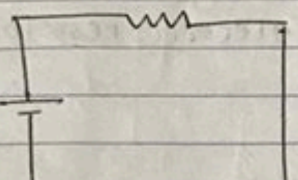
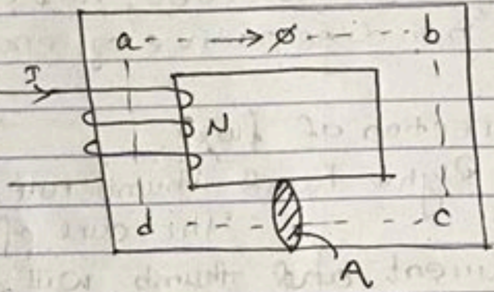
1.1> Magnetic circuits :





↳ A magnetic circuit is the path followed by a magnetic flux.

↳ Magnetic flux 'ϕ' is analogous to electric current 'I'.

In an electric circuit, the current flows due to an emf source and in an magnetic circuit, the magnetic flux is produced due to mmf (magnetomotive force)

$$mmf = NI$$

where N = No. of turns of winding
I = current flowing in the winding.

The current flow in any electric circuit is opposed by the resistance of the path. Similarly, the magnetic flux in a magnetic circuit is opposed by the reluctance (R) nature of the path.

$$R = \rho \frac{l}{A}$$

$$= \frac{1}{\sigma} \frac{l}{A}$$

$$R = \frac{1}{\mu} \frac{l}{A}$$

$$R = \frac{1}{\mu_0 \mu_r} \frac{l}{A}$$

↑ Reluctance.

l → mean length of magnetic path

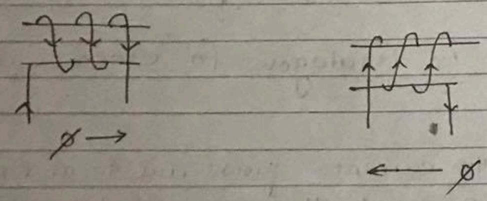
A ↳ cross sectional area of core.

The analogy (analogy with electric circuit) though useful is, however, not complete. Magnetic reluctance is non dissipative of energy unlike electric resistance.

Direction of flux:

→ Right hand thumb rule:

The curl of finger will show the direction of current and thumb will show the direction of flux.



1.2: Ohm's Law in Magnetic circuit

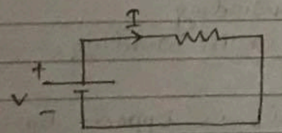


fig a: Electric ckt

$V = IR$

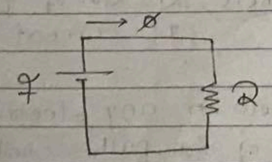


fig b: Equivalent mag. ckt.

$\mathcal{F} = \phi \mathcal{R}$

$NI = \phi \mathcal{R}$

Hence Ohm's Law in magnetic circuit is

$mmf(\mathcal{F}) = \phi \mathcal{R}$

Electrical Analogy

① current - flux

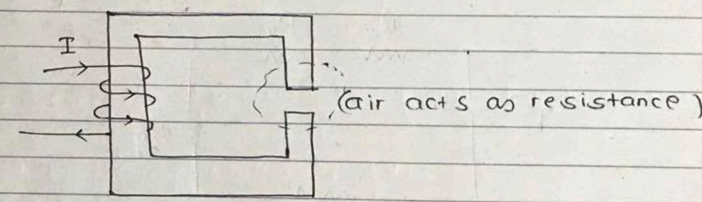
② Resistance - Reluctance

③ emf - mmf

$R = \frac{\rho l}{A}$

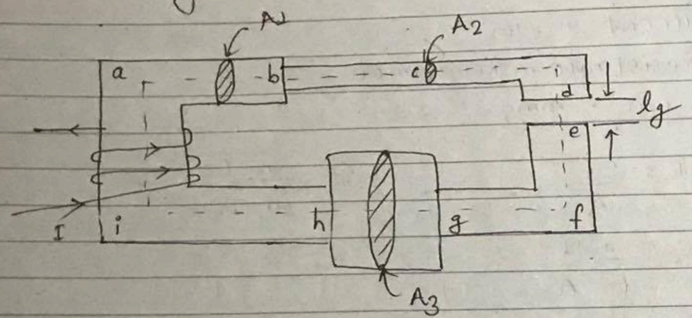
$= \frac{1}{\sigma} \frac{l}{A}$

$\mathcal{R} = \frac{1}{\mu} \frac{l}{A}$

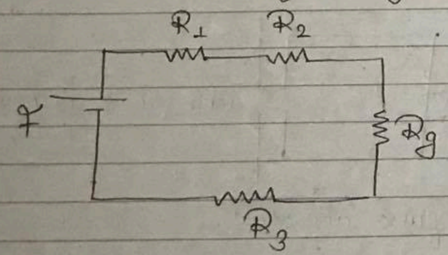


flux created.

Series magnetic circuit



The electrical analogy is given by,



Here,

$R_1 = \frac{1}{\mu_1} \frac{l_1}{A_1}$, $l_1 = baih$

$R_2 = \frac{1}{\mu_2} \frac{l_2}{A_2}$, $l_2 = bcdefg$

$R_3 = \frac{1}{\mu_3} \frac{l_3}{A_3}$, $l_3 = hg$.

$R_g = \frac{1}{\mu_0} \frac{l_g}{A_g}$, l_g = length of air gap.

$R = R_1 + R_2 + R_3 + R_g$

If the magnetic flux doesnot divide and passed through difference section of core then those section are said to be in series forming a series magnetic circuit as shown in figure above.

Here, mmf = NI and the resultant flux 'ϕ' flow through each section of core. Now relluctance of each portion can be calculated as,

Section 1,

$L_1 = ba + ai + ih$

Area = A_1 & permeability = μ_1

$\therefore R_1 = \frac{1}{\mu_1} \frac{l_1}{A_1}$

Section 2,

$L_2 = bc + cd + de + ef + fg$

Area = A_2 & permeability = μ_2

$\therefore R_2 = \frac{1}{\mu_2} \frac{l_2}{A_2}$

Section 3,

$L_3 = hg$.

$R_3 = \frac{1}{\mu_3} \frac{l_3}{A_3}$

Section (Air gap)

length = l_g, Area = A_2 (near area)

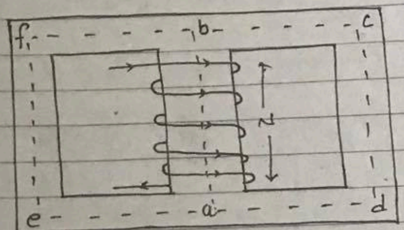
$R_g = \frac{1}{\mu_0} \frac{l_g}{A_g} = \frac{1}{\mu_0} \frac{l_g}{A_2}$.

Now total Reluctance is

$$R = R_1 + R_2 + R_3 + R_g$$

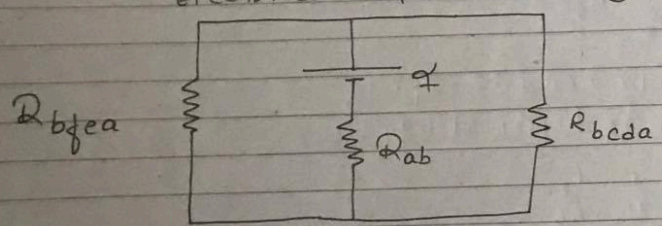
$$\therefore \phi = \frac{mmf}{R} = \frac{NI}{R_1 + R_2 + R_3 + R_g}.$$

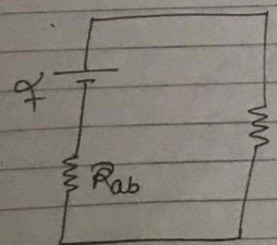
parallel Magnetic circuit



If the magnetic flux produced by mmf divides into two or more parallel path in some sections of magnetic circuit in the core then these section are said to be in parallel.

Electrical equivalent ckt :





$$R = \frac{R_{bfea} * R_{bcda}}{R_{bfea} + R_{bcda}}$$

Here,

$$R = \frac{R_{bfea} * R_{bcda}}{R_{bfea} + R_{bcda}}$$

Applying ohm's law,

$$\mathcal{F} = \phi(R + R_{ab})$$

or. $$\phi = \frac{\mathcal{F}}{R + R_{ab}}$$

$$= \frac{NI}{\frac{R_{bfea} * R_{bcda}}{R_{bfea} + R_{bcda}} + R_{ab}}$$

$$\therefore \phi = \frac{NI(R_{bfea} + R_{bcda})}{R_{bfea}R_{bcda} + R_{ab}R_{bfea} + R_{ab}R_{bcda}}$$

* 1.4 core with an gap

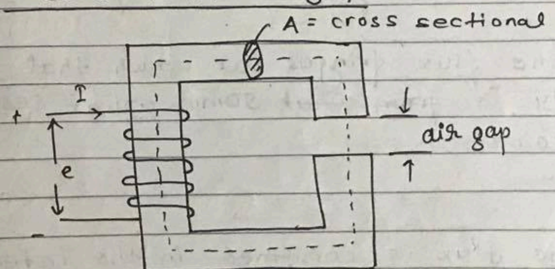
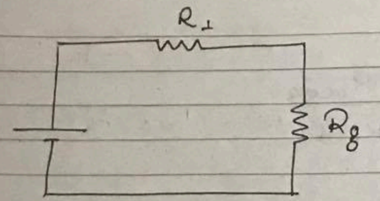


fig:. typical magnetic circuit with air gap.



$$R_g = \frac{1}{\mu_0}\frac{l_g}{A}$$

$$R_1 = \frac{1}{\mu_0 \mu_r}\frac{l_c}{A} \qquad [\ \mu_r \text{ is in } 1000 \ ]$$
iron = 6000

$$R = R_g + R_1 \quad \therefore$$

$$\phi = \frac{F}{R_1 + R_g} = \frac{NI}{\frac{1}{\mu_0 \mu_r}\frac{l_c}{A} + \frac{1}{\mu_0}\frac{l_g}{A}}$$

It is assumed that air gap is narrow and a flux coming out of the core passes straight down the air gap such that flux density in the air gap is same as that of core which practically not a case.

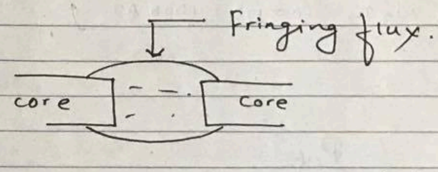
In real the flux fringes out such that air gap flux density is ~~from what~~ some what less than that of core.

* Leakage Flux

Most of the flux is confined in the intended by use of magnetic core but a small amout leaks through the air - which is called leakage flux.

Leakage flux is a characteristics of a magnetic circuit.

* Fringing

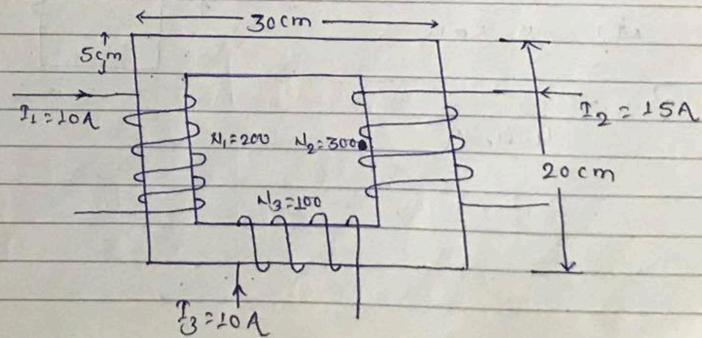


The flux fringes out in the neighbouring path as shown in the figure which intern decreases flux density.

The effect is more pronounced if the length of air gap is more.

Tutorial

Q. No. 3 :- Calculate the net magnetic flux in the core of the following magnetic circuit and show the direction of magnetic flux in the core. ~~of~~ Given that cross sectional area of the core is $25\,cm^2$ and $\mu_r = 4000$.



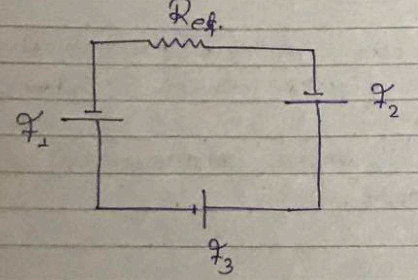
→ Given,

MMf.

$\mathcal{F}_1 = N_1 I_1 = 10 \times 200 = 2000\,AT$ ↗

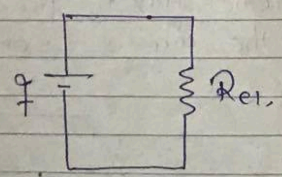
$\mathcal{F}_2 = N_2 I_2 = 300 \times 15 = 4500\,AT$

$\mathcal{F}_3 = N_3 I_3 = 10 \times 100 = 1000\,AT$



$Net\,(\mathcal{F}) = 4500 - 1000 - 2000$

$= 1500.$



we have,

$NI = \phi\, R_{el}.$

$$R_{el} = \frac{1}{\mu_0 \mu_r} \frac{l}{A}$$

outer perimeter = 100

inner perimeter = 60.

mean length $= \frac{100+60}{2} = 80$ cm.

$$R_{el} = \frac{1}{\mu_0 \times 4000} \times \frac{80 \times 10^{-2}}{25 \times 10^{-4}}$$

$= 63661.97$ AT/weber

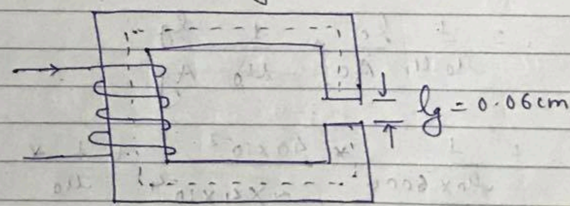
Now,

$$\phi = \frac{\mathcal{F}}{R_{el}} = \frac{1500}{63661.97}$$

$= 0.0235$ wb //

Q.NO.2

The magnetic circuit drawn yesterday (core with air gap) has dimension: $A_c = 4 \times 4\,cm^2$, $l_g = 0.06\,cm$, $l_c = 40\,cm$, $N = 600$ turns. find the exciting current for $B_c = 1.2T$.

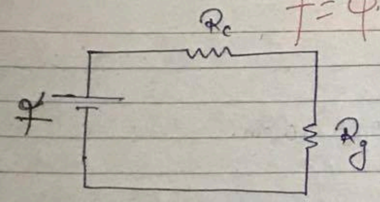


$V = IR$ | Current (I) | flux (ϕ)

$\mathcal{F} = \phi . Rel$. | Emf (V) | mmf ($\mathcal{F}$) = N

Rel | Reluctance

$V = IR$



Sol:

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

$\therefore \phi = BA = 1.2 \times 4 \times 4 \times 10^{-4}$

$= 1.92 \times 10^{-3}$ wb.

$Rel\ \phi = NI$

$\therefore I = \frac{\phi\, Rel}{N} \cdot \frac{1.92 \times 10^{-3}}{600}$

$= 3.2\ \mu A \times Rel$

where,

$Rel = R_c + R_g$

$= \frac{1}{\mu_0 \mu_r} \frac{l_c}{A_c} + \frac{1}{\mu_0} \frac{l_g}{A_g}$

$= \frac{1}{\mu_0 \times 6000} * \frac{40 \times 10^{-2}}{4 \times 4 \times 10^{-4}} + \frac{1}{\mu_0} * \frac{0.06 \times 10^{-2}}{4 \times 4 \times 10^{-4}}$

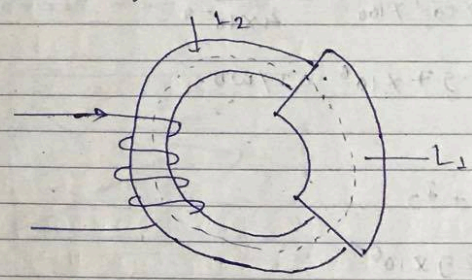
$= 331572.79$

$\therefore I = 3.2 \times 10^{-6} \times 331572.79$

$= 1.06$ A.

Q. NO. 7

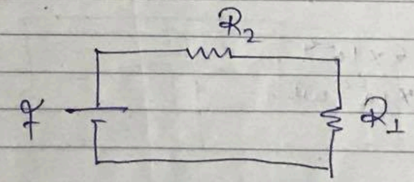
An uneven ring shaped core has $\mu_r = 100$ and flux density in the larger section is 0.75 T. If the current through the coil is 500 mA. Determine the no. of turns of coil.



$L_1 = 10$ cm, $A_1 = 6$ sq. cm

$L_2 = 25$ cm, $A_2 = 4$ sq. cm.

Here,



Here,

$$\mathcal{R}_1 = \frac{1}{\mu_0 \mu_r} \frac{l_1}{A_1}$$

$$= \frac{1}{4\pi \times 10^{-7} \times 100} \times \frac{10 \times 10^{-2}}{6 \times 10^{-4}}$$

$$= 1.32 \times 10^{6} \text{ AT/Wb.}$$

$$\mathcal{R}_2 = \frac{1}{\mu_0 \mu_r} \frac{l_2}{A_2}$$

$$= \frac{1}{4\pi \times 10^{-7} \times 100} \times \frac{25 \times 10^{-2}}{4 \times 10^{-4}}$$

$$= 4.97 \times 10^{6} \text{ AT/Wb.}$$

So,

$$\mathcal{R}_{eq} = \mathcal{R}_1 + \mathcal{R}_2$$

$$= 6.29 \times 10^{6}.$$

$$B_1 = \frac{\phi}{A_1}.$$

$$\therefore \phi = 0.75 \times 6 \times 10^{-4}$$

$$= 4.5 \times 10^{-4} \text{ Wb.}$$

Now,

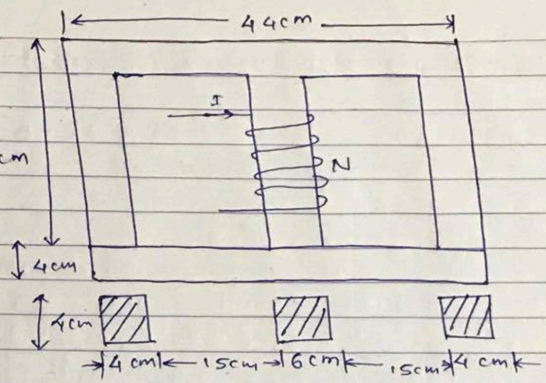
$$NI = \phi R.$$

or, $N \times 500 \times 10^{-3} = 4.5 \times 10^{-4} \times 6.29 \times 10^{6}.$

$\therefore N = 5669$ turns.

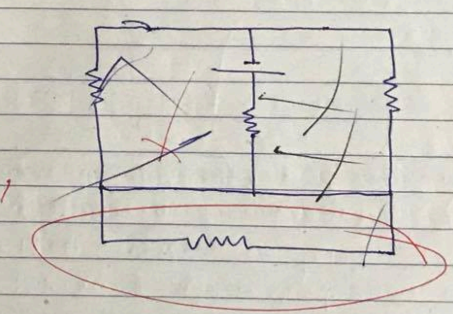
Ans = 40.4×10^{3} A turn.

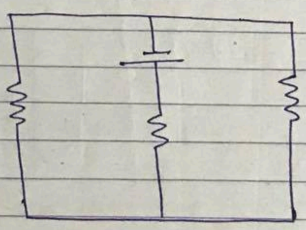
Q.



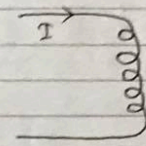
Calculate (NI) required to establish a flux of 0.75 Wb in the central limb, $\mu_r = 4000$ for iron core.

→





1.6 B-H relationship (Magnetization characterstics)



$$B = \mu_0 H$$
$$\mu_0 = 4\pi \times 10^{-7} \ H/m$$

Suppose the medium is air.

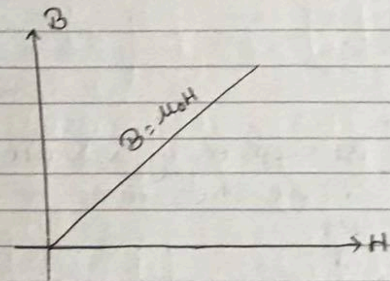


fig: B-H Characterstics

In free space, magnetic field density B is directly proportional to magnetizing force H.

i.e. $B \propto H$.

$B = \mu_0 H$

Where μ_0 is permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$ H/m.

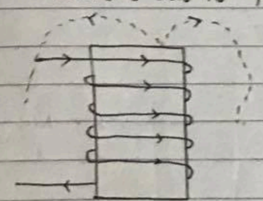
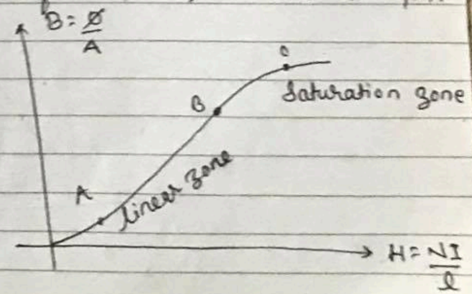
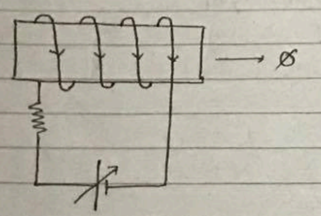


fig: Coil with core



1.7 Hysteresis with DC & AC excitation

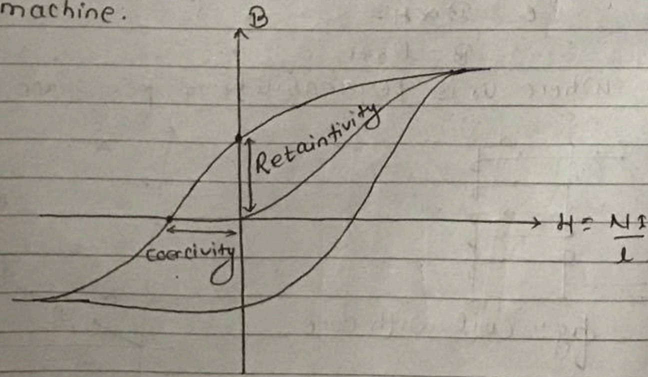
DC-excitation



Consider an electromagnet supplied by variable DC source. The magnetizing force inside the core is
$$H = \frac{NI}{l},$$

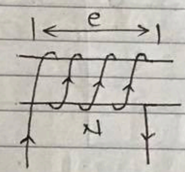
Thus, H can be varied by varying the current I and accordingly 'B' will vary.

The following curve will show the non-linear relationship between B & H in ferromagnetic material used in electric machine.



The curve is non linear in nature which makes it clear that the energy spent in magnetizing the core canot be recover by demagnetizing (the curve follows different path while magnetizing and demagnetizing) So there exist always some loss in the process which is due to the property of retaintivity.

The energy appears as heat within the core. It can be shown that the area of the hysteresis loop represents the energy loss ~~cycle of~~ per cycle of magnetization.



power across coil = power to maintain 'i' against 'e'
$$p = ei \quad \text{—— (1)}$$

The magnetic flux at any instant, $\phi = BA$.
Now, this time varying magnetic flux will induce an emf accros the coil, which is given by faraday's law of electromagnetic induction.

$$e = N\frac{d\phi}{dt} = N\frac{d}{dt}(BA) = NA\frac{dB}{dt} \quad \text{—— (2)}$$

Now magnetizing force, $H = \frac{NI}{l}$

$$\therefore I = \frac{Hl}{N} \quad \text{—— (3)}$$

from ①, ② & ③,

$p = ei = NA\frac{dB}{dt} \times \frac{Hl}{N}$

$p = AHl\frac{dB}{dt}$

∴ energy spent in small time interval,

$(dw) = p\,dt$

$\boxed{dw = AHl\,dB}$

∴ energy spent in each cycle of magnetization (i.e.) complete hysteresis loop.

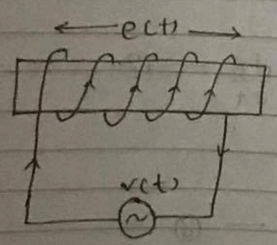
$w = \oint dw$

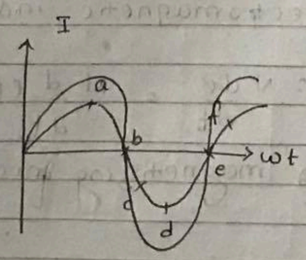
$w = Al \oint H\,dB$

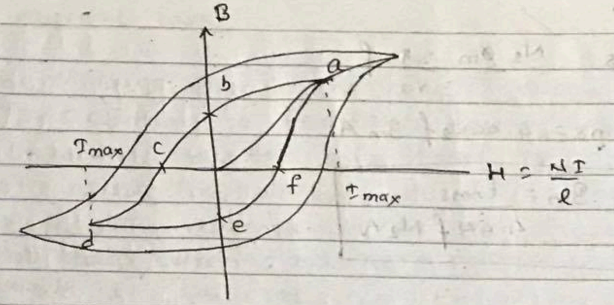
$\frac{w}{Al} = \oint H\,dB$

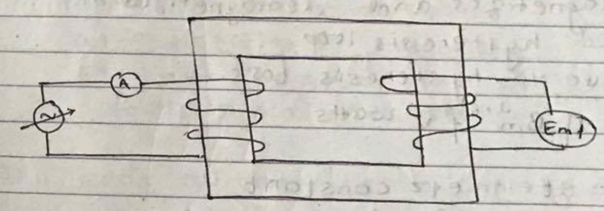
$\boxed{\text{Energy spent per unit volume} = \text{Area of Loop}}$

Hysteresis with AC excitation









$E = N_2\frac{d\phi}{dt}$

$E = N_2\frac{d\phi_m}{dt}\sin\omega t$

or, $E = N_2\,\phi_m\,\omega\cos\omega t$

or, $E = N_2\,\phi_m\,2\pi f\cos\omega t$

$\boxed{\therefore E = E_m\cos\omega t}$

$E_m = N_2\,\phi_m\,2\pi f$

$E_{rms} = \frac{E_m}{\sqrt{2}}$

$E_{rms} = N_2 \phi_m \frac{2\pi}{\sqrt{2}} f$

$E_{rms} = 4.44 N_2 f B_m A$

$$\boxed{\therefore B_m = \frac{E_{rms}}{4.44 f N_2 A}}$$

With varying voltage source, the core inside the coil gets magnetized and demagnetized in each cycle called hysteresis loop.

power loss due to hysteresis loss

$P_h = \eta B_m^{1.6} f v$ watts

Where, η = steinmetz constant

$= 502\ J/m^3$ (sheet steel)

$= 191\ J/m^3$ (silicon steel)

B_m = Max. flux density

f = frequency of current

v = volume of core.

Addition of silicon reduces 'η' hence hysteresis loss.

Eddy current loss

– The time varying flux in the core induces emf in the coils according to Faraday's law of electromagnetic Induction. But the core itself is a conductor (all magnetic core), Emf will be induced in the core resulting circulating currents in the core. These currents are known as eddy currents and have power loss (I^2R) associated with it. This loss is known as eddy current loss.

This loss depends upon

a) resistivity of material

b) Mean length of path of circulating current for a given cross section.

The eddy current loss is given by,

$P_e = K B_m^2 f^2 t^2 v$ watts.

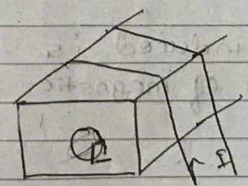
Where, B_m = Maximum value of flux density in the core

f = frequency of exciting current

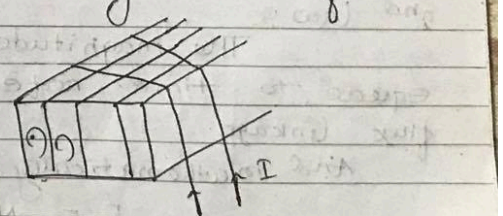
v = volume of iron core

t = thickness of each lamination.

K = Constant, depending on nature of core.



Solid core



Laminated sheet.

In practical application the eddy current loss can be reduced by

1. adding silicon to steel which will give a resistivity of the material.
2. By dividing of the solid core in to thin lamination while making sure that each lamination is insulated from eachother.

* Faraday's Law of electromagnetic Induction

- History was created in 1831 in the relationship between electricity and magnetism.

- Faraday observed the phenomenon and formulated Laws known as "Faraday's law of electromagnetic induction".

1st Law:

Whenever the magnetic flux linked with a conductor changes with respect to time, an emf will be always induced in a conductor.

2nd law:

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

And mathematically,

$$E = N\frac{d\phi}{dt}, \quad N \rightarrow \text{number of turns.}$$

The magnetic flux linkage could be changed in two ways,

ⓐ statistically induced Emf

ⓑ Dynamically induced Emf.

* statistically induced Emf

In this method, there is no physical movement of conductor and coil, Only the magnitude of magnetic flux is changed thereby changing flux linkage.

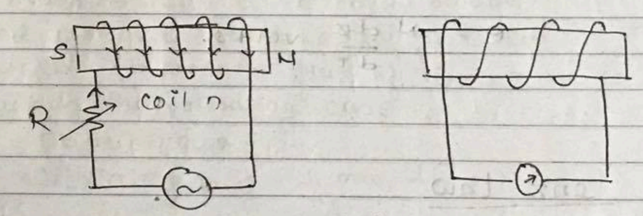


Fig: Illustration of statistically induced emf.

When the value of DC current is varied by varying the resistance R_v in coil A, the produced magnetic flux also varies. When current is not varies, magnetic flux remains constant.

When I is kept constant, no change in flux linkage occurs in coil B & thus no induced emf in coil B. When I is increased, change in flux linkage occurs in coil B & galvanometer shows deflection in one direction. And when current is decreased, galvanometer shows deflection in opposite direction.

- If the magnetic flux in coil B changes from ϕ_1 to ϕ_2 in small time interval t_1 to t_2, then according to second statement of Faraday's law of electromagnetic induction, emf induced in single term of coil B is,

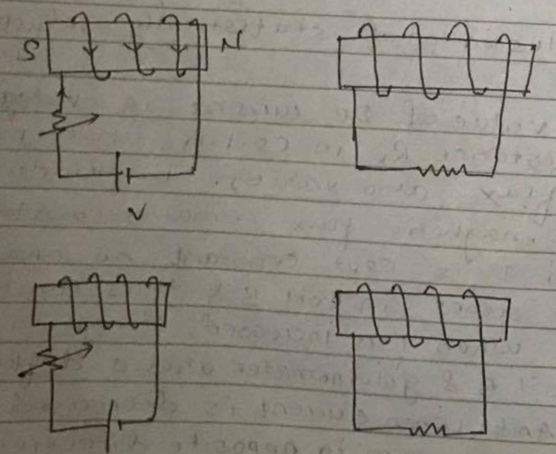
$$e(\text{per turn}) = \frac{\phi_2 - \phi_1}{t_2 - t_1} = \frac{d\phi}{dt}$$

= Rate of change of flux

for 'N' no. of turns in coil-B

$$e = N \frac{d\phi}{dt} \text{ volts.}$$

Lenz Law



Direction of induced emf/current in the conductor will be such that the magnetic field setup by the induced current opposes the cause by which current/emf was induced.

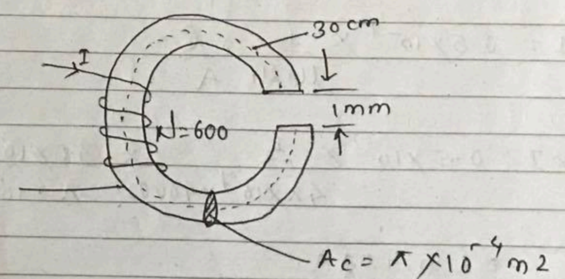
Now emf becomes,

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

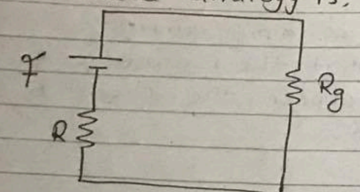
* A wrought iron bar 30cm long and 2cm in diameter is bent into a circular shape. It is then wound with 600 turns of wire. Calculate the current required to produce flux of 0.5mWb in magnetic circuit in the following case

(i) no air gap

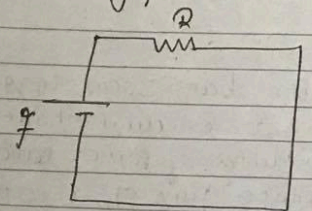
ii) with air gap of 1 mm, $\mu_r = 4000$.



It's electrical analogy is,



When there is no air gap,



$mmf = \phi R$

$NI = \phi R$

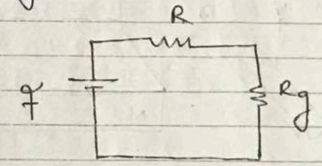
or, $600 \times I = 0.5 \times 10^{-3} \times R$.

or, $600 \times I = 0.5 \times 10^{-3} \times \frac{1}{\mu_0 \mu_r} \cdot \frac{l}{A}$

or, $600 \times I = 0.5 \times 10^{-3} \times \frac{1}{4\pi \times 10^{-7} \times 4000} \times \frac{30 \times 10^{-2}}{\pi \times 10^{-4}}$

$I = 0.152 A$.

When air gap is introduced:



$mmf = \phi (R + R_g)$

or, $NI = \phi \left(\frac{l_1}{\mu_0 \mu_r A_1} + \frac{l_2}{\mu_0 A_2} \right)$

or, $600 I = 0.5 \times 10^{-3} \left(\frac{30 \times 10^{-2}}{4\pi \times 10^{-7} \times 4000 \times \pi \times 10^{-4}} + \frac{1 \times 10^{-3}}{4\pi \times 10^{-7} \times \pi \times 10^{-4}} \right)$

$\therefore I = 2.26 A$.

b) Dynamically Induced Emf

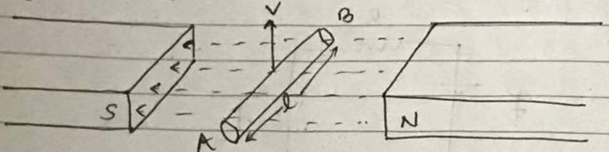


Fig: Illustration of Dynamically Induced emf

In this method field is stationary and conductors cut the flux, as it is in motion.

As shown in the figure, the Conductor is moving upward with velocity 'v'. Here in small time 'dt', the conductor sweeps a distance 'dx' with velocity 'v'.

When the conductor moves in magnetic field, then there is a change in flux linkage

Now,

$d\phi = B \times A$ where A = swept area in 'dt' time

$d\phi = B * l\, dx$

$d\phi = B * l\, v\, dt$ ($v = \frac{dx}{dt}$)

$\frac{d\phi}{dt} = Blv$

As we know, $e = \frac{d\phi}{dt}$

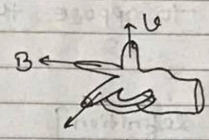
$e = BLV$

The direction of induced emf can be found by Fleming's

⊙ comes outward

⊗ = Goes inward.

right hand rule.



current (I)

(Direction of induced emf)

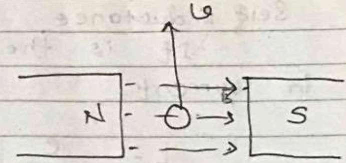


fig a.

*Find the dir^n of current using both rule (vector and Fleming RH Rule)

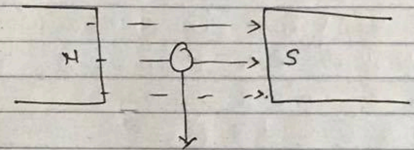
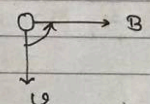


fig b



current outward

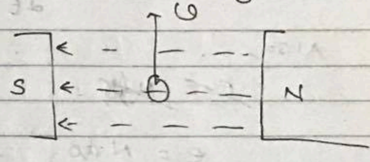
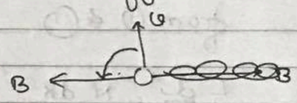
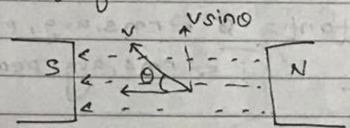


fig c.



current outward

for a conductor making an angle θ with the direction of flux



$e = BLv \sin\theta$

Where $v\sin\theta$ = component of v in direction perpendicular to direction of magnetic flux.

Self Inductance

It is the nature of coil to oppose the change in current.

$$L = \frac{e}{di/dt} \quad [\because \text{from definition}]$$

$$\Rightarrow e = L\frac{di}{dt} \quad \text{--- (I)}$$

Also,

$\cancel{e = N\phi}$

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

from (I) & (II)

$$L\frac{di}{dt} = N\frac{d\phi}{dt}$$

$$L = N\frac{d\phi}{di}$$

for,

$\phi \propto i$, $\frac{d\phi}{di} = \text{constant}$: $\bar{\phi} \leftarrow$ rms, avg, peak

$\bar{i} \leftarrow$ rms, avg, peak.

$$\therefore L = \frac{N\phi}{i}$$

Also,

$$\phi = \frac{NI}{Rel} = \frac{NI}{\frac{1}{\mu}\frac{l}{A}}$$

Then,

$$L = \frac{N}{i}\left(\frac{NI}{\frac{1}{\mu}\frac{l}{A}}\right)$$

$$= \frac{\mu N^2 A}{l}.$$

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

* Force on a current carrying conductor.

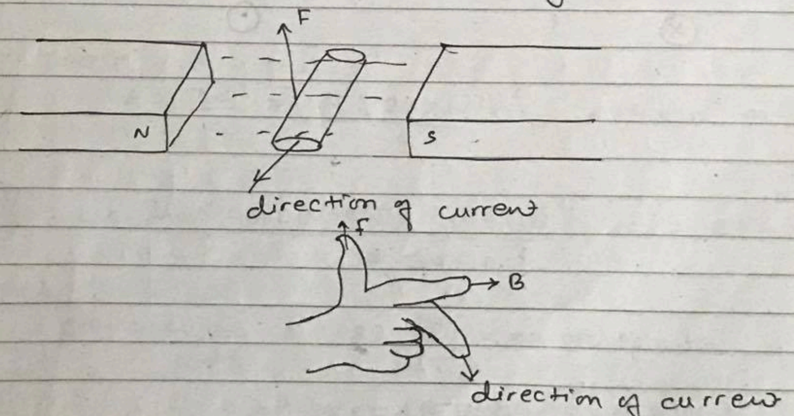


fig 1. Fleming left hand rule.

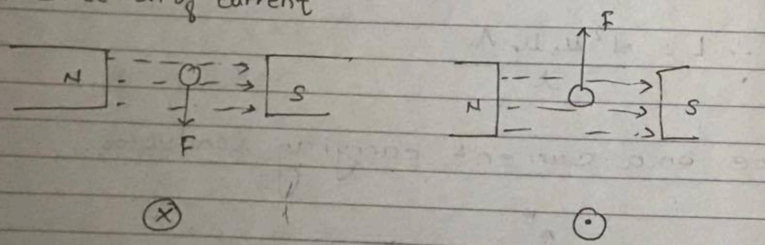
Whenever a current carrying conductor is placed in magnetic field a force will be develope in a conductor. that force is given by.

$F = BIL$

Where, L = ~~Inductance~~ length of conductor
I = current in conductor.

And direction of current is given by Fleming's left hand rule.

* Direction of current



Q.// A 30 cm Long circular iron rod is bent into circular ring and 600 turns of winding are wound on it. The diameter of rod is 20 mm and relative permeability is 4000. A time varying current $i = 5 \sin 314.16t$ is passed through the winding. Calculate the inductance of coil and average value of emf induced in coil.

→ solution.

$i = 5 \sin 314.16t$

comparing with $i = i_0 \sin \omega t$.

$\therefore i_0 = 5A$

$\omega = 314.16$

Now,

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

Here,

$$A = \frac{\pi d^2}{4} = \frac{\pi (20 \times 10^{-3})^2}{4} = 3.14 \times 10^{-4}\ m^2$$

$$\therefore L = \frac{\mu_0 \times 4000 \times (600)^2 \times 3.14 \times 10^{-4}}{30 \times 10^{-2}} = 1.89\ H.$$

Now,

$$emf = L\frac{di}{dt} = 1.89 \frac{d}{dt}(5 \sin 314.16t)$$

$$= 1.89 \times 5 \times 314.16 \times \cos 314.16t$$

$$\therefore e = 2968.812 \cos 314.16t$$

$e = e_0 \cos \omega t$,

$\therefore e_0 = 2968.812$.

$\therefore e_{avg} = \frac{2}{\pi} e_0 = \frac{2}{\pi} \times 2968.812$

$= 1890$ V.

Chapter 2: Transformer (2Ø)

2.1 Constructional Details

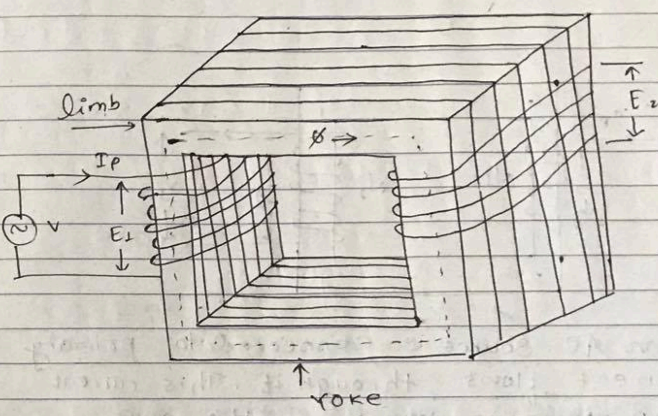
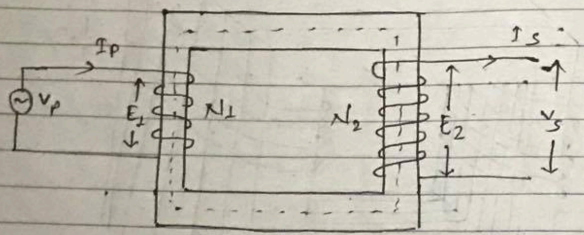


Fig: Simple constructional detail of 1-Ø transformer.

Transformer is the backbone of AC power system.
Transformer is the Static AC machine that

- Transfer energy between two isolated circuits through electromagnetic induction.
- does so without change in frequency of voltage and current.
- But magnitude of voltage and current can be varied.
- has electric circuits that are linked by a common magnetic circuit.
- primary winding is connected to source
  secondary winding is connected to load.

Working principle



When an AC source is connected to primary winding current flows through it. This current produces an alternating flux ϕ in the core.

The frequency of the induced emf will be same that of the frequency of flux which is same as the supply voltage.

Due to induced emf 'E_2', secondary winding can delivered current to the load if connected. The alternating flux in the core also links with the primary winding so produces self induced emf 'E_1' in the primary winding. This emf opposes the applied voltage thus sometime called 'back emf'. Which is responsible to limit the current in primory winding.

Emf Equation

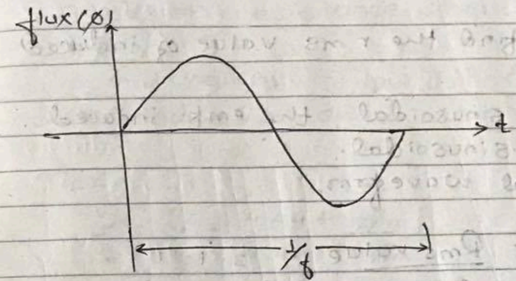


fig: Sinusoidal variation of flux with time.

pw = primary winding

When an alternating voltage is applied to pw of transformer an alternating (sinusoidal) flux gets set up in the iron core which links both pw & sw.

let, ϕ_m = Maximum value of flux
f = supply frequency.

from fig alongside, the value of flux increases from 0 to ϕ_m in $\left(\frac{1}{4f}\right)$ sec.

So, average rate of change of flux $= \frac{d\phi}{dt} = \frac{\phi_m - 0}{1/4f}$

$$\left.\frac{d\phi}{dt}\right|_{avg} = 4f\phi_{max}.$$

Since, average emf induced per turn in volts = average rate of change of flux.

Average emf induced = $4f \phi_m$ volts.

Now, we have to find the r ms value of induced emf.

Since the flux is sinusoidal, the emf induced in the coil will be sinusoidal.

And, for sinusoidal waveform,

$$\text{Form factor} = \frac{\text{Rms value}}{\text{Average value}} = 1.11$$

$\Rightarrow$ Rms value = 1.11 * Avg value

$\therefore$ Rms value of emf induced per turn
$= 1.11 * 4f \phi_m$

If N_1 & N_2 be the no. of turns of pw & sw, then
RMS value of induced Emf in pw = $4.44 N_1 f \phi_m$

Rms value of induced emf in secondary winding
$E_2 = 4.44 f N_2 \phi_m$ volts.

Alternative way:

$\phi = \phi_m \sin\omega t$

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

$= N\frac{d}{dt}(\phi_m \sin\omega t)$

$e = N\phi_m \omega \cos\omega t$

$e = E_m \cos\omega t$

$E_m = N\phi_m \omega$

$E_{rms} = \frac{E_m}{\sqrt{2}} = \frac{N\phi_m 2\pi f}{\sqrt{2}}$

$= N\phi_m f \frac{2\pi}{\sqrt{2}}$

$E_{rms} = 4.44 N\phi_m f$

Considering purely inductive winding i.e, with negligible resistance, there will be no voltage drop.

i.e, emf induced in pw E_1 = Applied voltage V_1,
& emf induced in sw E_2 = terminal voltage V_2.

Then,

$$\frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{4.44 f N_2 \phi_m}{4.44 f N_1 \phi_m}$$

$\boxed{\therefore \frac{V_2}{V_1} = \frac{N_2}{N_1} = K}$, where K is transformation ratio or turn ration.

$\boxed{V \propto N}$

$V \propto N$, means, more the no. of turns, higher the voltage.

$$\therefore K = \frac{V_{sec}}{V_{pri}} = \frac{N_{sec}}{N_{pri}} = \frac{N_2}{N_1}$$

If $K>1$, $N_2 > N_1 \Rightarrow V_2 > V_1$ step-up transformer.

If $K<1$, $N_2 < N_1 \Rightarrow V_1 > V_2$, step-down "

If $K=1$, $N_2 = N_1 \Rightarrow V_2 = V_1$ (isolation transformer)

In ideal transformer, losses are neglected.

So,

output VA = Input VA

$V_2 I_2 = V_1 I_1$ $\Rightarrow$ $\boxed{\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1} = K}$

2.3 Ideal Transformer

For a better understanding and easier explanation ~~of a practical~~ ideal case is assumed. The transformer with the ideal case listed below is called ideal transformer.

1) Zero winding resistance i.e, purely inductive with no ohmic loss (copper loss) & no resistive voltage drop.
2) No magnetic leakage i.e all the flux set up in the core links two windings.
3) With no iron loss i.e, no hysteresis & eddy current loss.
4) permeability of core is ∞.
i.e, no magnetizing current needed to setup flux in the core i.e, zero R (reluctance).

2.4 No load and Load operation.

Transformer on No-load.

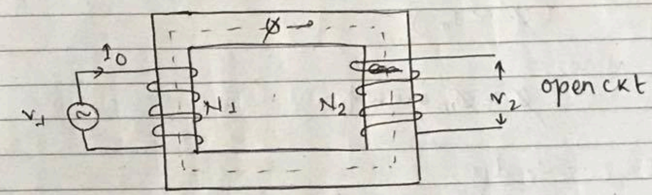
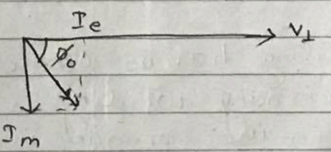


Fig:- Transformer on No load

When the primary winding of a transformer is connected to source of a supply and secondary is open, the transformer is said to be at no load.

In ideal transformer, where there is no losses in the core of a transformer, the current I_0 lags the primary voltage V_1 by $90°$. But in actual case there will be some power loss which the no load current I_0 has to supply. Thus the phasor between V_1 & I_0 will be less than $90°$.



Hence, from phasor diagram, we see I_0 (no load current) has two components.

i) $I_e = I_0 \cos\phi$ (Active/loss component which supply the active power loss in core)

ii) $I_m = I_0 \sin\phi$ (Reactive/magnetizing component) which is responsible to maintain flux in core

$(\phi \propto I_m)$

Now,

$\phi = \phi_m \sin\omega t$

$E_1 = -N_1 \dfrac{d\phi}{dt}$

$= -N_1 \dfrac{d}{dt}(\phi_m \sin\omega t)$

$= -N_1 \phi_m \omega \cos\omega t$

$= -E_m \cos\omega t$

$= -E_m \sin(90 - \omega t)$

$E = E_m \sin(\omega t - \pi/2)$

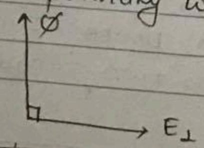
Similarly,

$E_2 = N_2 \phi_m \sin(\omega t - \pi/2)$

For no ohmic voltage drop,

$V_1 = -E_1 = -N_1 \phi_m \omega \sin(\omega t - \pi/2)$

(since primary winding has no ohmic resistance, applied voltage to primary winding is to oppose the induced emf in the primary winding)



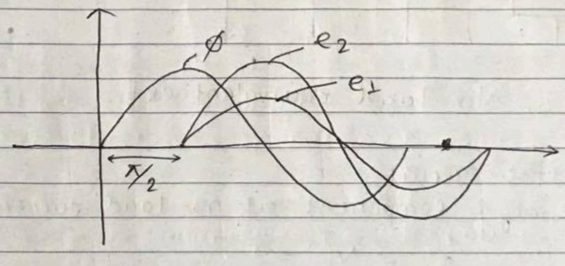
Now,

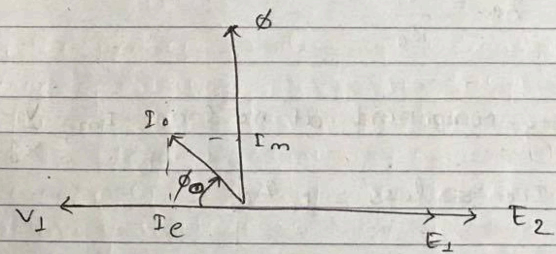
$\phi = \phi_m \sin\omega t$

$E_1 = \omega N_1 \phi_m \sin(\omega t - \pi/2)$

$E_2 = \omega N_2 \phi_m \sin(\omega t - \pi/2)$

$V_1 = -E_1$ (for no voltage drop)

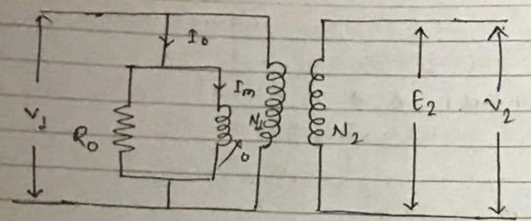




$I_0 = \sqrt{I_m^2 + I_e^2}$

$\phi = \tan^{-1}\left(\dfrac{I_m}{I_e}\right)$, Angle of lag.

At no load, Equivalent current becomes



No-load equivalent ckt

From the circuit

Energy component at no-load current,

$$I_e = \frac{V_1}{R_0}$$

and,

Magnetizing component at no load, $I_m = \frac{V_1}{X_0}$

Iron loss $= I_e^2 R_0$

* Transformer on load

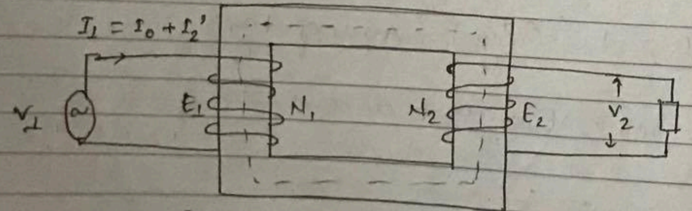


Fig:- Transformer on load

At no load, transformer draws I_0 current from supply mains. The no load current I_0 sets up mmf $N_1 I_0$ which produces flux ϕ in the core. When an impedance is connected across secondary terminals, current 'I_2' flows through secondary winding.

The secondary current I_2 sets up its own mmf and creates a secondary flux ϕ_2. The secondary flux ϕ_2 opposes main flux ϕ set up by exciting current I_0, according to Lenz law. The opposing secondary flux ϕ_2 weakens the main flux ϕ momentarily, so primary back emf E_1 tends to be reduced. So difference of applied voltage V_1 and back emf E_1 increases, therefore more current is drawn from source of supply flowing through primary winding until the original value of ϕ is obtained.

Let the additional primary current be I_2' and is in phase opposition to I_2 and is called counter balancing current. Thus addition current I_2' sets up $N_1 I_2'$ producing ϕ_2' in the same direction as that of ϕ and cancels ϕ_2 produced by mmf $N_2 I_2$.

Here,

Output $VA = I_2 V_2$

and Additional input $= V_1 I_2'$

For power balance,

$$I_2 V_2 = V_1 I_2'$$

$$\frac{V_2}{V_1} = \frac{I_2'}{I_2} = \frac{N_2}{N_1}$$

$$\boxed{\therefore I_2' N_1 = N_2 I_2}$$

Now,

$$\phi_2' = \frac{mmf}{Rel} = \frac{N_1 I_2'}{Rel} \text{ and } \phi_2 = \frac{N_2 I_2}{Rel}.$$

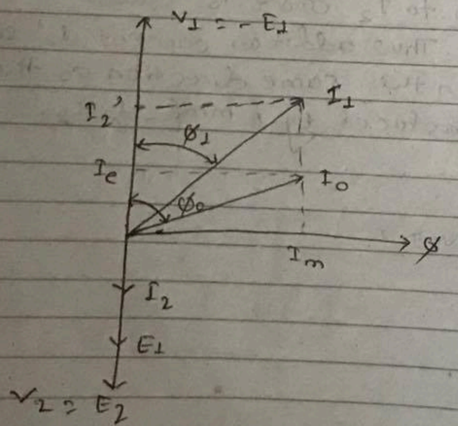
So, $\boxed{\phi_2' = \phi_2}$

Hence, the net magnetic flux in the core of a transformer is always constant irrespective of the load.

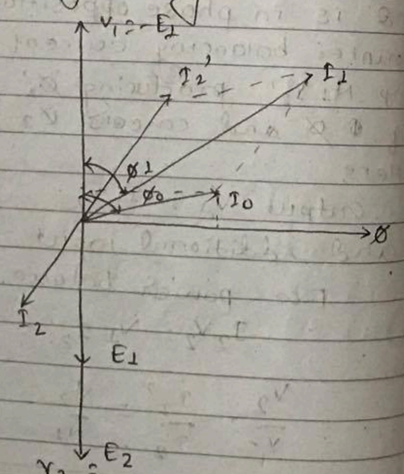
Also,

$$\frac{I_2'}{I_2} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = k.$$

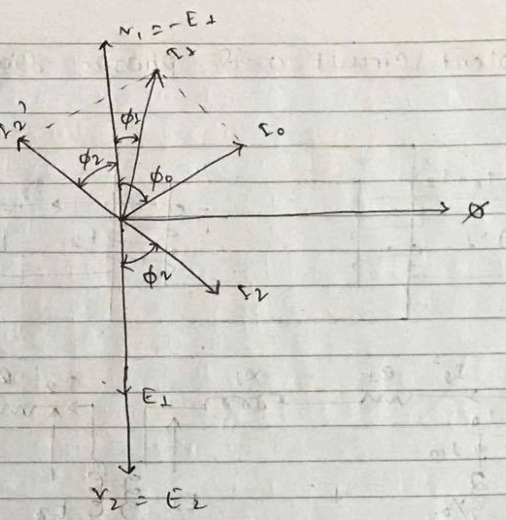
The nature of I_2 depends upon the type of load connected to secondary winding.



for resistive load

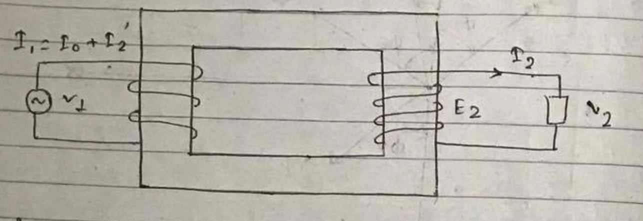


for inductive load.



For capacitive load

2.6 Equivalent circuit and phasor diagram



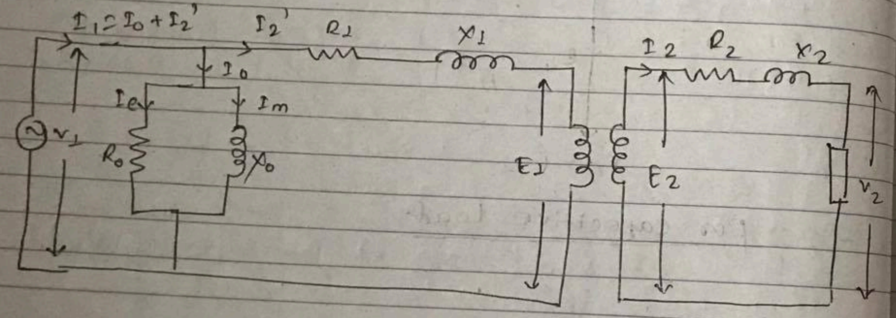


fig:- equivalent ckt of transformer.

Here,

R_1 = resistance of primary winding

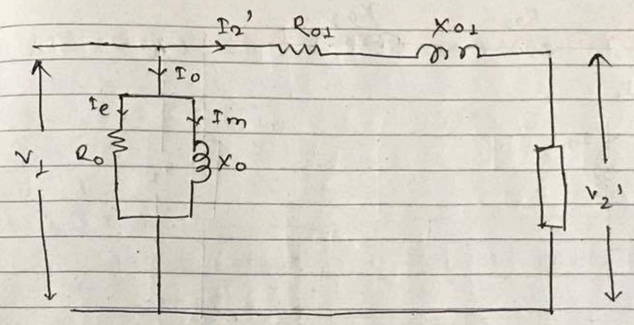
R_2 = resistance of secondary winding.

X_1 = leakage reactance of primary winding.

X_2 = leakage reactance of secondary winding

Pg → (*)

(* *)



Equivalent circuit

where,

$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$

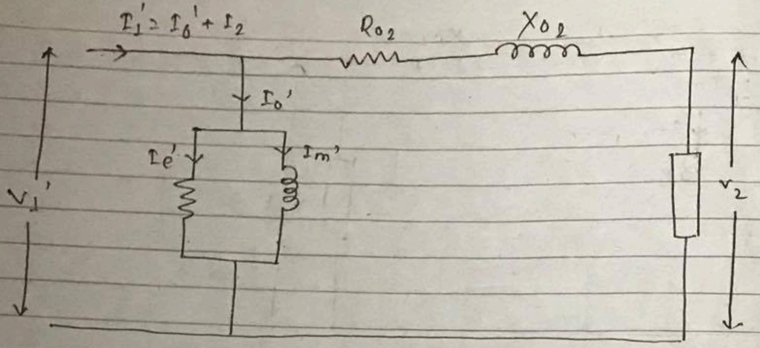
$X_{01} = X_1 + X_2'$

Now,

$V_2' I_2' = V_2 I_2$

$V_2' = V_2 \frac{I_2}{I_2'}$

$V_2' = \frac{V_2}{K}$



Equivalent circuit of a transformer referred to secondary side.

$R_{02} = R_2 + R_1'$
$X_{02} = X_2 + X_1'$

$I_2^2 R_{02} = I_2^2 R_1' + I_2^2 R_2$

$\therefore R_{02} = R_1' + R_2.$

Now, $(I_2')^2 R_1 = (I_2)^2 R_1'$

$\therefore R_1' = \left(\frac{I_2'}{I_2}\right)^2 R_1 = k^2 R_1$

Also,
$X_{02} = X_1' + X_2$

$(I_2')^2 X_1 = (I_2)^2 X_1'$

$\therefore X_1' = \left(\frac{I_2'}{I_2}\right)^2 X_1$

$X_1' = k^2 X_1$

Now,
$X_0' = k^2 X_0$
$R_0' = k^2 R_0$

And
$\frac{(I_2)_s}{(I_2')_p} = 1/k$

$\therefore I_2 = \frac{I_2'}{k}$

Now,
$I_1' V_1' = I_1 V_1$

$\therefore I_1' = \frac{V_1}{V_1'} I_1$

$\boxed{I_1' = \frac{1}{k} I_1}$

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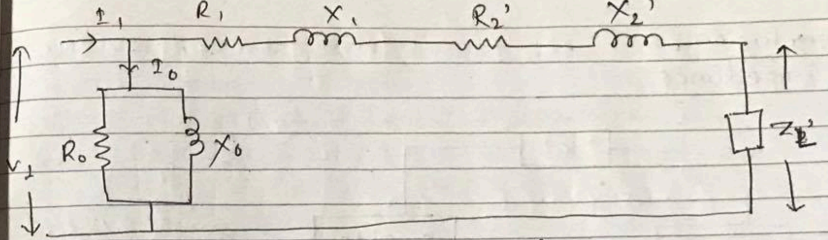


fig (2) Equivalent ckt referred to primary side.

copper loss in secondary $= I_2^2 R_2$
" " in primary $= (I_2')^2 R_2'$

for making eq^n ckt.

$I_2^2 R_2 = (I_2')^2 R_2'$

$R_2' = \left(\frac{I_2}{I_2'}\right)^2 R_2$

$R_2' = \left(\frac{1}{k}\right)^2 R_2 \quad \left(k = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = \frac{I_2'}{I_2}\right)$

$\therefore X_2' = \left(\frac{1}{k}\right)^2 X_2.$

$\therefore Z_L' = k Z_L$

for Z_L,
$(I_2')^2 Z_L' = I_2^2 Z_L$

$Z_L' = \left(\frac{I_2}{I_2'}\right)^2 Z_L = \left(\frac{1}{k}\right)^2 Z_L$

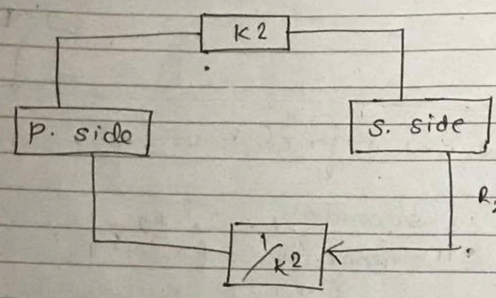
$\therefore Z_L' = (1/k)^2 Z_L$

back to page (**)

* * *

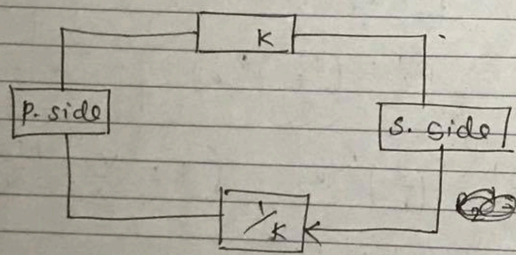
Conclusion

i) impedance



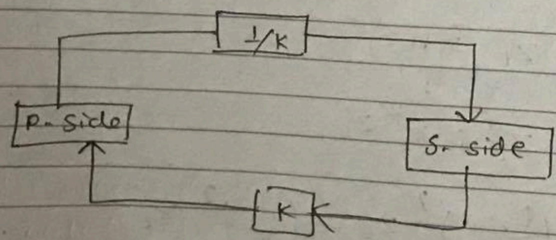
$R_2' = R_2 / K^2$

ii) Voltage



$V_2' = \frac{V_2}{K}$

iii) current



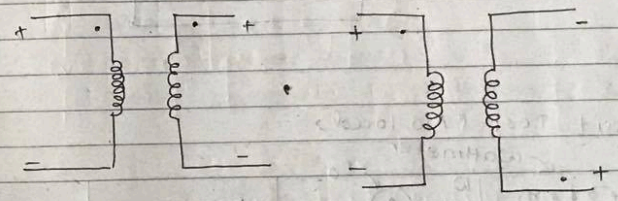
2.7 Test of Transformer

2.7.1 polarity Test

2.7.2 open circuit Test (No load test)

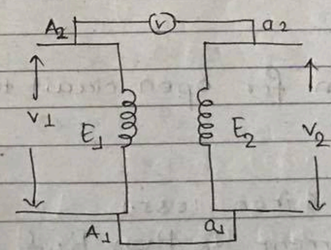
2.7.3 short circuit test

2.7.1 polarity test



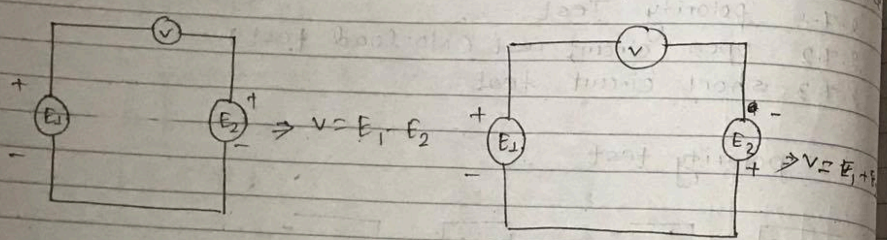
polarity test is represented by mark.

- polarity test is performed to determine the terminals having som instantaneous polority.



Necessity: while connecting windings of transformer in parallel or series.

- The idea is to connect the two windings of transforming in a series across a voltmeter and then one of the windings is excited from suitable source



2.7.2. Open Circuit Test (No load)

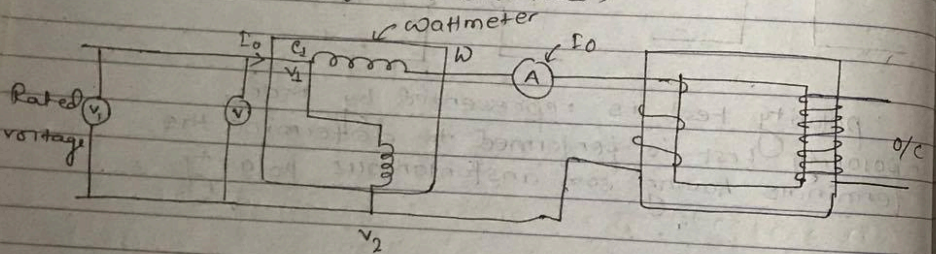


fig: Circuit diagram for open circuit test

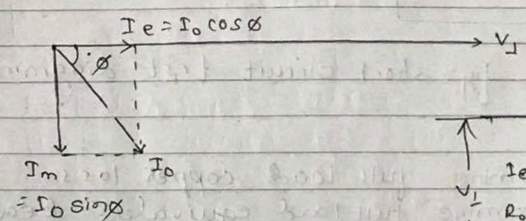
Objective of open ckt test

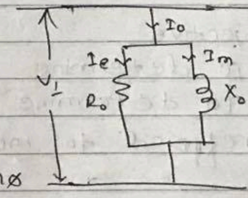
1. Determine the core loss (iron loss)
2. Determine the no load current I_0 then find out the shunt branch parameter.

steps

1. open the high voltage side
2. supply rated voltage from low voltage side (supplied rated high voltage would be different and no load current in high voltage side is very small to detect).
3. Ammeter A measures no load current I_0 and wattmeter W measures input power P_0.

for figure above
supply voltage = V_1
current from Ammeter = I_0
power measured by wattmeter = P_0.





$P_0 = V_1 I_0 \cos\phi$

$\cos\phi = \frac{P_0}{V_1 I_0}$

$\phi = \cos^{-1}\left(\frac{P_0}{V_1 I_0}\right)$

$I_m = I_0 \sin\phi$

$I_e = I_0 \cos\phi$

from equivalent ckt:

$R_0 = \frac{V_1}{I_e} = \frac{V_1}{I_0 \cos\phi}$

$X_0 = \frac{V_1}{I_m} = \frac{V_1}{I_0 \sin\phi}$

parameters are always calculated by reffering to the side where current, voltage and power were measured.

2.7.3 Short ckt test:

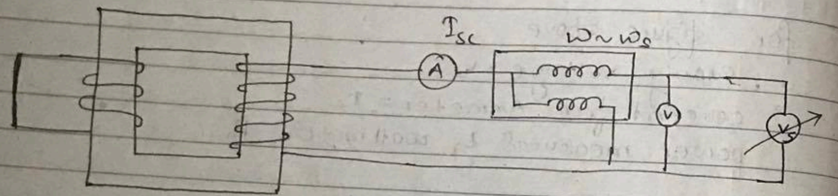


fig: short circuit test diagram.

Objective:

1. To determine full load copper loss
2. To determine full load equivalent leakage reactan referred to measuring side.

Steps:

1. Always short ckt the low voltage side
2. Increase voltage V_s gradually till ammeter A indicates the rated current (full load current) in high voltage side.

Since this voltage is very low so flux linking with core is very small and iron loss also very small thus can be neglected.

From the circuit
short circuit voltage = V_{sc}
short circuit current = I_{sc}
copper loss / power measured by wattmeter = W_{sc}.

$W_{sc} = I_{sc}^2 R_{02}$

$R_{02} = \frac{W_{sc}}{I_{sc}^2}$

$Z_{02} = \frac{V_{sc}}{I_{sc}}$

$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2}$

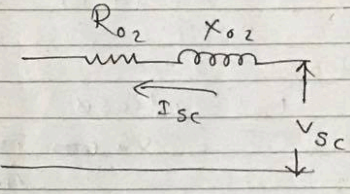


fig: Equivalent ckt.

If low voltage was used the required voltage would be very small (nearly 5% of rated voltage) and it would be inconvenient for precise measurement.

Q.1//
A 200 KVA, 2000/440V, 50HZ single phase transformer gave the following results.

Noload test	440V	1500W	8A
Short ckt test	30V	2000W	300A.

Given,
$V_1 = 440V$, $W = 1500\,W$, $I_0 = 8A$
$V_{sc} = 30V$, $W_s = 2000\,W$, $I_{sc} = 300\,A$

for open ckt test,

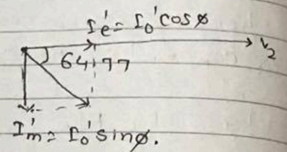
$V_2 = 440V$

$I_0' = 8A$.

$P_0 = V_2 I_0' \cos\phi$

$1500 = 440 * 8 * \cos\phi$

$\Rightarrow \phi = 64.77°$



Now,

$I_e' = I_0' \cos\phi$

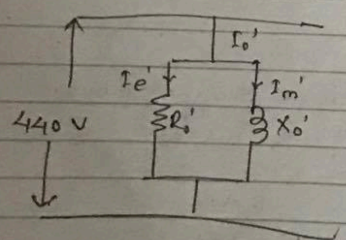
$= \cancel{8} * \frac{1500}{440 * \cancel{8}}$

$= \frac{150}{44} = 3.409\ A.$

$I_m' = I_0' \sin\phi$

$= 8 * \sin 64.77$

$= 7.236\ A$



$R_0' = \frac{V_2}{I_e'} = \frac{440}{3.409} = 129.07\Omega$

$X_0' = \frac{V_2}{I_m'} = \frac{440}{7.236} = 60.80\Omega$

Now,

$I_p^2 R_p = I_s^2 R_s$

$R_p = \left(\frac{I_s}{I_p}\right)^2 R_s$

$= \left(\frac{1}{K}\right)^2 R_s$

$R_0 = \left(\frac{1}{K}\right)^2 R_0'$

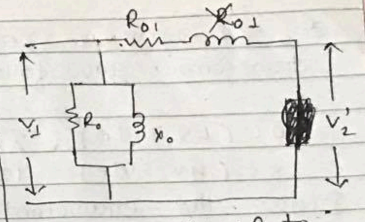
$= \left(\frac{2000}{440}\right)^2 * 129.07$

$= 2666.73\Omega.$

$X_0 = \left(\frac{1}{K}\right)^2 X_0'$

$= \left(\frac{2000}{440}\right)^2 \times 60.80$

$= 1256.198.$



Eq. ck referred to primary side.

~~...~~

$V_2' = V_1 -$

Short circuit test.

$V_{SC} = 30V$

$I_{SC} = 300A$

$W_{SC} = 2000W.$

$W_{SC} = I_{SC}^2 R_{01}$

$R_{01} = \frac{2000}{300^2} = 0.0222$

$Z_{01} = \frac{V_{SC}}{I_{SC}} = \frac{30}{300} = 0.1$

$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

$= \sqrt{0.1^2 - 0.0222^2}$

$= 0.0975\Omega.$

Q. A 20 kVA, 250/2500 V, 50 Hz, single phase transformer gave following tests.

OC (LV side)	250 V	1.4 A	105 W
SC (HV side)	120 V	8 A	320 W.

Draw the equivalent circuit of transformer referred to
(a) low voltage side
(b) HV side.

→ Solution

Given,

$V_1 = 250V$,

$V_2 = 2500V$.

Referred to LV side:

$V_1 = 250V$ $\qquad$ $V_{sc} = 120V$

$I_0 = 1.4A$ $\qquad$ $I_{sc} = 8A$

$P_0 = 105W$ $\qquad$ $W_{sc} = 320W$

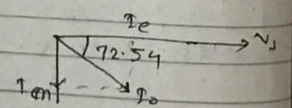
Now,

For open ckt test:

$P_0 = V_1 I_0 \cos\phi$

or, $105 = 250 \times 1.4 \times \cos\phi$

$\Rightarrow \phi = 72.54°$.



Now,

$I_e = I_0 \cos\phi$

$= 1.4 \times \cos 72.54$

$= 0.42A$.

$I_m = I_0 \sin\phi$

$= 1.4 \times \sin 72.54$

$= 1.33A$.

Now, short ckt test,

$R_{01} = R_1 + R_2'$ $\qquad$ $X_{01} = X_1 + X_2'$

$W_{sc} = I_{sc}^2 \times R_{02}$

or, $320 = 8^2 \times R_{02}$

$\therefore R_{02} = 5\Omega$.

Now,

$Z_{02} = \frac{V_{sc}}{I_{sc}} = \frac{120}{8} = 15\Omega$.

Now,

$X_{02} = \sqrt{(Z_{02})^2 - (R_{02})^2}$

$= \sqrt{15^2 - 5^2}$

$= 14.14\Omega$.

So,

$I_p^2 R_{01} = I_s^2 R_{02}$

or, $R_{01} = \left(\frac{I_s}{I_p}\right)^2 R_{02}$

$= \left(\frac{V_1}{V_2}\right)^2 R_{02}$

$= \left(\frac{250}{2500}\right)^2 \times 5$

$\therefore R_{01} = 0.05\Omega$

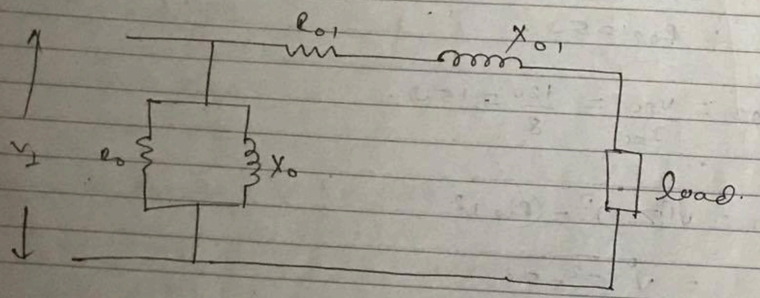
And, $X_{01} = \left(\frac{250}{2500}\right)^2 \times 14.14$

$= 0.01414\,\Omega$.

Now,

$R_0 = \frac{250}{0.42} = 595.23\,\Omega$

$X_0 = \frac{250}{1.33} = 187.96\,\Omega$



2.8 Voltage Regulation

The quantity of a transformer from the point of view of voltage drop is expressed in term of quantity called voltage regulation. Wheneve the current varies, the voltage drop across resistance and leakage reactance will vary, so does terminal voltage.

Voltage regulation of a transformer is defined as the change in magnitude of output voltage from full load to no load expressed as the % of full load or No load.

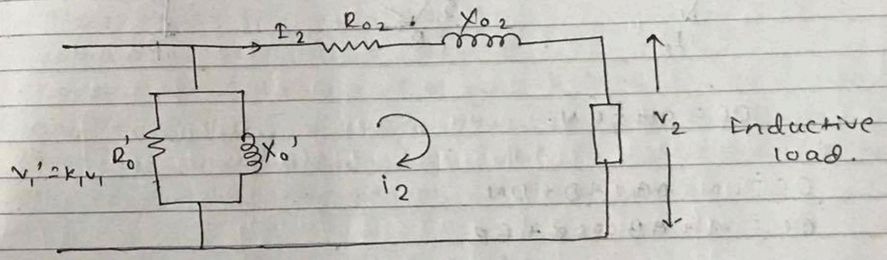


Fig: Equivalent ckt referred to sec. side

$$V_{reg} = \frac{{}_0V_2 - {}_fV_2}{{}_fV_2} \times 100\%$$

or,

$$V_{reg} = \frac{{}_0V_2 - {}_fV_2}{{}_0V_2} \times 100\%$$

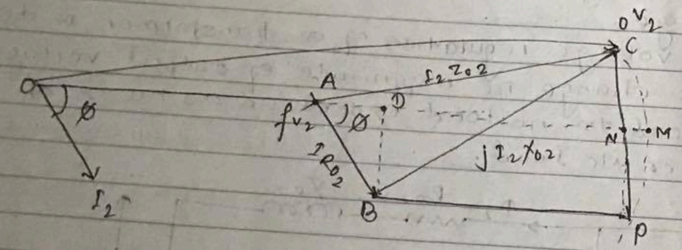
Where,

${}_0V_2$ = No load terminal votage.
${}_fV_2$ = full load terminal votage.

Applying KVL,

$V_1' = I_2 R_{02} + j I_2 X_{02} + V_2.$

$\therefore OV_2 = I_2 R_{02} + j I_2 X_{02} + fV_2$



$OC = OM \cong ON.$

$OC = ON = OA + AD + DN$

$OC = OA + AB\cos\phi + BP$

$OC = OA + I_2 R_{02}\cos\phi + j I_2 X_{02}\sin\phi$

$OV_2 = fV_2 + I_2 R_{02}\cos\phi + j I_2 X_{02}\sin\phi$

$$\frac{OV_2 - fV_2}{fV_2} = \left(\frac{I_2 R_{02}}{fV_2}\right)\cos\phi + \left(\frac{I_2 X_{02}}{fV_2}\right)\sin\phi$$

for inductive,

$$\boxed{\text{voltage } \epsilon_g = (R_{pu})\cos\phi + (X_{pu})\sin\phi}$$

2.9 Losses in a transformer

The output of a transformer is always less than input because there are some power losses within the transformer.

There are mainly two types of losses.

i) Iron loss $(W_i) = V_1 I_0 \cos\phi$

ii) Copper loss $(W_{cu}) = I_1^2 R_1 + I_2^2 R_2$.

Iron loss is the power loss due to heating of the iron core and the main causes for this heating are eddy current loss and hysteresis loss. This power loss is equal to no load loss and remains constant at any load.

Copper loss is power loss due to heating of primary and secondary coil. The main cause of coppor loss is heat generation due to resistance of coils. The copper loss depends on load & given by,

$W_{cu} = I_1^2 R_1 + I_2^2 R_2$ watts.

$= I_1^2 R_{01} = I_2^2 R_{02}$

2.10 efficiency

For ideal transformer,

$P_{input} = P_{output}$

$\eta = 100\%$

$P_{i/p} = V_1 I_1 \cos\phi$

$P_{o/p} = P_{i/p} - \text{losses}$

$= V_1 I_1 \cos\phi - W_i - W_{cu}$

$$\eta = \frac{P_{output}}{P_{input}}$$

$$\eta = \frac{V_1 I_1 \cos\phi - W_i - W_{cu}}{V_1 I_1 \cos\phi}$$

For maximum efficiency,

$$\frac{d\eta}{dI_1} = 0$$

$$\Rightarrow \frac{d\eta}{dI_1} = \frac{d}{I_1}\left[\frac{V_1 I_1 \cos\phi}{V_1 I_1 \cos\phi} - \frac{W_i}{V_1 I_1 \cos\phi} - \frac{W_{cu}}{V_1 I_1 \cos\phi}\right]$$

$$\therefore 0 = \frac{d}{I_1}\left[1 - \frac{W_i}{V_1 I_1 \cos\phi} - \frac{W_{cu}}{V_1 I_1 \cos\phi}\right]$$

$$\cancel{\text{or, } 0 = \frac{W_i}{V_1 \cos\phi\, I_1^2} + \frac{W_{cu}}{V_1 I_1^2 \cos\phi}}$$

$$\cancel{\text{or, } \frac{W_i}{V_1 I_1^2 \cos\phi} = -\frac{W_{cu}}{V_1 I_1^2 \cos\phi}}$$

$$\cancel{\text{or, } W_i = -W_{cu}}$$

$$\text{or, } 0 = \frac{d}{I_1}\left[1 - \frac{W_i}{V_1 I_1 \cos\phi} - \frac{I_1 R_{01}}{V_1 \cos\phi}\right]$$

$$\text{or, } 0 = \frac{W_i}{V_1 I_1^2 \cos\phi} - \frac{R_{01}}{V_1 \cos\phi}$$

$$\text{or, } \frac{W_i}{\cancel{V_1} I_1^2 \cancel{\cos\phi}} = \frac{R_{01}}{\cancel{V_1} \cancel{\cos\phi}}$$

$$\text{or, } W_i = R_{01} I_1^2$$

$$\therefore W_i = W_{cu}.$$

* $$\eta = \frac{P_{output}}{P_{input}}$$

$$= \frac{KVA * x * pf}{KVA * x * pf + W_i + W_{cu}}$$

Let $x = \dfrac{\text{Actual load}}{\text{Full load}} = \dfrac{\text{Actual KVA}}{\text{full KVA}}$.

Actual $= 0.7 \times 500$

$= 350$ KVA.

$$x = \frac{\text{Actual load}}{\text{full load}} = \frac{I_2 V_2}{(I_{2f}) * V_2}$$

$$I_2 = x * I_{2f}$$

W_{cu} loss $= I_1^2 R_{01} = I_2^2 R_{02} = (x I_{2f})^2 R_{02}$

$= x^2 I_{2f}^2 R_{02}$

$W_{cu} = x^2 W_{cu}$ at full load.

$$\eta = \frac{KVA * x * pf}{KVA * x * pf + W_i + x^2 W_{cu} \text{ at full load}}$$

Q.NO. 15 A:

11000/230V, 150KVA, 50HZ 1 phase transformer has a core loss of 1.4 kW and full load copper loss of 1.6 kW. Determine

(a) The KVA load for maximum efficiency and the maximum efficiency.

b) the efficiency at half load & full load at 0.8 pf lagging.

— Solution.

$$\boxed{x = \frac{\text{actual load}}{\text{full load}} = \frac{1.4}{1.6} = 0.875 \quad x^2}$$

$$\boxed{\text{Actual Load} = x \cdot \text{full load} = 150 * x \text{ KVA} = 150 * 0.875 = 140.312 \text{ KVA}}$$

To have maximum efficiency:

Iron loss = copper loss

iron loss = 1.4 kW (constant)

copper loss at full load = 1.6 kW.

So copper loss should be 1.4 kW (= iron loss) for the transformer to give maximum efficiency.

Copper loss at x load $= x^2 *$ Copper loss at full load

$1.4\text{ kW} = x^2 * 1.6\text{ kW}$

$x = \sqrt{\frac{1.4}{1.6}} = 0.935$

$x = \frac{\text{Actual Load}}{\text{Full Load}}$

$0.935 = \frac{\text{Actual Load}}{150 \text{ KVA}}$

$\therefore$ Actual Load $= 140.31$ KVA

$$\eta = \frac{KVA * x * pf}{KVA * x * pf + W_i + x^2 * W_{cu} \text{ at full Load}}$$

$$\eta = \frac{150 * 0.935 * 0.8}{150 * 0.935 * 0.8 + 1.4 + (0.935)^2 * 1.6}$$

$$= 97.566\%$$

$$\eta_{\frac{1}{2}load} = \frac{150 * 0.5 * 0.8}{150 * 0.5 * 0.8 + 1.4 + (0.5)^2 * 1.6}$$

$$= 79.087\%$$

$$\eta_{1\,load} = \frac{150 * 1 * 0.8}{150 * \cancel{0.935}\,1 * 0.8 + 1.4 + 1 * 1.6}$$

$$= 97.56\%$$

All day efficiency (Energy Efficiency)

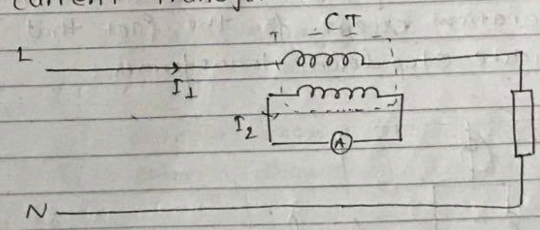
There are certain type of transformer which performance cannot be judged by its power efficiency. Take distribution transformer whose load is light for major portion of ~~whole~~ day. Though iron loss occurs whole day but copper loss occurs only when loaded. The performance of such transformer is judged by all day efficiency also called energy efficiency.

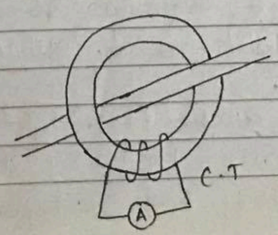
2.11: Special type of Transformer

1. Instrument Transformer — current transformer (CT) / potential transformer (PT)

2. Auto transformer.

1. Current Transformer





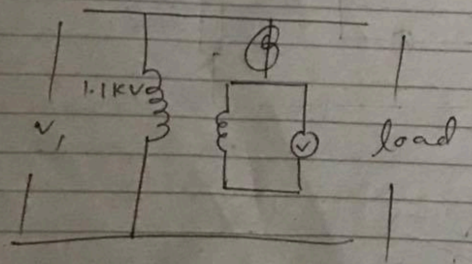
The CT sences the high current and step it down to a low value of current which can be measured using normal ammeter.

primary winding has small number of turns made up of thick wire. Similarly secondary winding has many number of turns of thin wire.

The secondary side of CT should never be kept open (without an ammeter), when the primary is carrying current. If the secondary is kept open (i.e $I_2 = 0$) as shown in the figure. So no opposing flux will be produced for opposing the additional flux produced by primary winding. Hence the net flux in the core increases with ~~increase in~~ induced emf and may cause insulation failure.

ii) potential

potential transformer is similar to normal transformer in operation except for the fact that it is extremly accurate step down transformer.



Auto Transformer

An auto transformer is a special type of transformer with only one winding. A part of the winding is common to both primary & secondary side.

The figure below shows a single phase auto transformer having N_1 turns in primary & N_2 turns tappal for secondary voltage.

The winding sector BC with N_2 turns is common to both primary & secondary side.

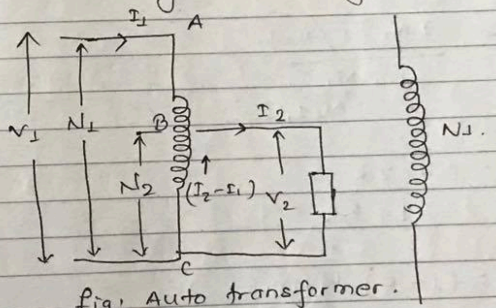


fig: Auto transformer.

Here,

I_1 = current drawn from supply

I_2 = current drawn by load.

Cu saving.

weight of copper in section AB $\propto (N_1 - N_2) I_1$

weight of copper in section BC $\propto N_2 (I_2 - I_1)$

weight of copper used in two winding

$\propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$

and weight of two winding $= N_1 I_1 + N_2 I_2$.

$$\frac{\text{weight of auto}}{\text{weight of two}} = \frac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2}$$

$$\frac{W_{auto}}{W_{two}} = \frac{N_1 I_1 + N_2 I_2 - N_2 I_1 - N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$\text{or } \frac{W_{auto}}{W_{two}} = 1 - \frac{2 N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$= 1 - \frac{2 N_2 I_1 / N_1 I_1}{1 + \frac{N_2 I_2}{N_1 I_1}}$$

$$= 1 - \frac{2k}{1 + k/k}$$

$$W_{auto} = (1-k)\, W_{two}$$

*

Case I: $V_1 = 220\,V$, $V_2 = 200\,V$

Case II: $V_1 = 220\,V$, $V_2 = 6\,V$.

Suggest the type of transformer for your clients for both the cases.

Case I → $\frac{N_2}{N_1} = V_2/V_1 = k = \frac{200}{220} = 0.9090$.

$W_{auto} = \cancel{1-0.93}\,(1-k)\, W_{tw}$

$W_{auto} = 0.091\, W_{tw}$

$W_{auto} = 9.1\%\, W_{two}$ auto suggest.

Case 2: $\frac{V_2}{V_1} = \frac{6}{220} = 0.027 = k$

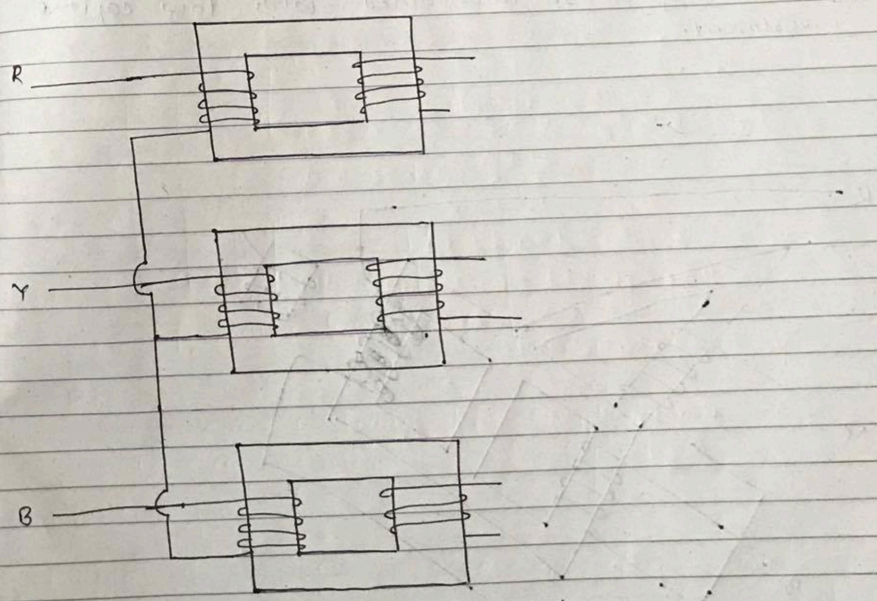
$W_{auto} = (1-k) W_{two}$

$W_{auto} = (1-0.027)\, W_{two}$

$W_{auto} = 97.2\%\, W_{two}$. two suggest.

Hence the saving of copper is used in auto transformer is only significant only when transformer ratio is near unity.

* Three phase Transformer



Disadvantage of this way of connection

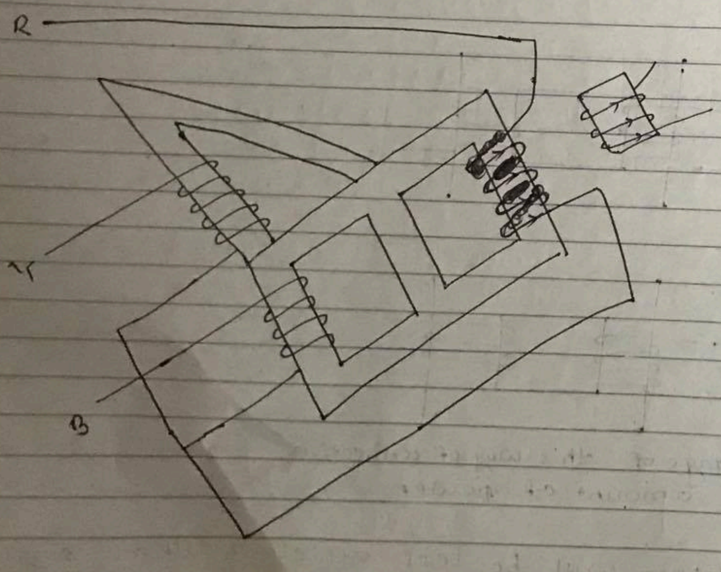
- For same amount of power

- This system will be less efficient than single unit of 3 phase transformer. because of iron loss due to large volume of iron core.

- This system occupy more space compared to single unit of 3 phase transformers.

Disadvantages:

- When single unit of 3-phase transformer is very large for transportation, 3 unit of 1-ϕ transformer would be easier.
- Reliability can be maintained with low capital investment.



$\phi_R = \phi_m \sin\omega t$

$\phi_y = \phi_m \sin(\omega t - 120)$

$\phi_B = \phi_m \sin(\omega t - 240)$.

$\phi_T = \phi_R + \phi_{eY} + \phi_B$.

put $\omega t = 90°, 0°$

$\phi_T = \phi_m \sin 90 + \phi_y \sin(90-120) + \phi_B \sin(90-240)$

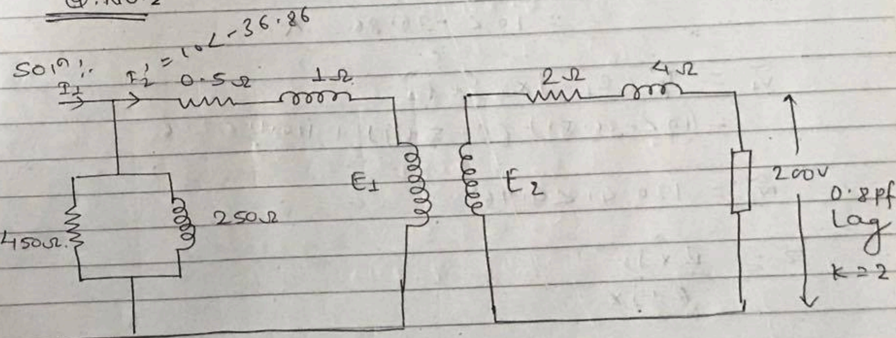
$= 0$.

So no flux passes through central limb.

Tutorial

Q.NO.2

Soln:

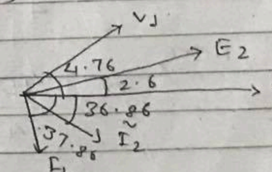


$\tilde{E}_2 = \tilde{I}_2 (R_2 + j\tilde{X}_2) + (\tilde{V}_2 \angle 0)$

$\tilde{V}_2 = 200\angle 0$

$\tilde{I}_2 = 5\angle -\cos^{-1}(0.8)$

$= 5\angle -36.86$



$\tilde{E}_2 = (5\angle -36.86)(2+4j) + (200\angle 0)$

$= 220.22\angle 2.60$

$\frac{E_2}{E_1} = k$

$\therefore \tilde{E}_1 = \frac{\tilde{E}_2}{2} = \frac{220.22\angle 2.60}{2}$

$= 110.11\angle 2.6$

$\frac{I_p}{I_s} = k$

$I_p = k \times I_s = 2 \times (5\angle -36.86)$

$= 10\angle -36.86$ A.

$\tilde{V}_1 = I_2'(R_1 + jX_1) + \tilde{E}_1$

$= (10\angle -36.81)(0.5+j) + 110.11\angle 2.6$

$\tilde{V}_1 = 120.41\angle 4.76°$

$Z = \frac{R \times jX}{R + jX}$

$I_0 = \frac{\tilde{V}_1}{Z}$

Here,

$Z = \frac{450 \times j250}{450 + j250}$

$= (218.53\angle 60.94)\ \Omega$

$\therefore \tilde{I}_0 = \frac{\tilde{V}_1}{Z} = \frac{120.41\angle 4.7}{218.53\angle 60.94}$

$= 0.55\angle -56.24)$

$\therefore I_1 = \tilde{I}_0 + I_2'$

$= (0.55\angle -56.24) + (10\angle -36.86)$

$I_1 = 10.52\angle -37.85$

power factor (p.f) = $\cos\phi = \cos(4.76 + 37.85)$

$= 0.736$ lag.

(14 left)

(11)

Soln:

	V	I	P
O/C	500	2.4 A	
S/C	80	25 A	250w.

$I_0' = 2.4A.$

$pf = 0.35$ lag

$\phi = 65.51$

Here

power in O/C = $VI\cos\phi$

Here

$I_e' = I_0' \cos\phi$

$= 0.84 A.$

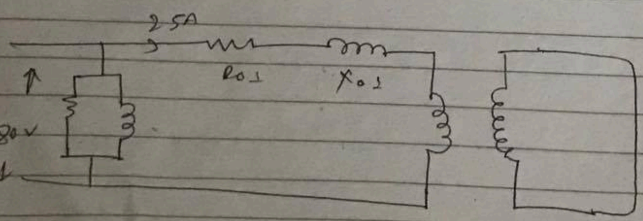
$I_m' = I_0' \sin\phi$

$= 2.248A.$

$R_0' = \frac{V_2}{I_e'} = \frac{500}{0.84} = 595.93$

$X_0' = \frac{V_2}{I_m'} = \frac{500}{2.248} = 222.22\Omega.$

for S/C



$V_{SC} = 80v$

$I_{SC} = 25A$

$W_{SC} = 250w$

$\Rightarrow W_{SC} = I_{SC}^2 R_{01}$

$\therefore R_{01} = \frac{250}{25^2} = 0.4$

$Z_{01} = \frac{V_{SC}}{I_{SC}} = 3.2\Omega$

Now,

$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$

$= \sqrt{3.2^2 - 0.4^2}$

$= 3.17\Omega.$

Here,

$K = \frac{V_2}{V_1} = \frac{500}{1000} = 0.5$

Here,

$R_{02} = K^2 R_{01} = (0.5)^2 \times 0.4 = 0.1\Omega$

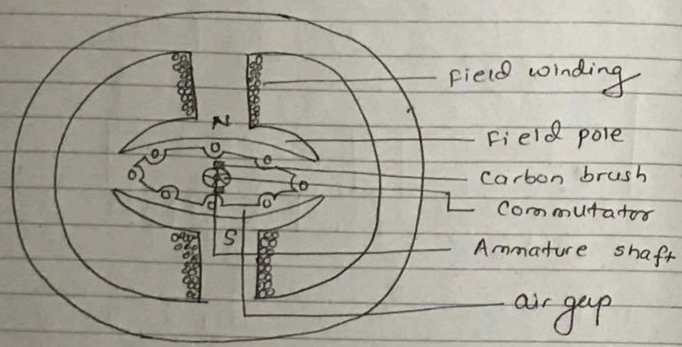
Again,

$X_{02} = K^2 X_{01} = (0.5)^2 \times 3.17 = 0.7925\Omega$

Chapter : 3

DC Generator

3.1 > constructional Details



Commutator :

The commutator is form of rotating switch placed between the armature and external ckt and so arrange that it will reverse the connection to the external ckt at the instant of each reversal of current in armature coil.

Carbon brush :

function :

- collects current from the ~~stationary~~ rotating armature coil to stationary load.
- The carbon brush are fixed and touching over the commutator segment.

Armature Winding

It is the enamel insulated copper wire wound on the slots of armature core.

(i) pole pitch (Distance bet^n adjacent poles)

(ii) Conductor : Length of armature wire lying in magnetic field.

(iii) coil span : Distance between two sides of a coil

Coil span = pole pitch = full pitch

Coil span < pole pitch = short pitch

* Types of winding

1) lap

2) wave

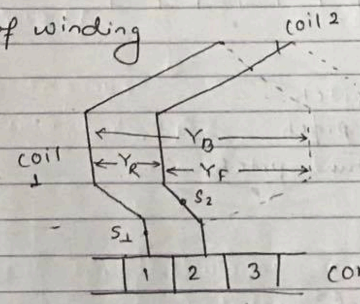
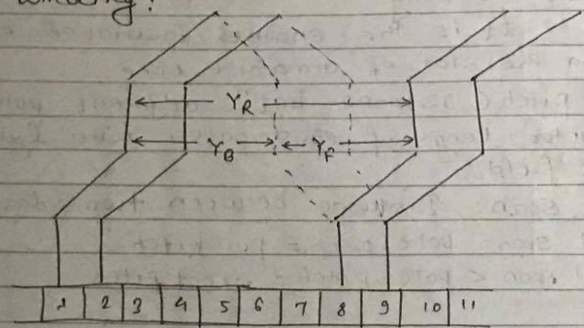


fig : lap

Here, finishing end F_1 of coil 1 is connected to starting end of S_2 of coil2 under same pole as the starting of S_1 of first coil.

* wave winding:

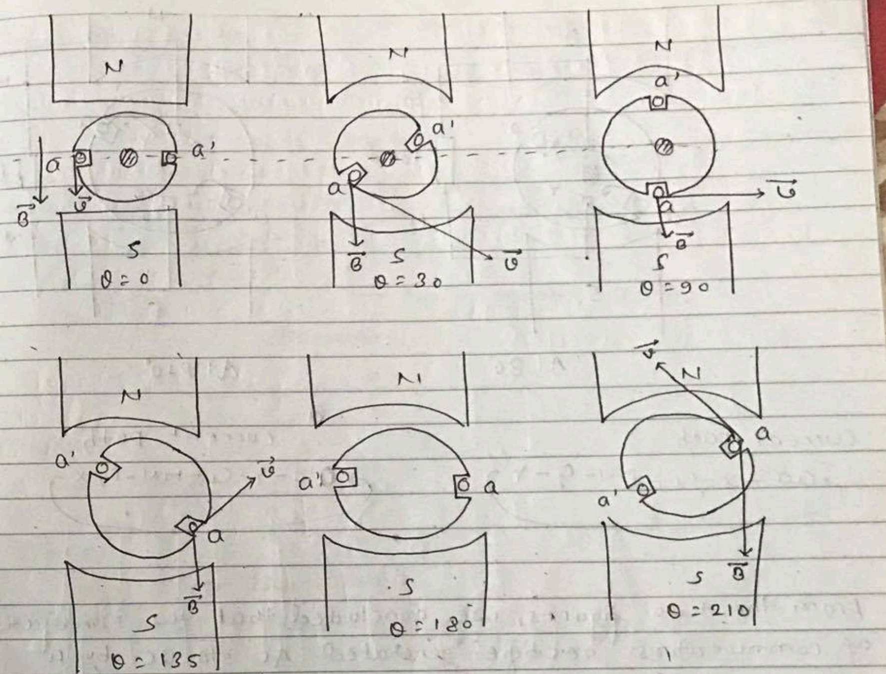


Notations

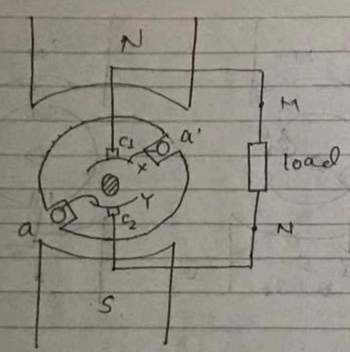
Y_B = Back pitch
Y_F = Front pitch
Y_R = Resultant pitch.

3.2 Working principle

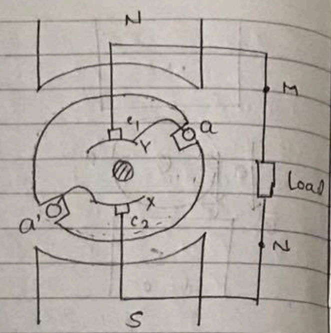
$e = (\vec{v} \times \vec{B})\, l$



This shows that DC machine is actually an alternating current machine. But the introduction of commutator converts the generated AC in to DC and process is commutation.



At 30°



At 210°

Current path

aa' – x – C_1 – MN – C_2 – Y

current path

a'a – Y – C_1 – MN – C_2 – X

From the two figures, we concluded that the introduction of commutators rectifies generated AC to DC by a process called mechanical rectification.

3.3 Emf Equation

$d\phi \rightarrow$ magnetic flux cut by conductor in one revolution

ϕ = flux per pole

p = No. of poles

$dt \rightarrow$ time for one revolution

Z = Total no of conductor

N = speed in rpm

$d\phi = P\phi$ & $dt = \frac{60}{N}$ sec

average emf generated per conductor,

$$E_{avg} = \frac{d\phi}{dt} = \frac{P\phi N}{60} * \frac{Z}{A}$$

No. of conductor

No. of parallel paths

Revolution.

$$= \frac{P\phi N}{60}$$

$$\therefore E = \frac{Z\phi N}{60} * \frac{P}{A}$$

Now,

$$E = \frac{Z\phi N}{60} \cdot \frac{P}{A} \text{ volts}$$

Here,

$A = P$ for Lap winding

$A = 2$ for wave winding.

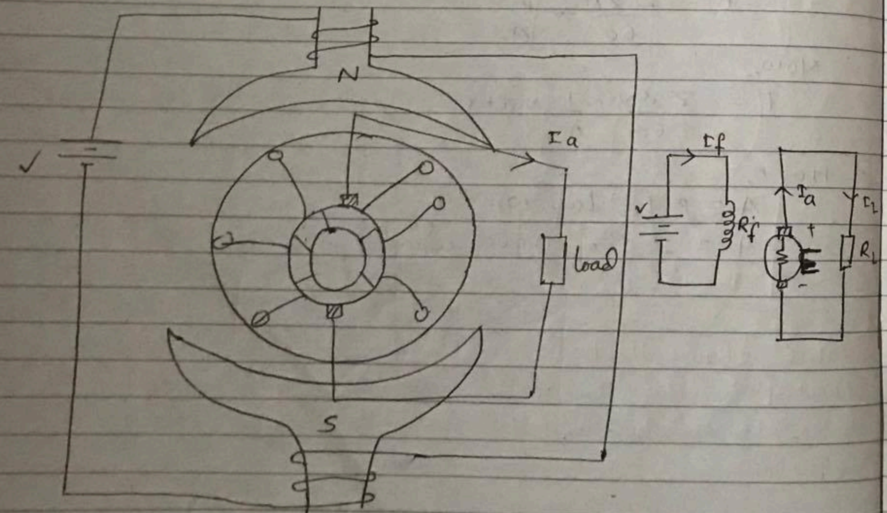
* Methods of Excitation

The field winding of a dc generator is excited by DC current to produce magnetic field.

There are two ways to excite dc generator

a) separately excited DC generator
b) self - excited DC generator.

a) Separately Excited



R_f → Resistance of field winding
E → Emf induced
R_a → Resistance of armature circuit

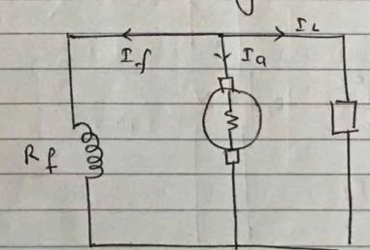
I_a → Armature current
I_f → field current

b) Self- Excited DC generator :

In self excited generators the field winding is produced by the armature of the machine itself.

a) Shunt DC generator
b) Series DC generator
c) compound generator
- Long shunt
- short shunt

a) shunt DC generator



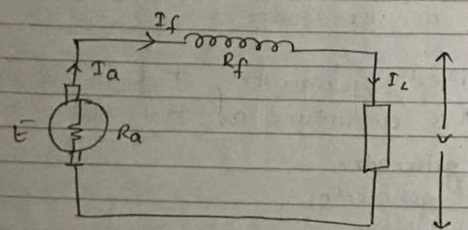
$E = I_a R_a + V$

$V = E - I_a R_a$.

Initially the field current & Armature current both are zero. Now the Armature is rotated by some external means then the conductor cuts the residual magnetic flux and emf is induced in armature conductors.

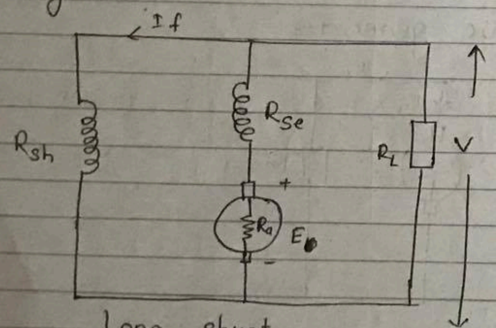
Shunt DC generator are started without load so that the voltage built up can take place.

b) Series DC generator



$E = I_a R_a + I_f R_f + V$

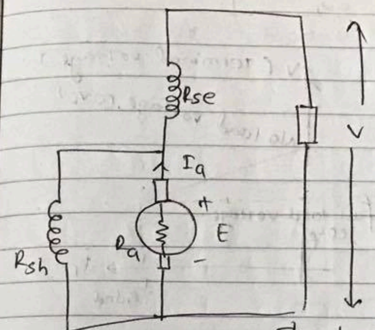
c. Compound generator :



Long shunt

$I_f = \frac{V}{R_{sh}}$.

$V = E - I_a R_a - I_a R_{se}$.



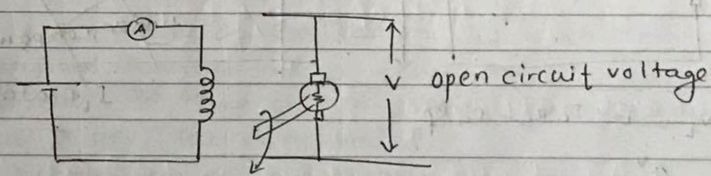
short shunt :

$I_f = \frac{E - I_a R_a}{R_{sh}}$

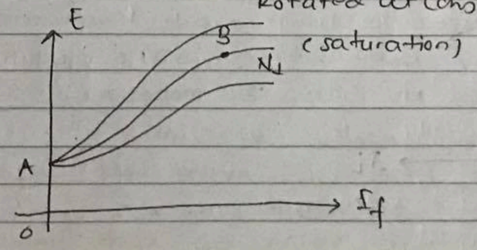
$V = E - I_a R_a - I_L R_{se}$

* Characteristics of DC generator

1) No load characteristics



Rotated at constant speed



$E = \frac{Z \phi N}{60} \frac{P}{A}$

$E \propto \phi N$

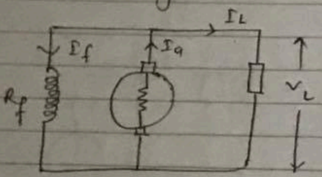
for N_1 speed.

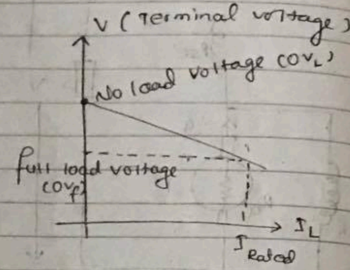
$\boxed{E \propto \phi}$

$$VR = \left| \frac{OV_L - OV_f}{OV_L} \right|$$

2 Load characteristics:

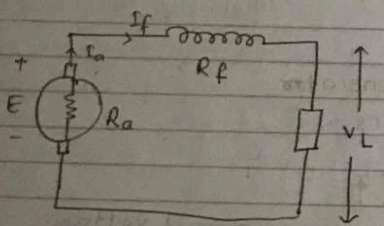
a) Dc shunt generators

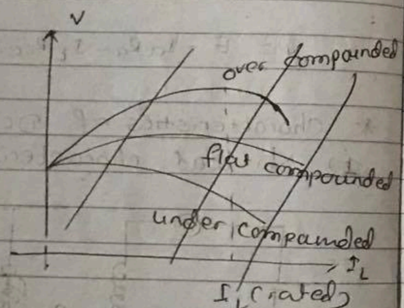




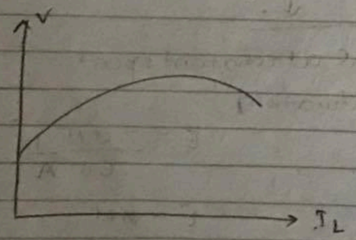
This characteristics is called drooping characteristics.

b) Dc Series Generator

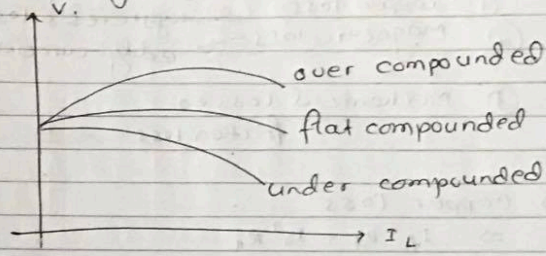


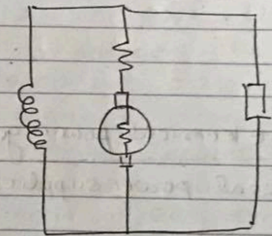


$V_L = E - I_a R_a - I_a R_f$



for DC compound generator.





If the series excitation is such that the terminal voltage of a generator on full load is same as that on no load. The generator is said to be flat compounded.

If the series excitation becomes more prominant than that of shunt field, the terminal voltage rises with the increase in load and the generator is said to be over compounded.

Similarly, when the shunt field excitation plays the prominant part then full load terminal voltage is less than no load terminal voltage then the generator is said to be under compounded.

3.6 losses in DC generator

1. copper loss
2. Magnetic loss < hysteresis loss, eddy current loss
3. Mechanical losses
   friction loss

1> Copper loss

$\Rightarrow I_f^2 R_f + I_a^2 R_a$

$$\eta = \frac{\text{output}}{\text{input}} \times 100\%$$

Mechanical efficiency = $\dfrac{\text{Total electrical power generated}}{\text{Mechanical power supplied}}$

$$\eta_m = \frac{E_a I_a}{\text{output of driving Engine}}$$

Electrical efficiency,

$$\eta = \frac{\text{Watts available in load ckt}}{\text{Total watt generated}}$$

$$= \frac{V I_L}{E_g I_a}$$

$$\eta = \frac{\text{output}}{\text{Input}} \times 100\%$$

overall efficiency (commercial)

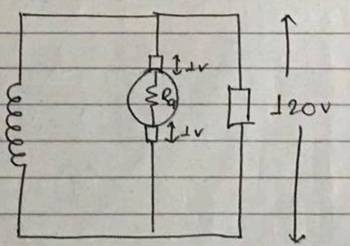
$$\eta = \frac{\text{Watt available in load}}{\text{Mechanical power o/p}}$$

$$= \frac{V I_L}{V I_L + \text{losses}}$$

Tut. No. 1

A 4 pole dc short generator has wave wound armature. The armature and field winding resistances are 0.2 Ω and 60 Ω respectively. The brush contact drop is 1 V per brush. The generator is delivering a power of 3 kW at 120 V. calculate

(a) Total armature current
(b) current in each armature conductor
(c) Emf generated.



$R_a = 0.2\,\Omega$
$R_f = 60\,\Omega$

$P = V I_L$

$3000 = 120 \times I_L$

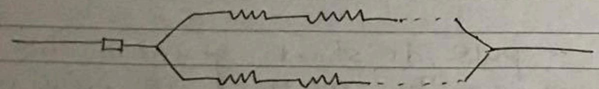
$\therefore I_L = \frac{300}{12} = 25\,A$

Now,

$I_f = \frac{120}{60} = 2\,A$

$\therefore I_a = 25A + 2A = 27\,A.$

current in each armature conductor $= 13.5\,A.$ $\left(\frac{27}{2}\right)$



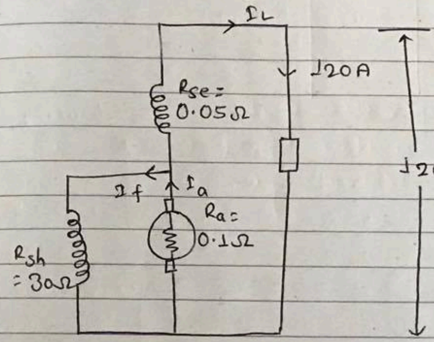
$E = I_a R_a + V_L + 2$
$= 27 \times 0.2 + 120 + 2$
$= 127.4V.$

DC Generator

Tutorial 3

Q.No.3

→ Solution



$I_L = 120A$

Applying KVL'

$V = E - I_a R_a - I_L R_{se}$

or, $120 = E - I_a \times 0.1 - 120 \times 0.05$

or, $120 = E - 0.1\,I_a - 6$

or, $126 = E - 0.1\,I_a$

$\therefore E = 126 + 0.1\,I_a$

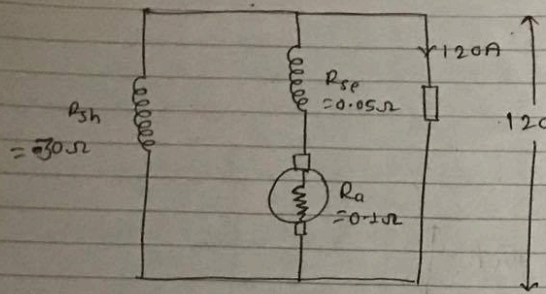
$E = I_a R_a + I_f R_{sh}$

or, $126 + 0.1\,I_a = I_a \times 0.1 + I_f \times 30$

or, $126 + 0.1\,I_a = 0.1\,I_a + 30\,(120 - I_a)$

$\therefore I_a = 124.2A$

and $E = 138.4V.$



Here,

$I_f = \frac{120}{30} = 4A.$

$I_L = 120A$

So,

$I_a = 124A.$

So

$E - I_a R_a - I_a \times 0.05 - I_f \times 30 = 0$

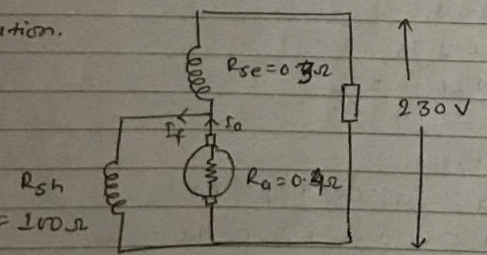
or, $E - 124 \times 0.1 - 124 \times 0.05 - 4 \times 30 = 0.$

$\therefore E = 138.6V.$

Q.NO.5

Solution.

→



$p = 7.5kW$

$p = V I_L$

$7.5 \times 10^3 = 230 \times I_L$

$\therefore I_L = \frac{7.5 \times 10^3}{230} = 32.608 A.$

Now,

$\cancel{E = 0.4 I_a + 0.3 \times 32.608 + 230}$

or, $\cancel{E = 0.4 I_a + 239.7824}$

I_a

or, $\cancel{E = 0.4 I_a + I_f \times 100}$

or, $E = 0.4 I_a + (I_a - I_L) \times 100$

$I_f = \frac{0.3 \times 32.608 + 230}{100}$

$= 2.397 A.$

$I_a = I_f + I_L$

$= 35.005 A.$

$E = I_a R_a + I_f R_{sh}$

$= 35.005 \times 0.4 + 2.397 \times 100$

$= 253.7V.$

Now,

$p = \frac{V^2}{R}$

or, $R = \frac{230^2}{7500} = 7.05Ω.$

Things to be noted

① $E = \frac{Z\phi N}{60} \cdot \frac{P}{A}$

$A = 2$ for wave winding & P for lap winding

① $P = \omega \tau$ $\omega = \frac{2\pi N}{60}$

(ii) Always draw fig & use KVL

(iii) Generator will be motor if it consumes power instead of delivering.

Q. No. 7

$P = 6$ poles

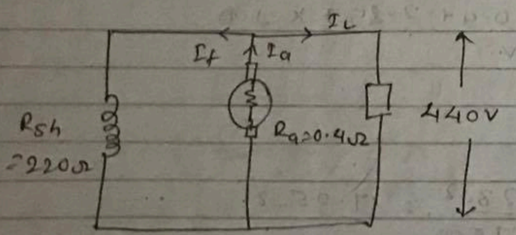
$N = 400$ rpm

$Z = 1200$

$\phi = 0.02$ wb

$R_a = 0.4\Omega$

$R_{sh} = 220\Omega$



$E = \frac{Z\phi N}{60} \cdot \frac{P}{A}$

$E = \frac{1200 \times 0.02 \times 400}{60} \times \frac{6}{2} = 480$ V.

$E = I_a R_a + 440$

or, $480 = I_a * 0.4 + 440$

$\therefore I_a = 100$ A.

Now, $I_f = \frac{440}{220} = 2$ A.

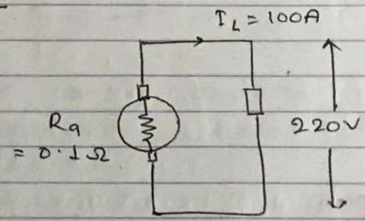
Hence.

$I_L = I_a - I_f$

$= 100 - 2$

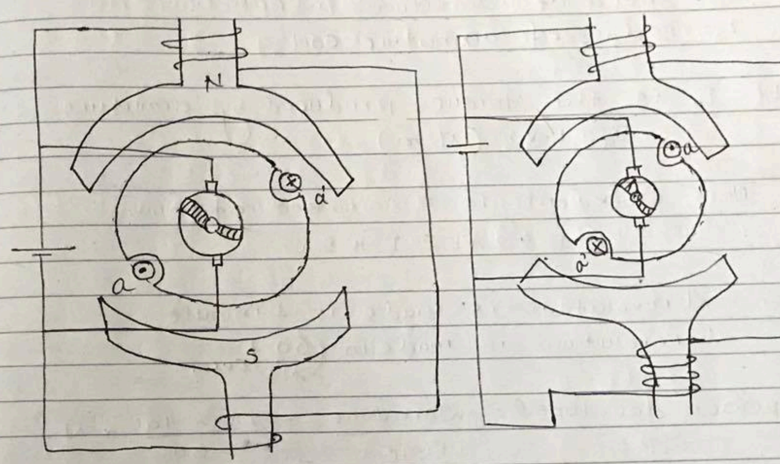
$= 98$ A.

Q. No. 9



Chapter 4 DC MOTOR

4.1 Working principle and Torque equation



A current carrying conductor placed in a magnetic field experiences a force in the direction Fleming's left hand Rule.

When a conductor aa' is supplied by DC source, the conductor will experience force as it is in magnetic field. Now it rotates in anticlockwise direction. The carbon brush and commutator reverse the current direction after half cycle and the force reverse back and armature rotates continuously.

Torque equation

let, N = speed of armature in Rpm.

r = radius of armature coil

If 'T_a' is the torque produced by armature,

$T_a = F \times r$ (N-m)

Then, workdone in 1 complete rotation,

$= F * 2\pi r = T * 2\pi$

Here,

N revolution is made in 1 minute

1 revolution is made in $\left(\frac{60}{N}\right)$ sec.

$\therefore$ power developed $= \frac{\text{Workdone}}{\text{Time}} = \frac{2\pi * T_a}{60} * N$.

$$\boxed{P_a = \frac{2\pi N}{60} * T_a \text{ watt}}$$

Now, the rotating armature conductor are cutting the magnetic flux. So Emf will be induced across armature coils. This Emf is called Back Emf

$$E_b = \frac{\phi Z \phi N}{60} \frac{P}{A}$$

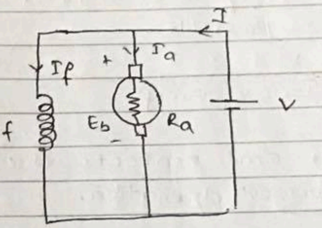
This flux opposes the applied voltage and this opposition converts electrical to mechanical power.

$P = E_b * I_a$

$$\frac{2\pi N}{60} T_a = \frac{Z\phi N}{60} \frac{P}{A} * I_a \Rightarrow T_a = \frac{1}{2\pi} Z \phi I_a * \frac{P}{A}$$

$$\therefore \boxed{T_a \propto \phi I_a}$$

4.2 Back Emf



We know that, emf is generated in rotating armature conductor due to generator action in DC motor.

According to lenz law, the direction of emf induced across armature winding is opposite to applied ~~to~~ voltage. So this opposing induced emf is called back emf. This applied voltag V pushes I_a against E_b.

$$\frac{V - E_b}{R_a} = I_a$$

$$V - E_b = I_a R_a$$

Multiplying by I_a,

$$V I_a - E_b I_a = I_a^2 R_a$$

$$V I_a - I_a^2 R_a = E_b I_a$$

Input power to armature - Copper loss in armature = power developed by armature.

Back emf plays an essential role in operation of DC motor. without ~~emf~~ back emf no conversion of electrical energy to mechanical energy is possible.

Role of Back emf:

Back emf protects the armature from short ckt during normal operation.

$$\frac{V - E_b}{R_a} = I_a$$

If $E_b = 0$,

$$I_a = \frac{V}{R_a}$$

as R_a is small,

I_a is very high.

Back emf acts as a feedback mechanism in a DC motor helping to produce the required amount of torque.

Back emf acts as an opposing agent required for energy conversion from electrical to mechanical.

4.3 Methods of Excitation

DC motor

(a) DC shunt motor

(b) DC series motor

(c) DC compound motor — Commutative / Differential

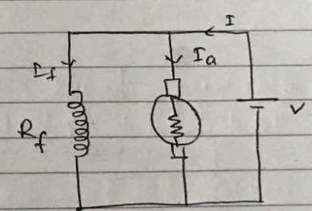
4.4: Performance Characteristics.

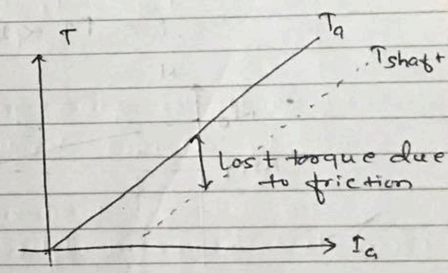
a) Torque - Armature current

b) $N - T_a$

(For shunt Motor)

a) Torque - Armature current





$$T = \frac{1}{2\pi} Z \phi I_a \frac{P}{A}$$

$T \propto \phi I_a$

ϕ constant

$T \propto I_a$

b) speed-torque characteristics

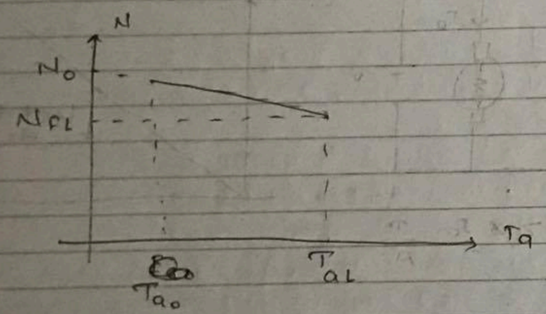
$\downarrow E_b = \frac{Z\phi N \downarrow}{60} \frac{P}{A}$

$N \propto \frac{E_b}{\phi}$; as ϕ is constant for DC shunt motor.

$N \propto E_b$

$\uparrow I_a = \frac{V - E_b \downarrow}{R_a}$

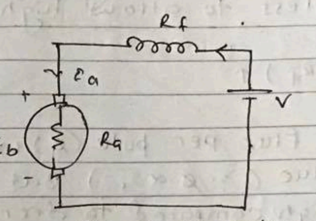
i.e, $\uparrow T \propto I_a \uparrow$



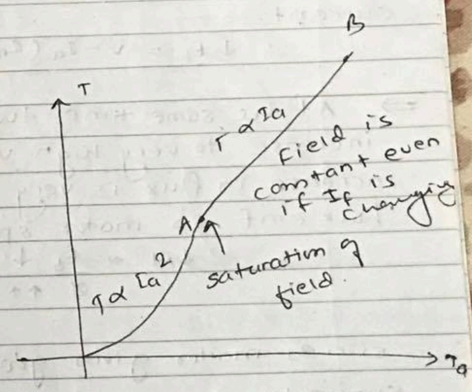
So, it is clear from the above graph that there is not much change in the speed of DC shunt motor even if there is large variation of load torque. So DC shunt motor usually find application when constant speed is required even if motor is carrying different amount of load.

(For series motor)

a) Torque armature current



DC series motor



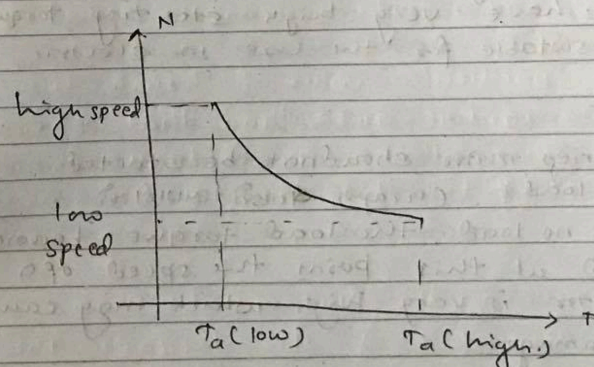
$T_a \propto I_a \phi$

$T_a \propto I_a I_a$

$T_a \propto I_a^2$

$\boxed{T \propto I_a}$

b) speed torque characterstics



At heavy torque, ($T_a \uparrow$)
The armature current needs to be very high ($\because T \propto I_a^2$)
The back emf will be less to allow high armature current.

$$\therefore \downarrow E_b = V - I_a(R_a + R_f) \uparrow$$

$\Rightarrow$ At the same time, the flux per pole (ϕ) will increase to very high value ($\because \phi \propto I_a$). But the increase in flux is very high compared to decrease in back emf so motor speed is low at high torque.

$$\downarrow N \propto \frac{E_b \downarrow}{\phi \uparrow\uparrow}$$

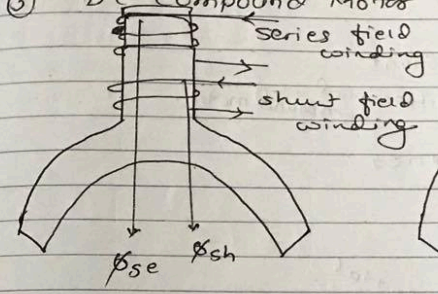
$\therefore$ series motor gives good starting torque.
Similarly at low torque, $T_a \downarrow$, $I_a \downarrow$, $I_f \downarrow$, $E_b \uparrow$, $\phi \downarrow$

From the above analysis, we know that DC series motors have very high starting torque so they are suitable for the use in electric trains.

Q. Why DC series motor shouldnot be started without any load? (graph [illegible])

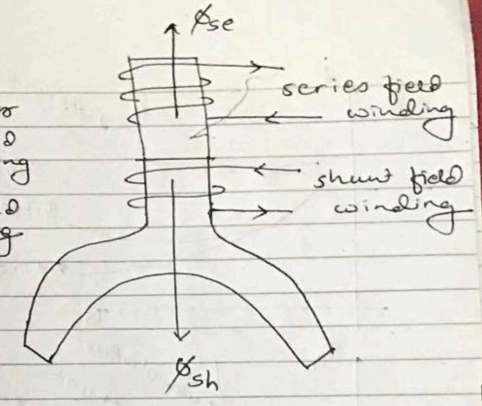
→ Because at no load, the load torque becomes very low and at this point the speed of a DC series motor is very high which may cause mechanical damage.

③ DC compound Motor



$\phi_{total} = \phi_{se} + \phi_{sh}$

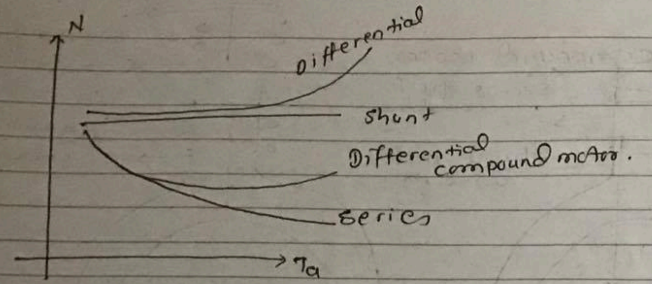
fig:- Cummulative compound

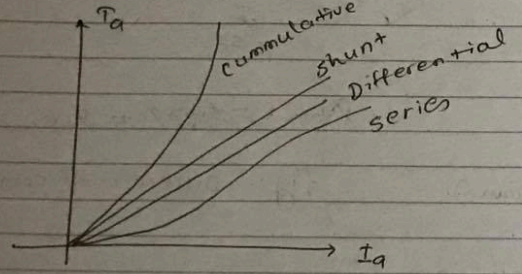


$\phi_{total} = \phi_{sh} - \phi_{se}$.

fig:- Differential compound

DC compound motor has two sets of field winding series & shunt.
If the series field winding produces the flux in same direction as produced by shunt field winding then such motor is called cummulative compound.
On the other hand, if the series field winding produces the flux in opposite direction as produced by shunt field winding then such motor is called differential compound motor.





In cummulative compound motor, the flux from both winding support eachother. Hence the flux per pole will be higher with increase in armature current.

Similarly at a particular value of torque, the flux per pole will be more than that compared to DC shunt motor. Hence, speed torque characterstics is more slopy but less than DC series motor.

* Differential

In this case, the flux opposes each other so with increase in I_a flux decreases. The $T_a - I_a$ curve lies below that of DC shunt motor. Similarly, the flux at a particular value of torque will be less than DC shunt motor. Hence the characterstics will be as shown in the fig.