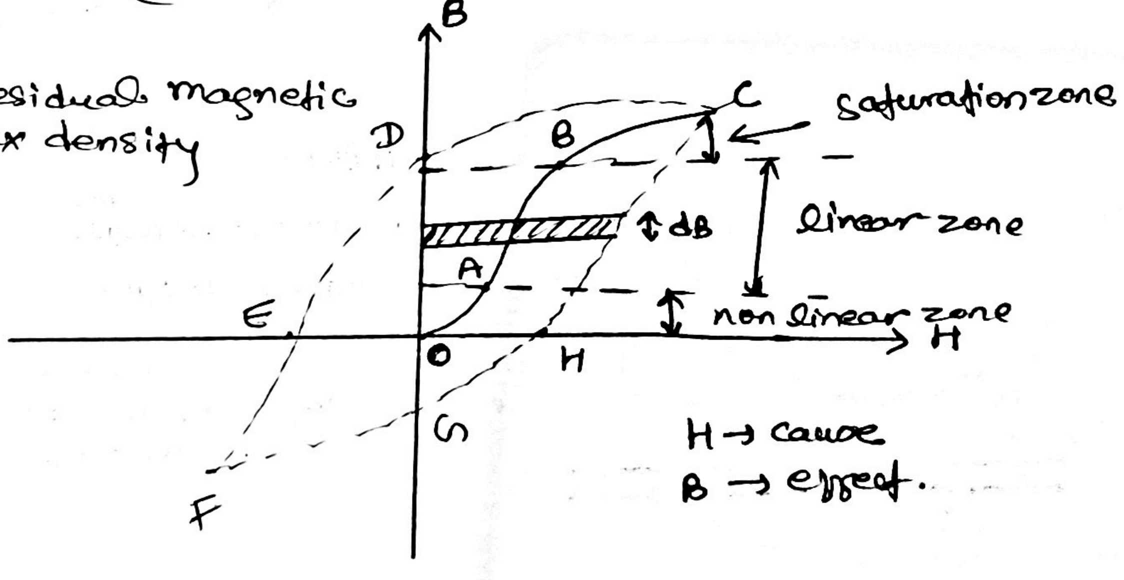
Fig B-H characteristics curve with core

Hysteresis curve | B-H curve | magnetizing curve

→ Consider an electromagnet supplied by a variable DC supply, the magnetising force inside the core is given by $H = NI/l$, Hence varying I, H in the material can be varied and accordingly 'B' will also vary.



OD = residual magnetic flux density



H → cause
B → effect.

→ There is a loss in the process of magnetization and demagnetization in the form of heat and is called hysteresis loss, due to the property of magnetic material known as retentivity.

→ The magnetic flux at any instant is given by

$$\phi(t) = B(t) \cdot A.$$

then emf induced in the coil according to Faradays law of electromagnetic induction,

$$e = N\frac{d\phi}{dt} = N\frac{d(B \cdot A)}{dt} = NA\frac{dB}{dt} \quad -①$$

and Also,

$$\text{magnetising force } (H) = NI/l$$

$$P = eI = NA\frac{dB}{dt} * \frac{Hl}{N}$$

$$P = AlH\, dB/dt$$

∴ Energy spent in small time interval

$$dw = P\,dt$$

$$dw = AlH \cdot dB$$

∴ Energy spent in one cycle of magnetisation (i.e the complete hysteresis loop) $= \oint dw$

$$w = \oint AlH\,dB = Al\oint H\,dB$$

$$\frac{w}{Al} = \oint H \cdot dB$$

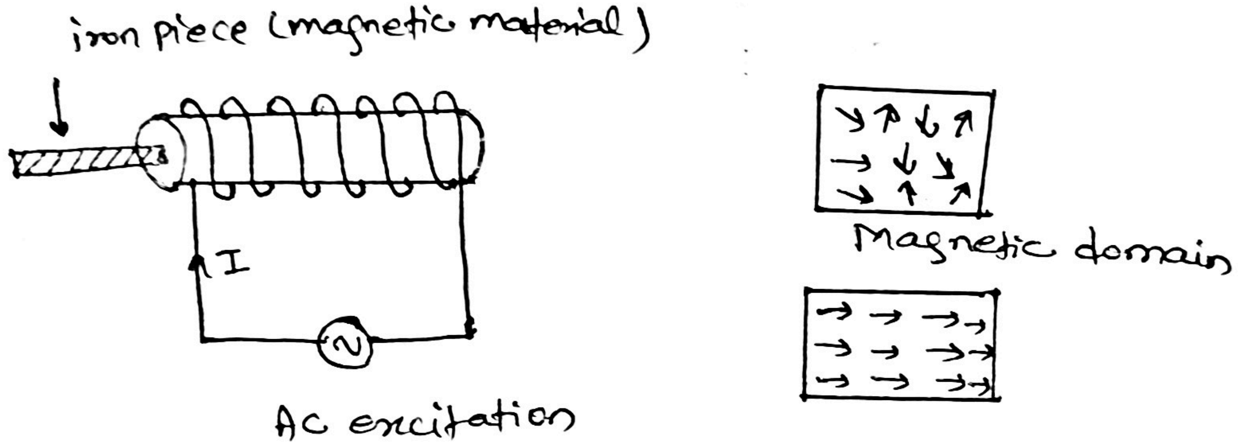
if $H \cdot dB$ = shaded area
$\oint H \cdot dB$ = complete area of loop.

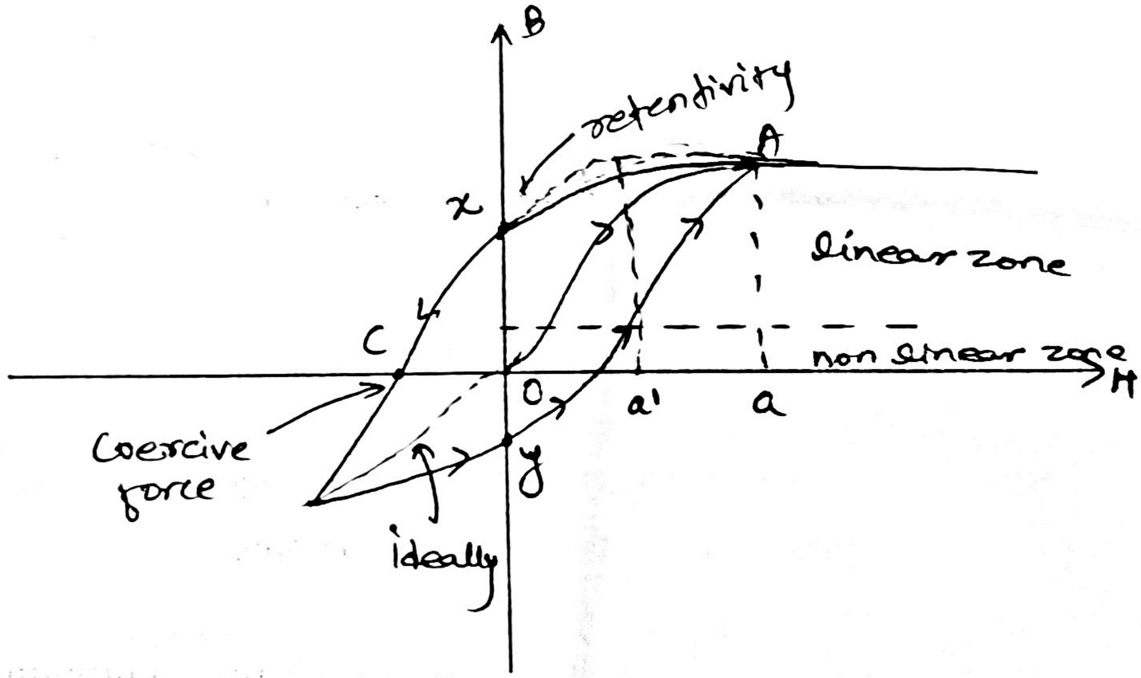
$$\frac{W}{A l} = \oint H \cdot dB$$

$$\frac{W}{V} = \oint H \cdot dB$$

Energy loss per unit volume = Area of the loop.

B-H curve with Ac excitation





→ Firstly increasing current then H will increase which will cause increase in B but it will increase proportionally (linearly) up to saturation.

→ Now decreasing current, H will reduce through Ax (not through Ao) and x is the point called retentivity (store magnetic flux).

→ Hysteresis loss
↳ Hysterein (greek)
that stands for lagging behind.
H is 0 but $B \neq 0$ so B is lagging behind H.

→ Retentivity (store residual magnetism)
due to which if we start the system next time then it will start from higher value (i.e from x) not from zero and magnetic material will saturate in less time as before (oa') and if we start again for next time the same system then may be the system will not start as it will be saturated when we start so we need to eliminate residual flux (residual magnetism).

→ To eliminate residual magnetism, we apply H in negative direction.

→ When we apply H in negative direction, B will reduce through xc and at c, B will be zero. where $H \neq 0$. C point is called coercive force and is defined as force required to eliminate or to reduce residual magnetism.

Faradays law of electromagnetic Induction

1) <u>First law</u> – whenever the magnetic flux linked with conductor changes with respect to time, an emf will be induced in it.

2) <u>Second law</u> – The magnitude of emf induced is equal to time rate of change magnetic flux linkages.

$$e \propto \frac{d\phi}{dt}$$

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

The magnetic flux linkage could be changed in two different ways, therefore emf can be produced in two different ways.

a) Statically induced emf

b) Dynamically induced emf

a) <u>Statically induced emf</u> –

Coil or conductor → Stationary (rest)

magnetic field or magnetic flux (ϕ) → changing

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

b) <u>Dynamically induced emf</u> -

coil or conductor → changing (motion)

magnetic field or magnetic flux (ϕ) → Stationary (rest)

↳ constant flux

$$e = Blv$$

and the direction of induced emf is given by Flemmings right hand rule.

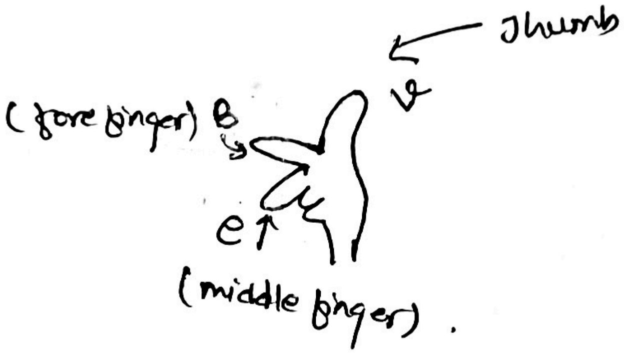
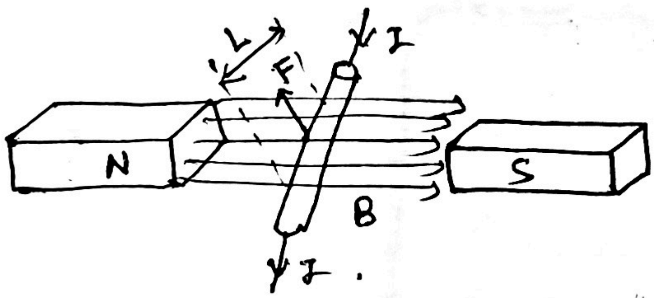


fig. flemming right hand rule.

Force on current carrying conductor



→ When a current carrying conductor is placed in a magnetic field, then a force will develop on the conductor, whose magnitude is given by.

$F = BIL$ N

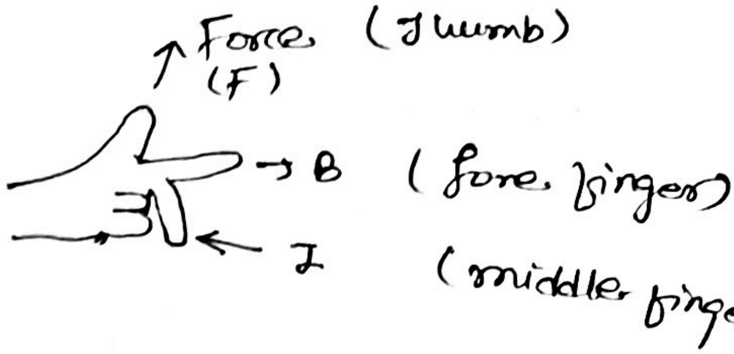
where,

B = magnetic flux density

I = current

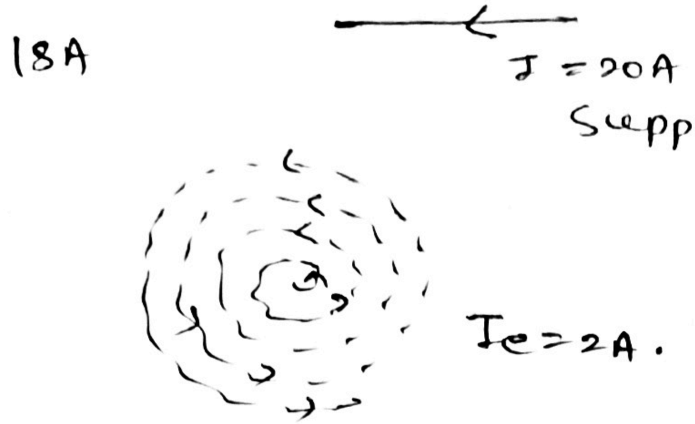
L = length of conductor.

and the direction of force is given by the Flemmings left hand rule.



Eddy currents

→ continous circular current



→ Nothing but leakage current.

→ It is opposing in nature (opposite to supply current).

→ Available on the surface of the system.

Eddy current ↑ Surface Area ↑

→ To reduce eddy current, we have to reduce surface area.

→ while designing transfomer, we use thin laminated sheet and combine many sheets to make core instead of using single sheet for core.

Application of magnetic circuit

- → Microphones, transformer, generators
- → Hard disks
- → MRI machines
- → Speaker
- → radio etc.