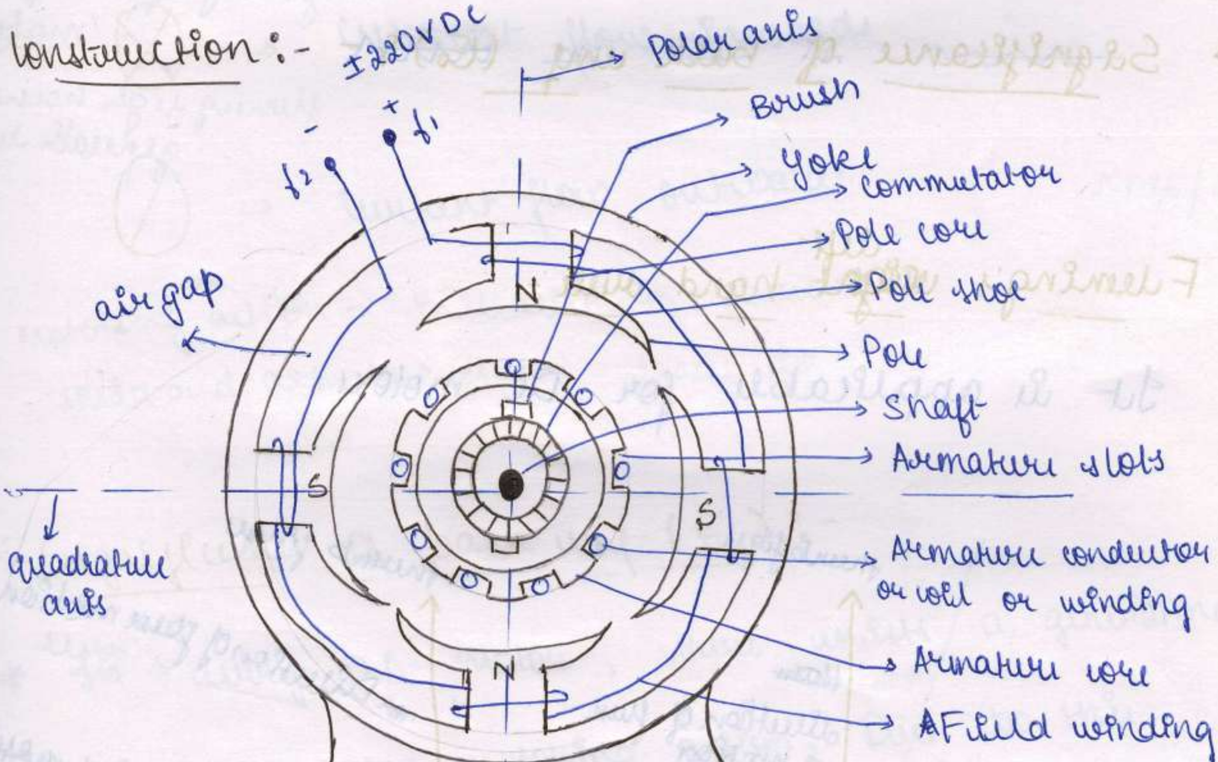
MODULE-1

DC-MOTORS

DC-motor :-

Construction :-



Principle :- DC motor

* whenever a current carrying conductor / coil is placed in a magnetic field, it experiences a mechanical force.

* The magnitude of ~~the~~ force experienced is given by

$$F = B I l \text{ Newtons}$$

where B = Magnetic flux density - Wb/m^2

I = current flowing through coil/conductor - Amps

l = Active length of conductor

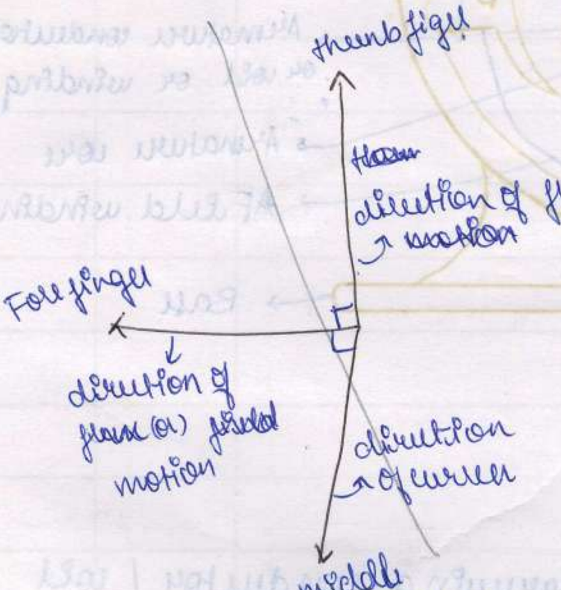
Fleming left hand rule - motors

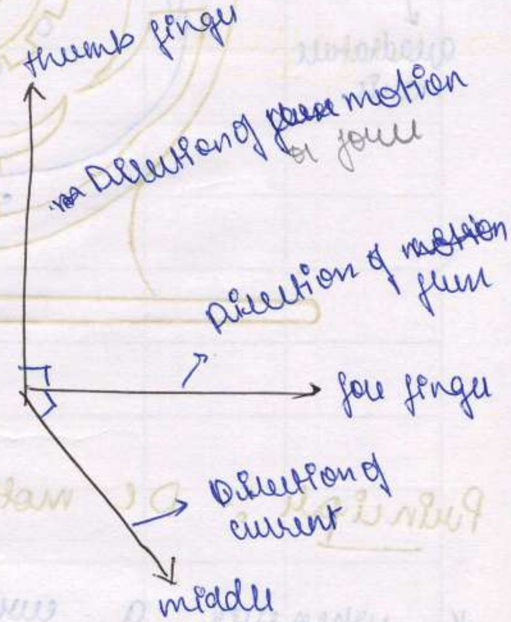
Fleming right hand rule - generator

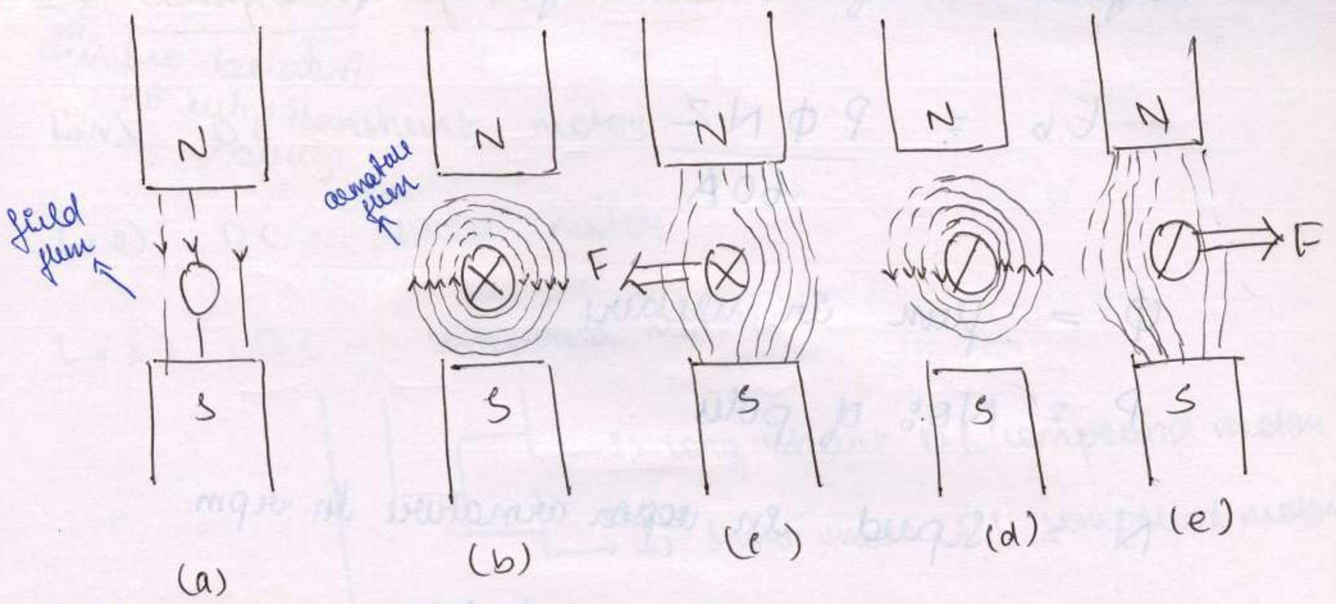
* ⇒ ~~Significance of back emf (Eb)~~

Fleming's ~~right~~ left hand rule -

It is applicable for DC motors







field

⊗ → current flow inwards

⊘ → current flow outwards

motoring action - interaction of 2 fluxes - field and armature fluxes leads to

⇒ Significance of back emf (E_b) :-

* In every DC motor, there exists a generating action after the motoring action. Due to this generating action, an emf gets induced in the armature winding / conductor.

* This induced emf opposes the supply voltage V. due to Lenz's law and is known as the back emf E_b

* Magnitude of E_b is given by

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

induced emf in motor due to generating action

ϕ = flux in Webers

P = No: of poles

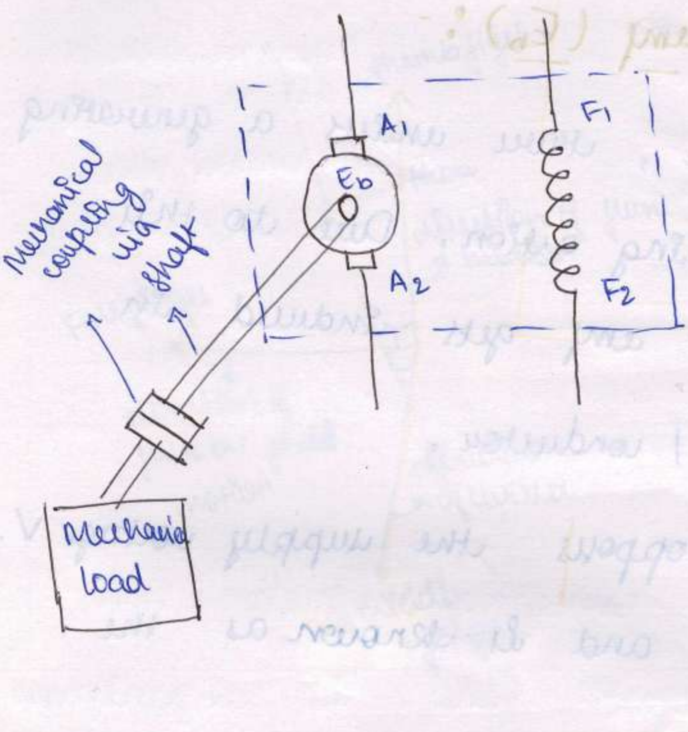
N = Speed in ~~arma~~ armature in rpm

Z = ~~conductor~~ Armature conductors

A = No: of parallel paths.

⇒ Symbolic representation of a DC-motor :-

DC motor



⇒ Classification of DC - motors :-

↳ 1) DC - shunt motor

↳ 2) DC - series motor

↳ 3) DC - compound motors

—— i) long shunt DC compound motor

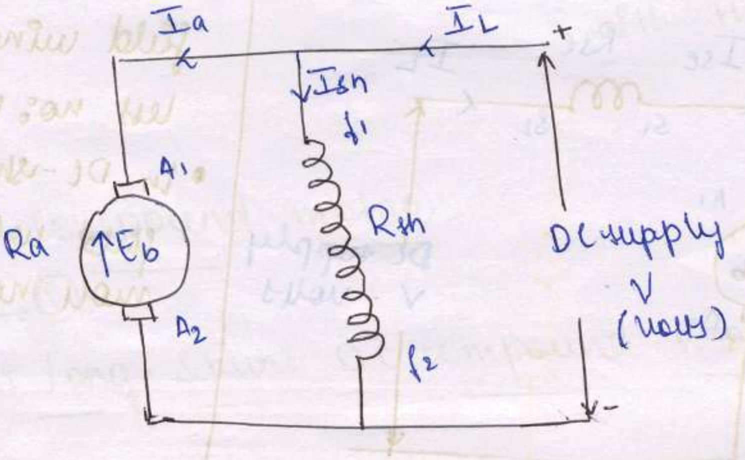
—— ii) Short shunt DC compound motor

—— (i) Cumulative

—— (ii) Differential

↳ 1) DC - shunt motor :-

$I_L \rightarrow$ line current



→ Current relationship

$$\boxed{I_L = I_a + I_{sh}}$$

$$\boxed{I_{sh} = \frac{V}{R_{sh}}}$$

→ Voltage equation

$$\Rightarrow \boxed{V = E_b + I_a R_a + V_{brush}}$$

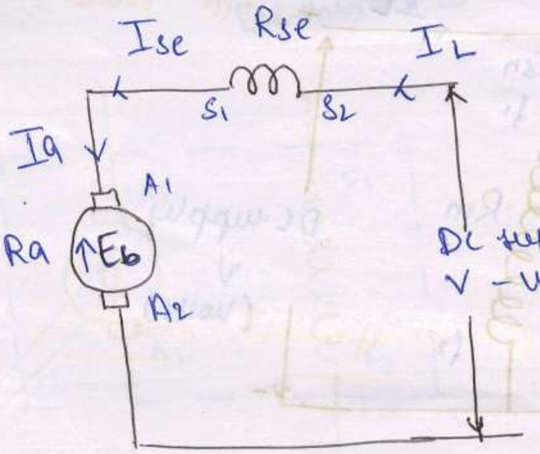
Generally V_{brush} is neglected

$$\boxed{V = E_b + I_a R_a}$$

→ relation of flux and shunt current

$$\boxed{\phi \propto I_{sh}}$$

↳ 2) DC - series motor



- In DC- series motor field winding has less no: of turns
- In DC-shunt motor field winding has more no: of turns

→ current relationship

$$\boxed{I_L = I_{se} = I_a}$$

→ relation of flux and series current and line current

$$\phi \propto I_{se} \propto I_L \propto I_a$$

→ Voltage equation

$$\Rightarrow \boxed{V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}}$$

$$\boxed{V = E_b + I_a (R_a + R_{se})}$$ neglecting Vbrush

Rsh should be high value

Rse should be low value

Voltage drop across Armature should be high in series

$R_a \rightarrow$ low value
$R_{se} \rightarrow$ low value
$R_{sh} \rightarrow$ high value

$R \propto \frac{l}{a} \Rightarrow R \propto l \,;\, R \propto \frac{1}{a}$

$\therefore R_{sh}$ - more no: of turns (l) ⇒ higher value with thin crossection (area)

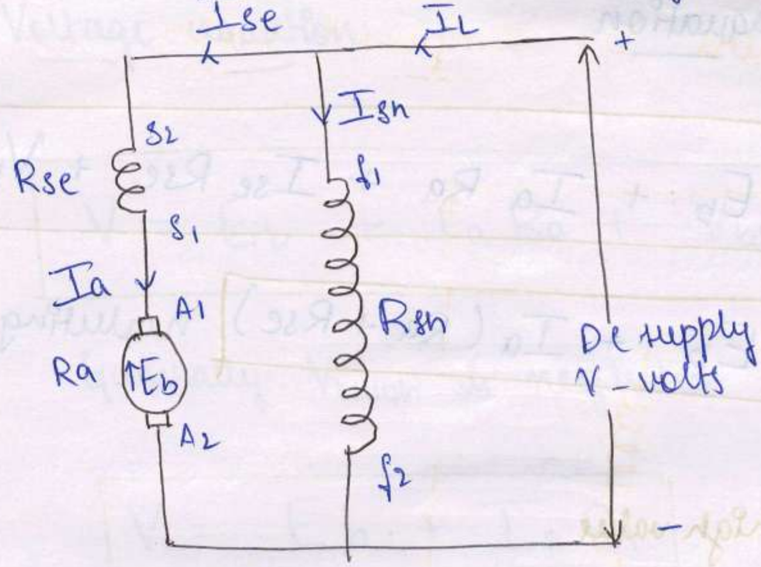
R_{se} - less no: of turns (l) ⇒ ~~Volt~~ lower value with thick value (area)

↳ 3) Compound motor
↳→ (i)
↳(ii) Long shunt DC compound motor:-

Types of winding

1) Armature
2) shunt field winding
3) series field winding

long sh



→ Current relationship

$$\boxed{I_L = I_{se} + I_{sh}}$$

$$\boxed{I_{se} = I_a}$$

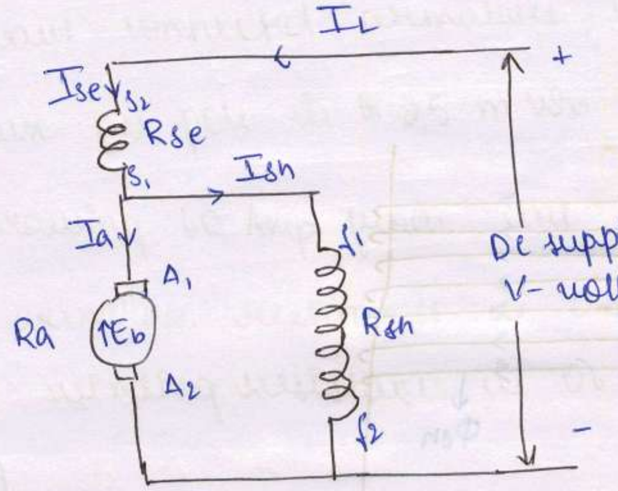
(or) $$\boxed{I_L = I_a + I_{sh}}$$

→ Voltage equation

→ $$\boxed{V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}}$$

$$\boxed{V = E_b + I_a (R_a + R_{se})}$$ neglecting V_{brush}

↳ (iii) Short shunt DC compound motor



→ Current relationship

$$\boxed{I_L = I_a + I_{sh}}$$

$$\boxed{I_L = I_{se}}$$

$$\boxed{I_{se} = I_a + I_{sh}}$$

→ Voltage equation

$$\rightarrow \boxed{V = E_b + I_{se} R_{se} + I_a R_a + V_{brush}}$$

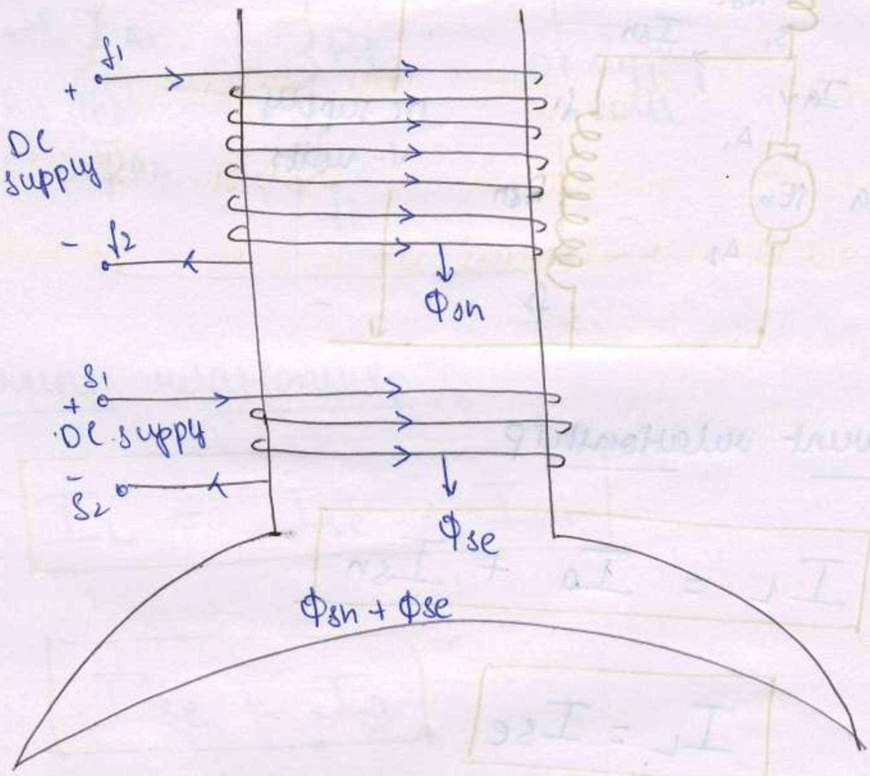
$$\boxed{V = E_b + I_{se} R_{se} + I_a R_a} \text{ neglecting } V_{brush}$$

⇒ shunt current equation

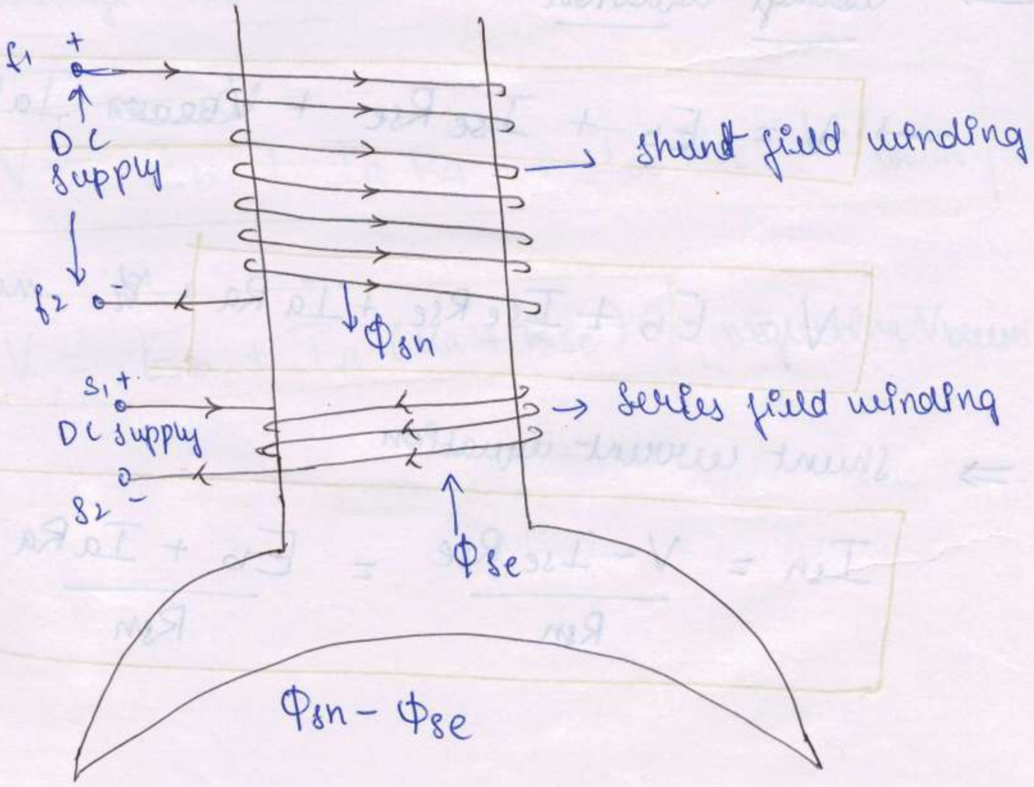
$$\boxed{I_{sh} = \frac{V - I_{se} R_{se}}{R_{sh}} = \frac{E_b + I_a R_a}{R_{sh}}}$$

↳ → (iii)

↳ (i) Cumulative compound DC motor:-



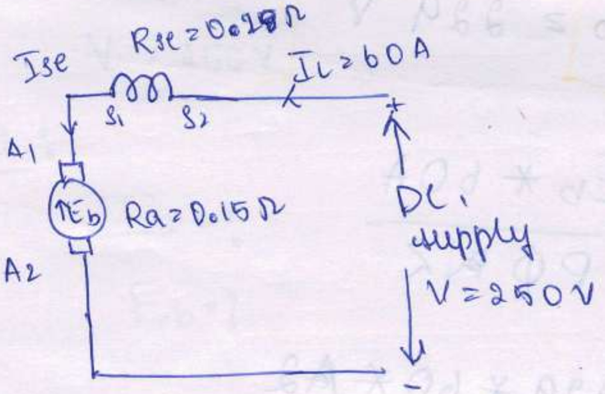
↳ (ii) Differential compound DC motor:-



Q1) A 4 pole, 250V, DC series motor has a wave connected armature with 200 conductors. A flux per pole is ~~&~~ 25 mWb when the motor is drawing 60 Amp from the supply.

The armature resistance is 0.15Ω while series field winding resistance is 0.2Ω calculate the speed

Soln



Given data:-

$P = 4$

$\phi = 25 \times 10^{-3}$ Wb

$Z = 200$

$R_a = 0.15\,\Omega$

$R_{se} = 0.2\,\Omega$

$I_L = 60$ A

$V = 250$ V

$A = 2$

To find:-

$N = ?$

* Motor takes a current

(or)

Motor draws a current

⇒ Means line current I_L not I_a

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

$$= \cancel{2 \times 25 \times 10^{-3}}$$

$$V = E_b + I_{se} R_{se} + I_a R_a$$

$$250 = E_b + 60 * 0.2 + 60 * 0.15$$

$$E_b = 229 \text{ V}$$

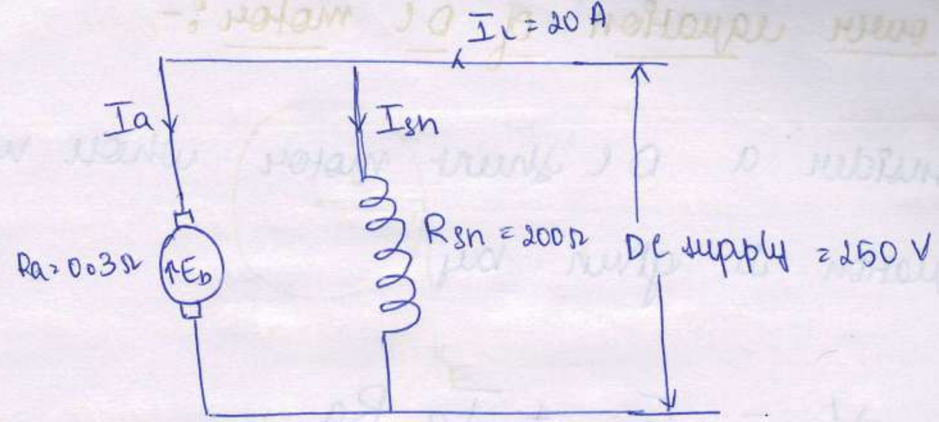
$$\hookrightarrow N = \frac{E_b * 60A}{P \phi \cancel{N} Z}$$

$$= \frac{229 * 60 * \cancel{A}2}{4 \times 25 \times 10^{-3} \times 200}$$

$$N = 1374 \text{ rpm}$$

Q2) A 250V, DC shunt motor takes a line current of 20 Amps. The resistance of shunt field winding is 200 Ω and resistance of armature is 0.3 Ω. Find the armature current and back emf

Soln :-



Given data :-

$I_L = 20A$

$R_{sh} = 200\Omega$

$R_a = 0.3\Omega$

$V = 250V$

To find :-

$I_a = ?$

$E_b = ?$

Soln :-

$I_L = I_a + I_{sh} \Rightarrow I_a = I_L - I_{sh} \rightarrow (1)$

$I_{sh} = I_L - I_a \rightarrow (2)$

$V = I_{sh} R_{sh}$

$I_{sh} = \frac{V}{R_{sh}}$

$= \frac{250}{200}$

$I_{sh} = 1.25$ Amps $\rightarrow (2)$

Sub (2) in (1)

$I_a = I_L - I_{sh} = 20 - 1.25 = 18.75$ Amps

$V = E_b + I_a R_a$

$E_b = 250 - 18.75 * 0.3$

$E_b = 244.375 V$

// (O/P = I/P − losses) // (I/P = O/P + loss)

⇒ Power equation of DC motor:-

Consider a DC shunt motor whose voltage equation is given by

$$V = E_b + I_a R_a$$

Multiply both sides by current I_a

$$\boxed{V I_a = E_b I_a + I_a^2 R_a}$$

Power eqn of DC motor

where $V I_a$ = Power input to the armature in watts

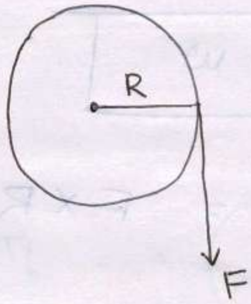
$I_a^2 R_a$ = Power loss in armature in watts

$E_b I_a$ = Electrical equivalent of gross mechanical power developed (power output)

⇒ Torque equation of a DC motor:-

The turning and twisting movement of force about a particular axis is called torque.

Consider a wheel of radius 'R'-meters acted upon by a circumferential force 'F'-newtons



Let the wheel rotate at 'N' rpm

i) The angular speed is given by

$$\omega = \frac{2\pi N}{60} \text{ rad / sec}$$

~~Power developed~~

ii) Work done is given by

$$W = \text{Force} * \text{distance travelled}$$

$$= F * 2\pi R \quad N\text{-}m$$

iii) Power developed ~~by~~ is given by -

$$P = \frac{\text{workdone}}{\text{Time taken (in secs)}}$$

$$P = \frac{F \times 2\pi R}{\left(\frac{60}{N}\right)}$$

$$P = (F \times R)\left(\frac{2\pi N}{60}\right)$$

$$P = (F \times R) \times \omega$$

$$\boxed{P = T \times \omega}$$

where torque $T = F \times R$

when the speed of ~~rpm~~ the armature is "N" rpm

$E_b I_a$ = Electrical equivalent of mechanical power developed in armature.

let T_a = the torque developed in the armature

$$\therefore P = T_a \times \omega$$

$$E_b I_a = T_a \times \left(\frac{2\pi N}{60}\right)$$

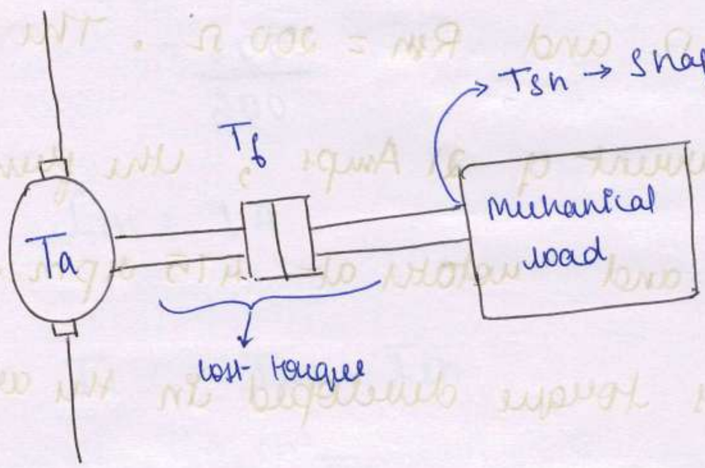
w.k.t $E_b = \frac{P\phi N Z}{60A}$

$$\frac{P\phi \cancel{N} Z}{\cancel{60} A} I_a = T_a \times \frac{2\pi \cancel{N}}{\cancel{60}}$$

$$T_a = \frac{1}{2\pi} \frac{\phi P Z}{A} I_a = 0.159 \frac{P\phi Z I_a}{A}$$

$$\boxed{T_a = \frac{1}{2\pi} \frac{P\phi Z I_a}{A}} \text{ — Nm}$$

⇒ Types of Torques in a DC motor :-



i) armature Torque
ii) lost torque
iii) shaft torque

- The entire armature torque (Ta) developed in the armature is not transmitted to the load because there are some losses i.e., friction and windage losses at the shaft (coupling) known as lost torque - T_f

- The useful torque available to the mechanical load at the end of the end of the shaft is called shaft torque - T_{sh}

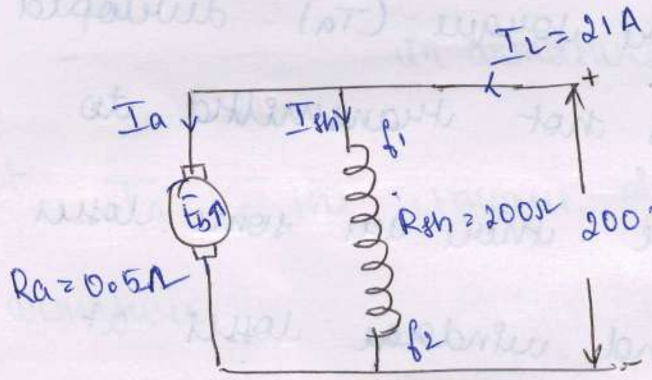
$$\boxed{T_{sh} < T_a} \rightarrow \text{[Due to losses)}$$

(i) Armature torque
(ii) lost torque → Friction losses, → windage loss
(iii) Shaft torque

Q) A 200 V, 4 pole, lap wound DC shunt motor has 800 armature conductors. $R_a = 0.5\,\Omega$ and $R_{sh} = 200\,\Omega$. The motor takes a current of 21 Amps, the flux / pole is 30 mWb and rotates at 475 rpm.

Find gross torque developed in the armature.

Soln



Given:-

$\phi = 30 \times 10^{-3}$ Wb

$N = 475$ rpm

Lap $= A = P = 4$

$Z = 800$

To find :- $T_a = ?$

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

$I_L = I_a + I_{sh}$

$\rightarrow I_{sh} = \frac{V}{R_{sh}}$

$= \frac{200}{200}$

$I_{sh} = 1\,A$

$\rightarrow I_L = I_a + I_{sh}$

$21 - 1 = I_a$

$I_a = 20\,A$

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

$$= \frac{4 * 30 \times 10^{-3} \times 800 \times 20}{2\pi \times 4}$$

$$T_a = 76.39 \text{ N-m}$$

⇒ Speed and Torque equations :-

W.K.T General torque expression is -

⟶ $T_a = \frac{1}{2\pi A} * P \phi Z I_a$ N-m

$$\boxed{T_a \propto \phi I_a} \rightarrow (1)$$

because $\frac{1}{2\pi}$, P, A, Z are all constants

For DC shn

1) ⟶ For DC shunt motors:- (constant ϕ flux machines) as I_a is constant → ϕ is also cont

As long as the supply 'V' remains constant,

I_{sh} also remains constant and ϕ also remains constant ($\phi \propto I_{sh}$)

→ Thus DC shunt motors are also called constant flux machines

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

Application:-

→ Used for moderate starting torque applications

2) → For DC series motor :-

WKT

$$I_L = I_{se} = I_a$$

Now $\phi \propto I_{se}$

$\Rightarrow \phi \propto I_a$

$T_a \propto \phi I_a$ from eqn ①

$T_a \propto I_a * I_a$

$$\boxed{T_a \propto I_a^2}$$

⇒ Speed equations :-

WKT

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

$$\boxed{E_b \propto \phi N}$$

because P, Z, 60, A are all constants

$\therefore \Rightarrow$ $\boxed{N \propto \frac{E_b}{\phi}}$ → ②

⟹ For DC shunt motors:-

w.k.T ϕ remains constant

$$N \propto E_b$$

$[\because V = E_b + I_a R_a]$

from voltage equations

$$\boxed{N \propto (V - I_a R_a)}$$

⟹ For DC series motors:-

$$N \propto \frac{E_b}{I_a}$$

from eqn ②

$$\phi \propto I_a$$

$[V = E_b + I_a (R_a + R_{se})]$

From voltage equations

$$\boxed{N \propto \left[\frac{V - I_a R_a - I_{se} R_{se}}{I_a} \right]}$$

⟹ characteristics of DC motors :-

1) Torque versus armature current (T_a Vs I_a) :-

↳ Electrical characteristics (also called)

2) speed versus armature current (N Vs I_a)

3) speed versus Torque (N Vs T_a)

↳ Mechanical characteristics (also called)

↳ characteristics of DC shunt motors :-

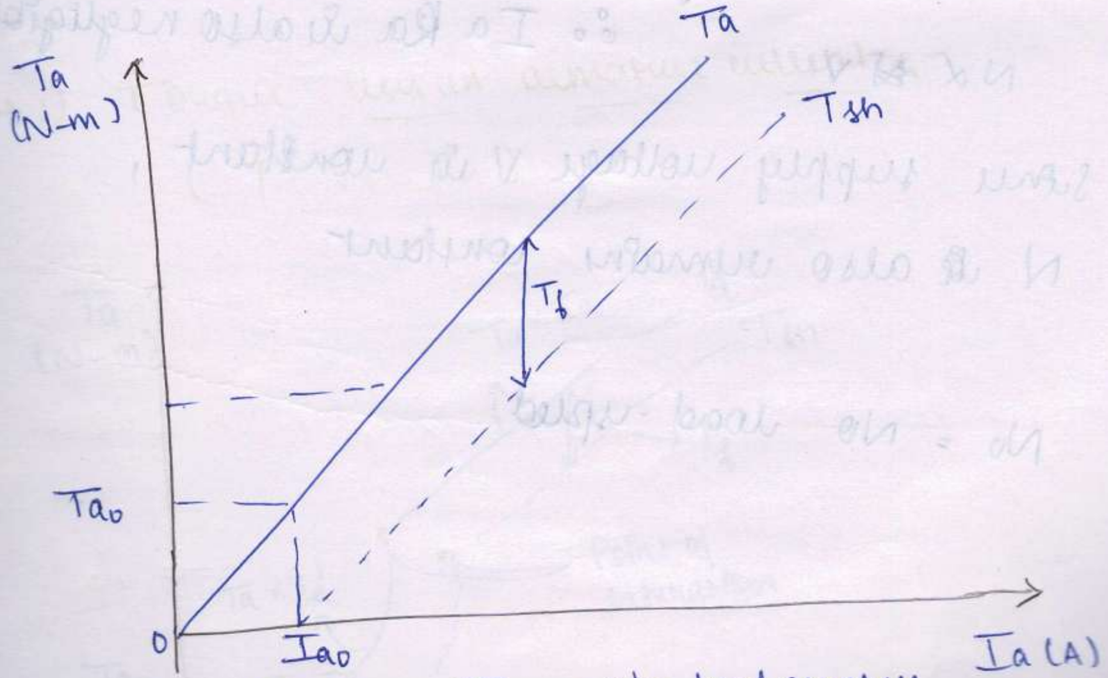
1) Torque versus armature current :-

T_a Vs I_a

- shunt motor can be started on no load
- series motor requires load to

w.K.T

$T_a \propto I_a$



T_a - armature torque

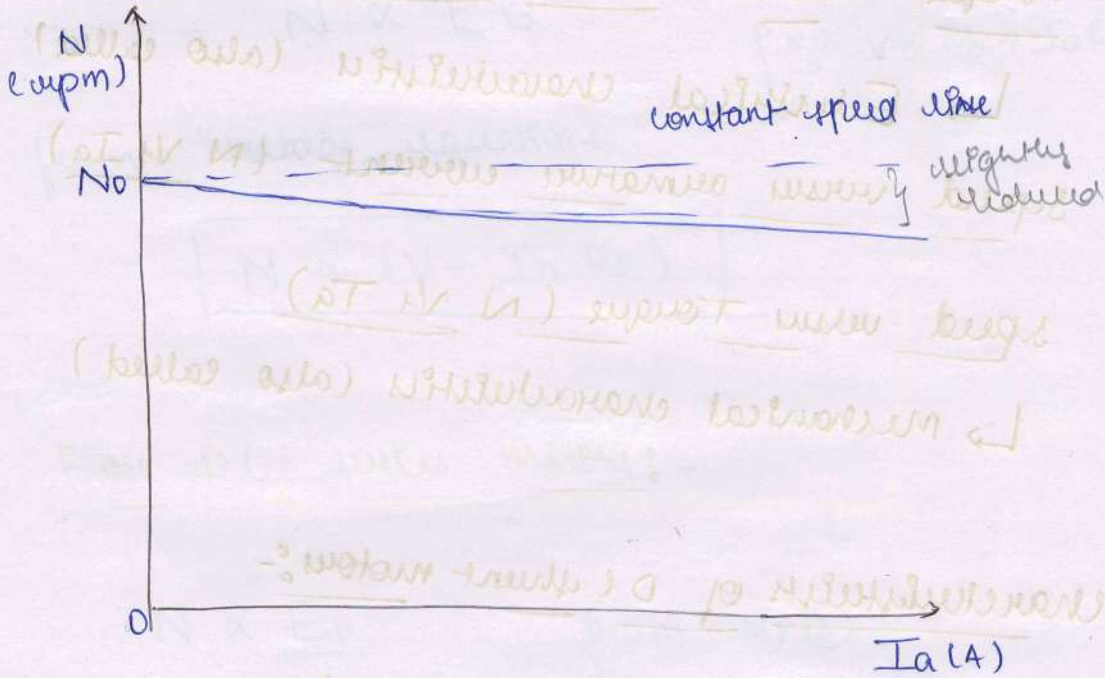
T_{sh} - shaft torque

T_{a0} → No load armature torque

I_{a0} → No load armature current

↳ 2) Speed versus armature current :-

(N vs Ia)



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

$$N \propto (V - I_a R_a)$$

R_a → is very small (or) negligible
∴ $I_a R_a$ is also negligible

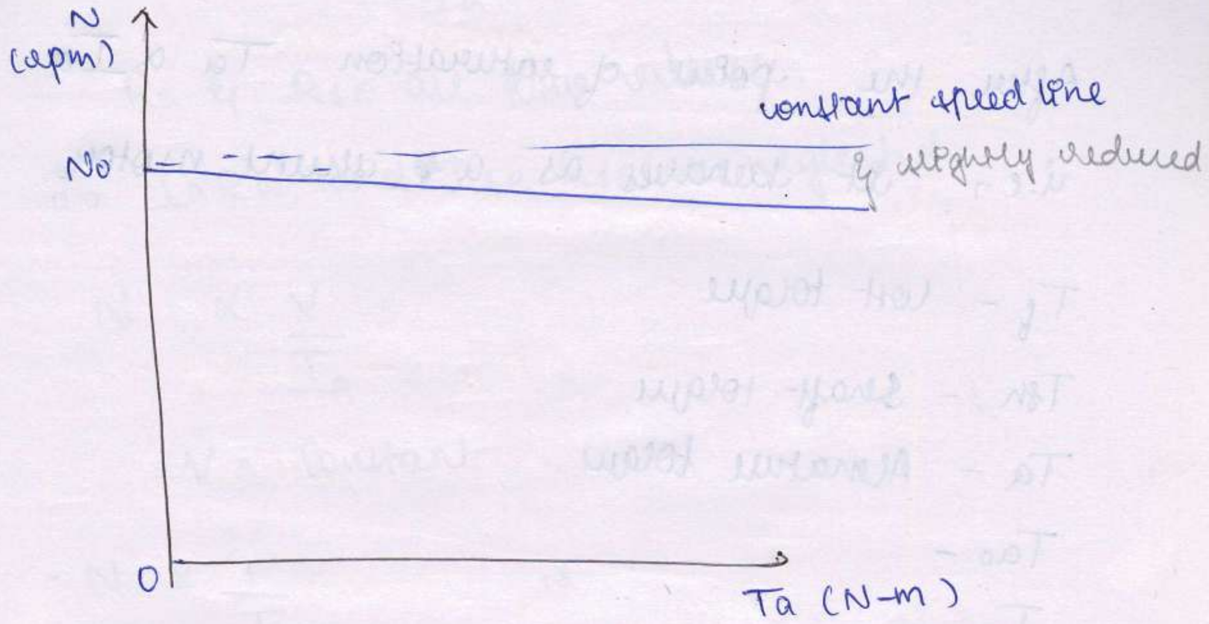
$$N \propto V$$

Since supply voltage V is constant,
N also remains constant

N_0 = No load speed

↳ 3) Speed versus Torque :-

(N Vs Ta)



Since $T_a \propto I_a$

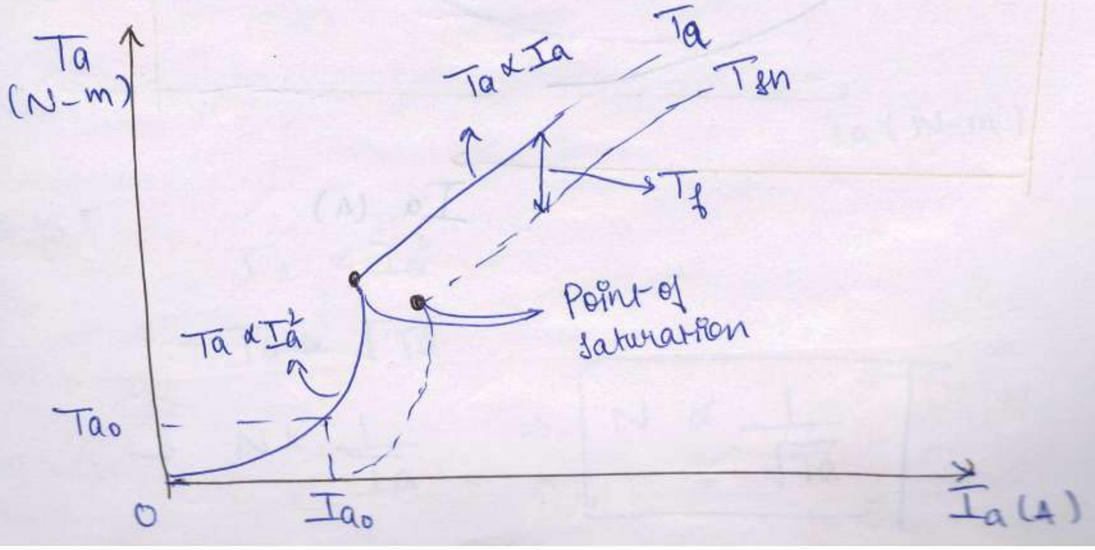
(graph :. N Vs Ta is similar to N Vs I_a

characteristics

↳ Characteristics of DC series motors :-

↳ 1) Torque versus armature current :-

(T Vs I_a)



w.K.T

$$T_a \propto I_a^2$$

After the point of saturation $T_a \propto I_a$

i.e., It behaves as a shunt motor

T_f - lost torque

T_{sh} - shaft torque

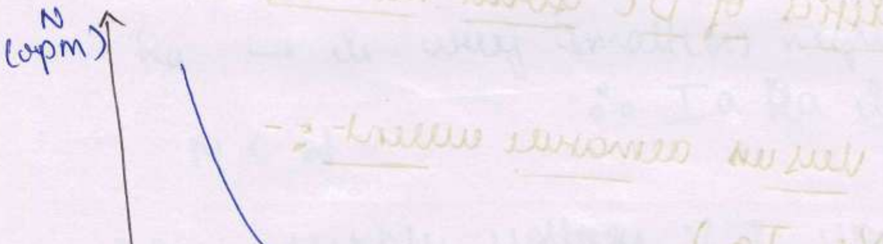
T_a - Armature torque

T_{a0} -

I_{a0} -

↳ 2) Speed versus armature current :-

(N Vs I_a)



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

$$N \propto \frac{V - I_a R_a - I_{se} R_{se}}{I_a}$$

R_a & R_{se} are low values

$\therefore$ $I_a R_a$ and $I_{se} R_{se}$ are neglected

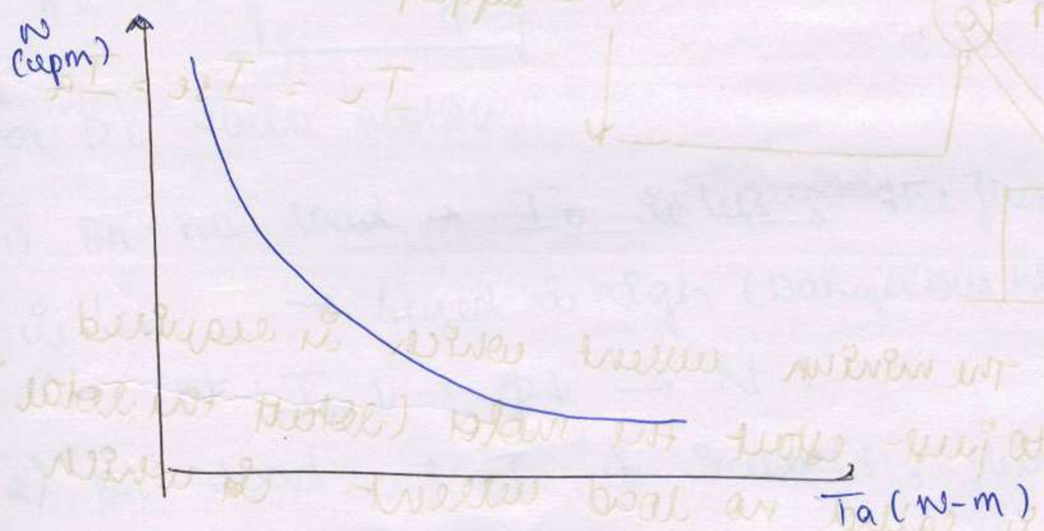
$$N \propto \frac{V}{I_a}$$

V = constant

$$N \propto \frac{1}{I_a}$$

↳ 3) Speed versus Torque :-

(N Vs Ta)



W.K.T $T_a \propto I_a^2$

$$I_a \propto \sqrt{T_a}$$

$$\rightarrow N \propto \frac{1}{I_a} \Rightarrow \boxed{N \propto \frac{1}{\sqrt{T_a}}}$$

Applications

Series motors are always started with load

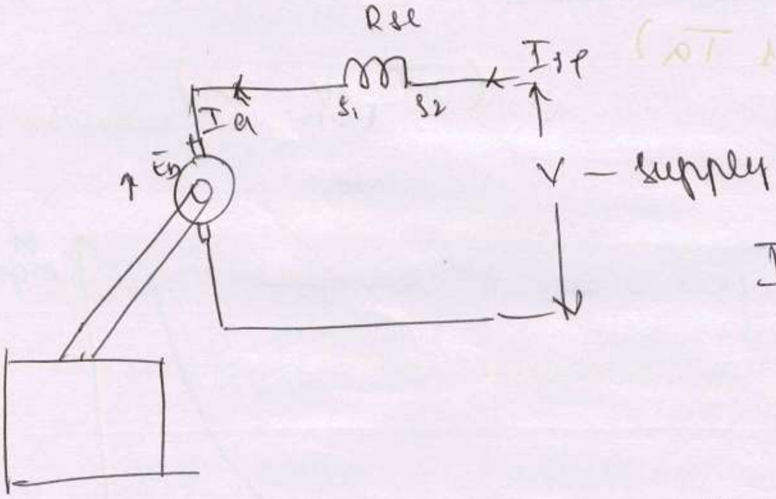
$N \propto \frac{E_b}{\phi}$ ⇒ general eqn

$N \propto \frac{V - I_a R_a - I_{se} R_{se}}{\phi}$

$I_a R_a$; $I_{se} R_{se}$ → negligible

$N \propto \frac{V}{\phi}$ [V - constant]

$N \propto \frac{1}{\phi}$



$I_L = I_{se} = I_a$

* The minimum current which is required to just start the motor (rotate the rotor) is called no load current which is very-very small

if I_{a0} - no load current is very small speed is high (v.s) ↑ $N \propto \frac{1}{\phi} \propto \frac{1}{I_a}$ ↓ cow

$I_0 \downarrow , \phi \downarrow \rightarrow N \uparrow$ (motors run at

If there is load → current (~~no load~~)
(not-no-load)

~~For decrease~~ and
current increase, flux also increases,
speed decrease
$I\uparrow$; $\phi\uparrow$; $N\downarrow\downarrow$

DC series motor should never be started on no-load.

→ W.K.T

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

$$N \propto \frac{(V - I_a R_a - I_{se} R_{se})}{\phi}$$

$$N \propto \frac{V}{\phi}$$ (V is constant)

∴ $\boxed{N \propto \frac{1}{\phi}}$

For DC series motor

↳ 1) On no-load → I_0 is less, the flux ϕ is less, → speed is high (Dangerous high speed)

$I_0\downarrow \rightarrow \phi\downarrow \rightarrow N\uparrow$

↳ 2) On load → I is increase, flux increase and speed decrease

$I\uparrow$, $\phi\uparrow$; $N\downarrow\downarrow$.

$\Rightarrow$ Applications of DC - motors:-

Type of motor	characteristics	Applications
DC shunt motor	- speed is fairly constant and - medium starting torque	Fans, blowers, centrifugal pumps, lathe machines, Drilling machines, machines tools ... etc
DC - series motor	- high starting torque, variable speed - No load condition is dangerous	cranes, elevators, trolleys, conveyor belts, electric locomotives and traction
cumulative compound motor	- high starting torque, - No load condition is allowed	Rolling mills, elevators, lifts ... etc (For bidirectional application - lifts)
Differential compound motor	- speed increases as the load increases	Not suitable for any practical application

Differential compound motor

$I_L = I_a + I_{sh}$

$\phi_{sh} - \phi_{se}$ $\quad \uparrow N \propto \frac{E_b}{\phi \downarrow}$

$(\phi_{sh} - \phi_{se}) \downarrow$

In $\phi_{se} \rightarrow I$ current is more $\rightarrow$ ϕ_{se} will be more

Due to more ϕ_{se} $\Rightarrow$ Difference of $(\phi_{sh} - \phi_{se})$

decreases

due to speed increases

⟹ Factors affecting speed of a DC motor:-

WKT

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

Say

$$N \propto \frac{V - I_a R_a}{\phi}$$

$$\therefore \boxed{N \propto \frac{V}{\phi}}$$ as $E_b \simeq V$ [approximately equal to V]

Factors affecting the speed are -

↳ (i) Flux (ϕ)

↳ (ii) Voltage across the armature

↳ (iii) Supply voltage (V)

⟹ Depending on these factors, the various methods of speed control are -

↳ (i) Flux control method:-

By changing the flux ϕ, by controlling the current through field winding

↳ (ii) Rheostatic control:- (or) Armature voltage control:-

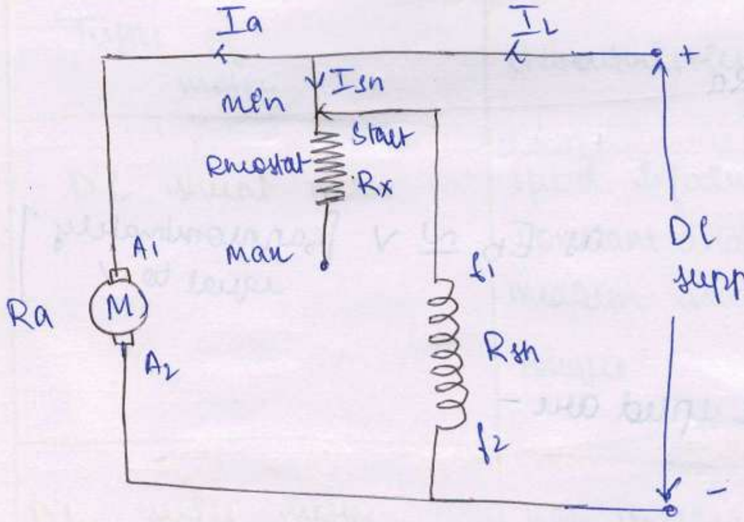
changing the armature path resistance which intern changes the voltage across the armature.

↳ (iii) Voltage control method:- (or) [illegible] method:-

changing the applied voltage

⟹ Speed control of DC shunt motors :-

↳ (i) Flux control method :-



As resistance ↑ through Rheostat

I_{sh} decreases ↓

so ϕ_{sh} decreases ↓

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

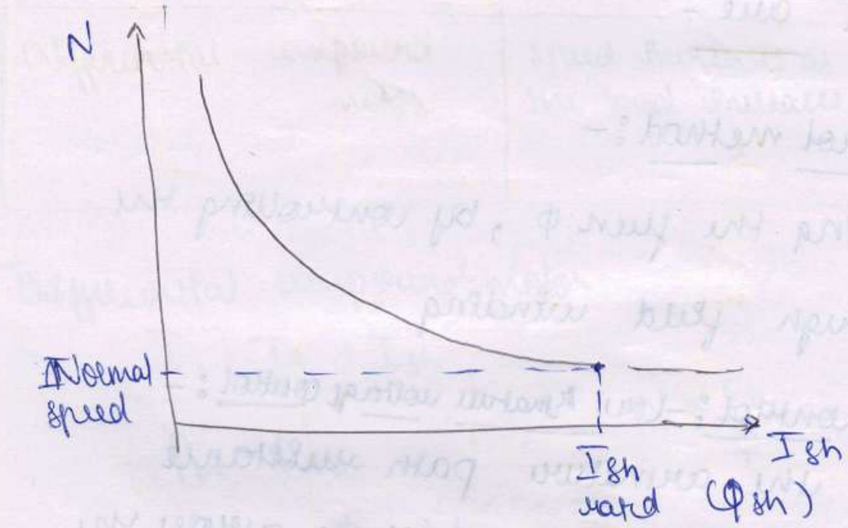
∴ N increases ↑

Disadvantage

Speed cannot be decreased in this type of control method

[∴ i.e., below the rated speed]

↳ N Vs Ish :-



$I_{sh} \propto \frac{V}{R_{sh}}$

as $R_{sh} \uparrow \rightarrow I_{sh} \downarrow$

as $I_{sh} \downarrow \rightarrow$ speed $N \uparrow$

→ Advantages :-

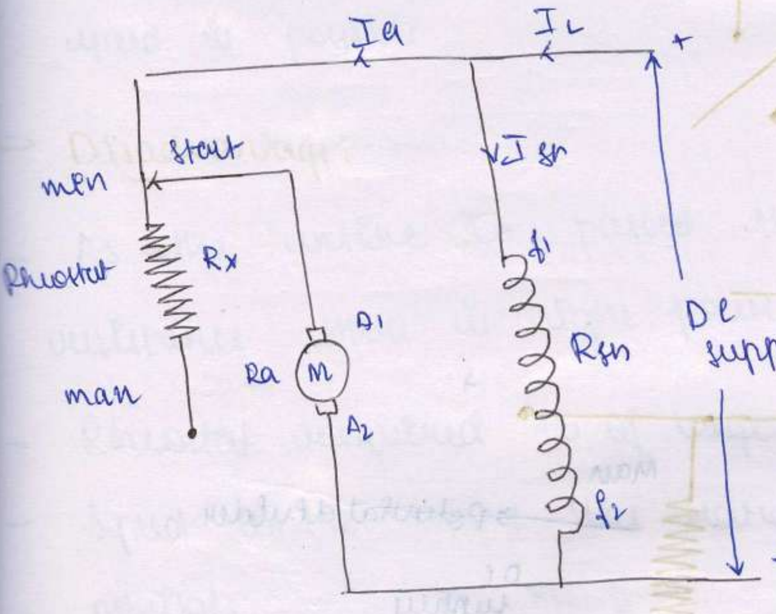
- Speed control above rated speed is possible
- It provides smooth and easy control.
- As field current is low, the rheostat required is small.

Thus the power loss in the rheostat is also less

→ Disadvantages :-

- Speed control below the normal rated speed is not possible
-

↳ (iii) Rheostatic control (or) Armature voltage control :-

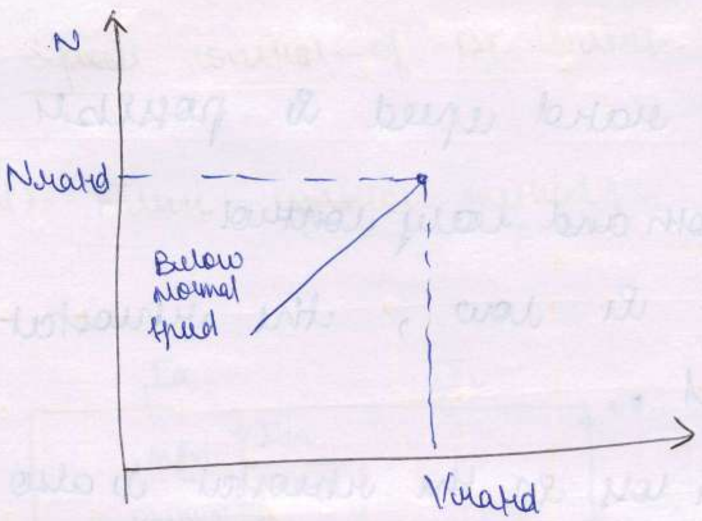


as R_x ↑ → voltage Drop across $I_a R_x$ increases ↑

→ Due to $I_a R_a$ → voltage drop decreases ↓

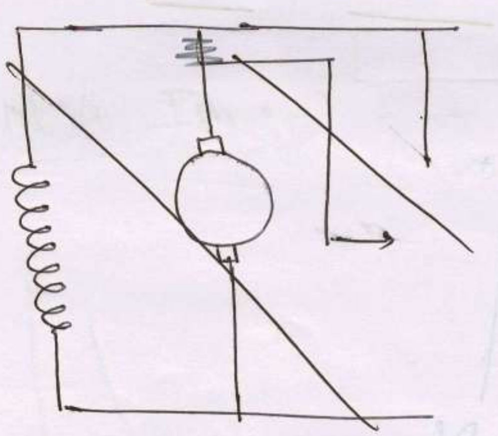
In this method voltage can only be decreased → Voltage across armature is reduced.

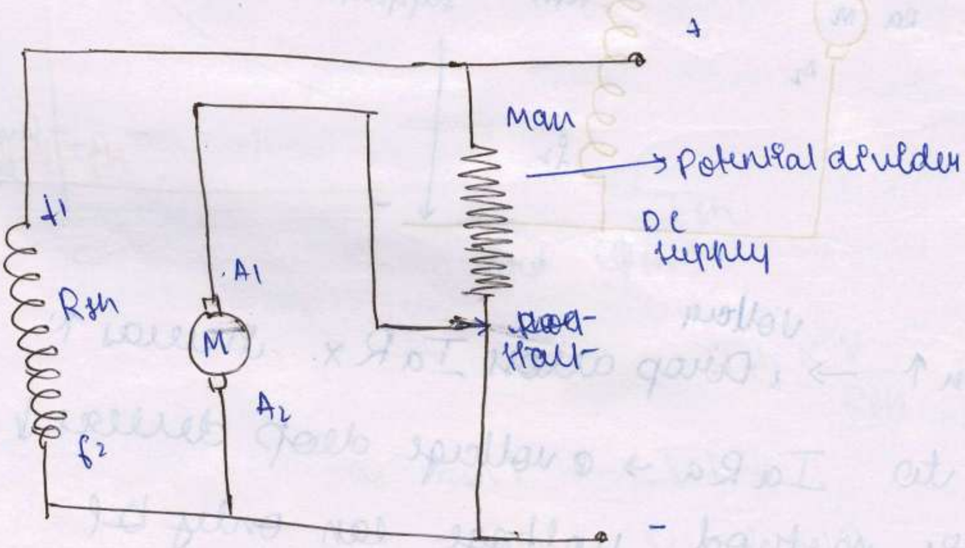
↳ N Vs Va

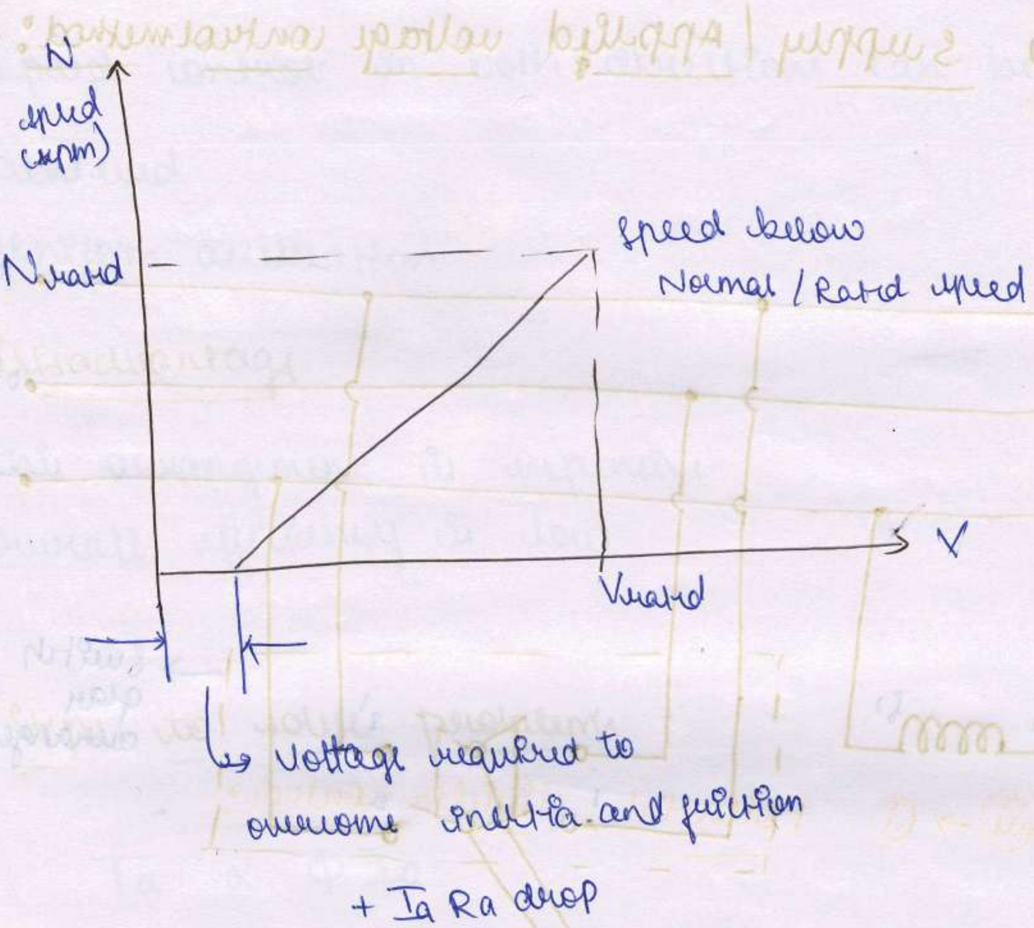


18/2/2017

↳ → (iii) → (i) Potential divider control:-







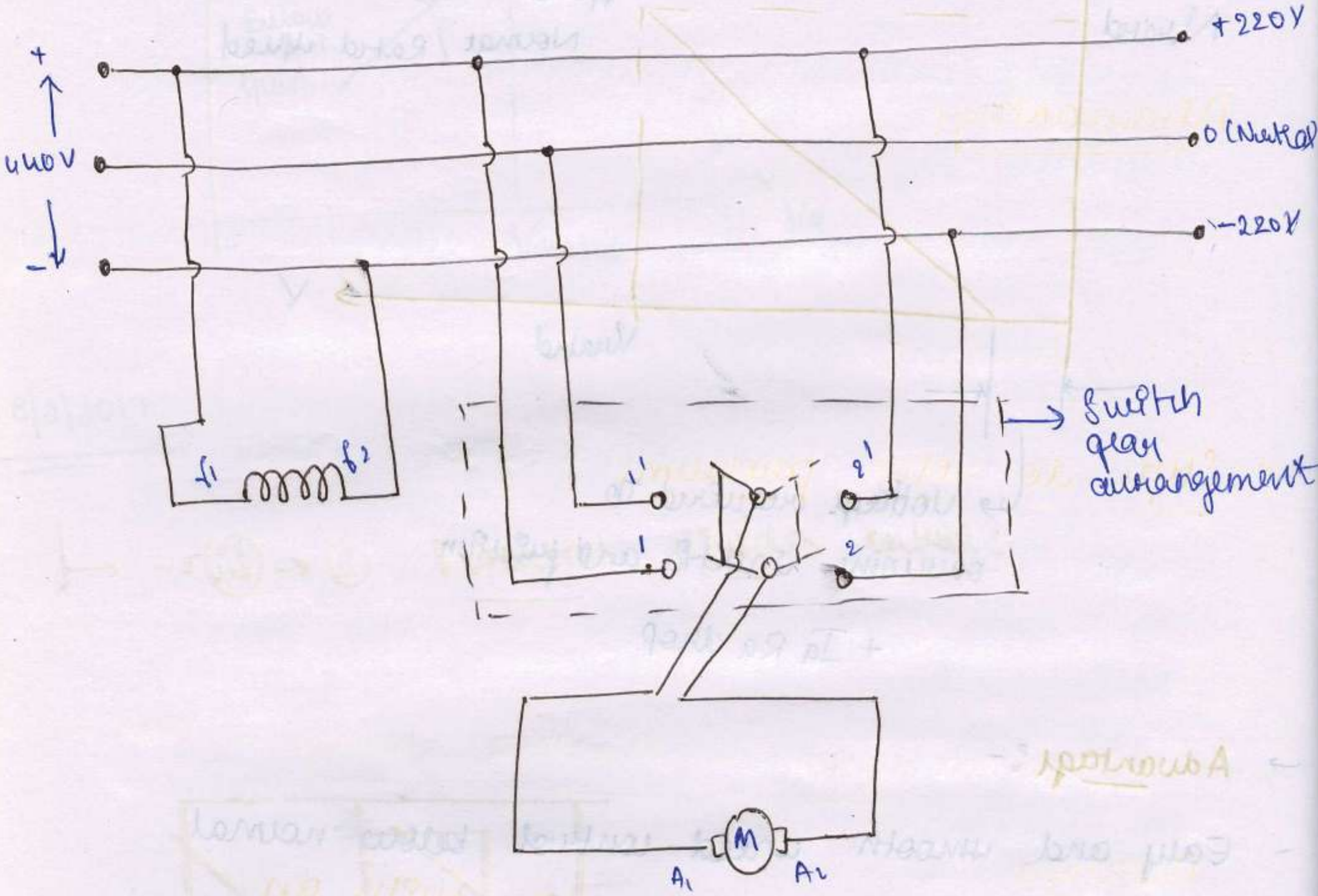
→ Advantage :-

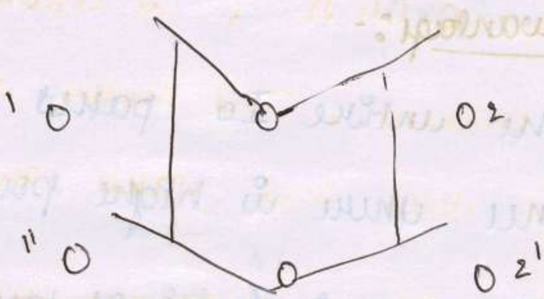
- Easy and smooth speed control below normal speed is possible

⇒ Disadvantage :-

- As the entire Ia passes through the external resistance there is higher power loss
- Rheostat required is of large size.
- Speed control above the rated speed is not possible

↳ iii) Supply / Applied voltage control method :-





Advantages

- Wide range of speed control by suitable arrangement in the field or armature circuit

- Speed control in both directions can be achieved
- Uniform acceleration

Disadvantage

- This arrangement is expensive
- Overall efficiency is low

→ Steps to solve problems

1) $T_a \propto \Phi I_a$

2) $N \propto \frac{E_b}{\Phi}$

Problems

Q1) A 230 volts, DC shunt motor with an $R_a = 0.4\ \Omega$, is excited to give constant field current. The motor runs at 500 rpm at full load and takes armature current of 30 Amps if an external resistance of $1.1\ \Omega$ (R_x) is placed in the armature circuit, Find the speed of the motor at (i) full load torque (ii) 1.5 times full load torque.

Soln :-

Given :-

$V = 230\ V$

$R_a = 0.4\ \Omega$

~~Rsh~~ =

$I_{a1} = 30\ A$

$R_x = 101\ \Omega$

$N_1 = 500\ rpm$

To find :- $N_2 = ?$

1) (i) → under full load torque condition -

$$\underline{T_{a_1} = T_{a_2}}$$

Then $T_a \propto \phi I_a$ [constant General torque condition]

$T_a \propto I_a$ [shunt motor]

- ↳ $T_{a1} \propto I_{a1}$

↳ $T_{a2} \propto I_{a2}$

$I_{a1} = I_{a2} = 30\ A$ [from above eqn]

- $N \propto \frac{E_b}{\phi}$ [general eqn]

$N \propto E_b$ [ϕ = constant]

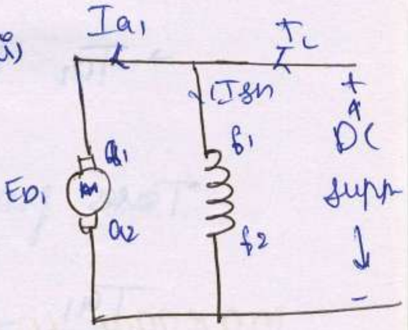
$N_1 \propto E_{b1} \rightarrow (1)$

$N_2 \propto E_{b2} \rightarrow (2)$

Taking ratio of (1) and (2)

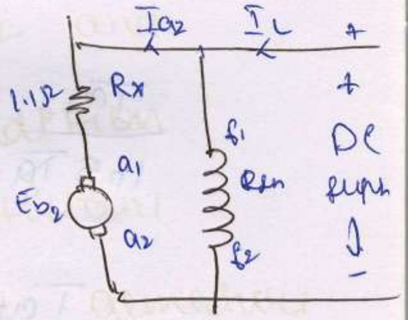
$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}}$$

(ii)



• → $E_{b1} = V - I_{a1} R_a$

* → $E_{b2} = V - I_{a2}(R_a + R_x)$



• → $E_{b1} = 230 - 30 * 0.04$

$= 218\ V$

* → $E_{b2} = 230 - 30(0.04 + 1.1)$

$= 185\ V$

$$\frac{N_1}{N_2} = \cancel{218}\ \frac{E_{b1}}{E_{b2}}$$

$$N_2 = \frac{500 * 185}{218}$$

$N_2 = 424$ rpm

2) iii) Under 1.5 times full load torque

$$T_{a2} = 1.5\, T_{a1}$$

$$T_a \propto I_a$$

$\rightarrow T_{a1} \propto I_{a1} \rightarrow ①$

$\rightarrow T_{a2} \propto I_{a2} \rightarrow ②$

Take from ① and ②

$$\frac{T_{a1}}{T_{a2}} = \frac{I_{a1}}{I_{a2}}$$

$$\frac{T_{a1}}{1.5\, T_{a1}} = \frac{I_{a1}}{I_{a2}}$$

$$I_{a2} = 1.5\, I_{a1}$$

$$= 1.5 \times 30$$

$$\underline{\underline{I_{a2} = 45 \text{ Amps}}}$$

$\hookrightarrow E_{b1} = V - I_{a1} R_{a1}$

$= 230 - (30 \times 0.04)$

$= 218$

$\hookrightarrow E_{b2} = V - I_{a2}(R_a + R_x)$

$= 230 - 45(0.04 + 0.1)$

$= 162.5\, V$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}}$$

$$\frac{500}{N_2} = \frac{218}{162.5}$$

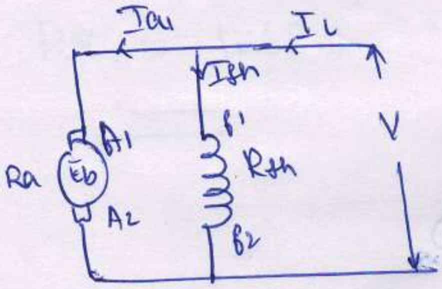
$$N_2 = 372.70 \text{ ve}$$

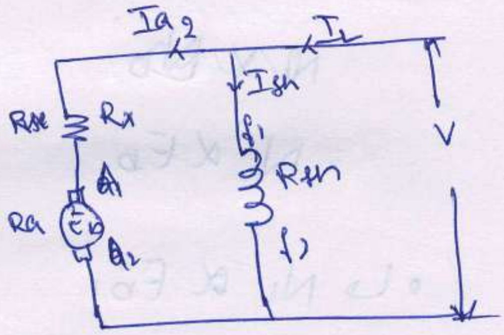
$\simeq$

$$N_2 = \underline{373 \text{ rpm}}$$

Q2) A DC shunt motor ~~the~~ runs at 1000rpm on 200V volts supply, Ra = 0.8 Ω and the current taken is 40 Amps (I_{a1}) in addition to the field current. What resistance must be connected in series with armature to reduce the speed to 600 rpm, the armature torque remaining the same.

Soln





Given

$V = 200\text{ V}$; $N_1 = 1000\text{rpm}$

$R_a = 0.8\ \Omega$; $N_2 = 600\text{rpm}$

$I_{a1} = 40\text{ A}$

// $T_{a1} = T_{a2}$

To find :-

$R_x = ?$

$\Rightarrow$ General torque eqn

$T_a \propto \phi I_a$

$T_a \propto I_a$ [DC shunt motor ϕ = constant]

$\rightarrow T_{a1} \propto I_{a1}$

$\rightarrow T_{a2} \propto I_{a2}$

$\because T_{a1} = T_{a2}$

$I_{a1} = I_{a2} = 40$ Amps

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

ϕ = constant

~~$N \propto E_b$~~

$N \propto E_b$

$\rightarrow N_1 \propto E_{b1}$ $\rightarrow$ (1)

$\rightarrow N_2 \propto E_{b2}$ $\rightarrow$ (2)

① ÷ ②

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}}$$

$\rightarrow E_{b1} = V - I_{a1} R_a$

$= 200 - (40 * 0.8)$

$= 168V$

$\rightarrow E_{b2} = V - I_{a2}(R_a + R_x)$

$\hookrightarrow \dfrac{1000}{600} = \dfrac{168}{E_{b2}} \Rightarrow E_{b2} = 100.8\ V$

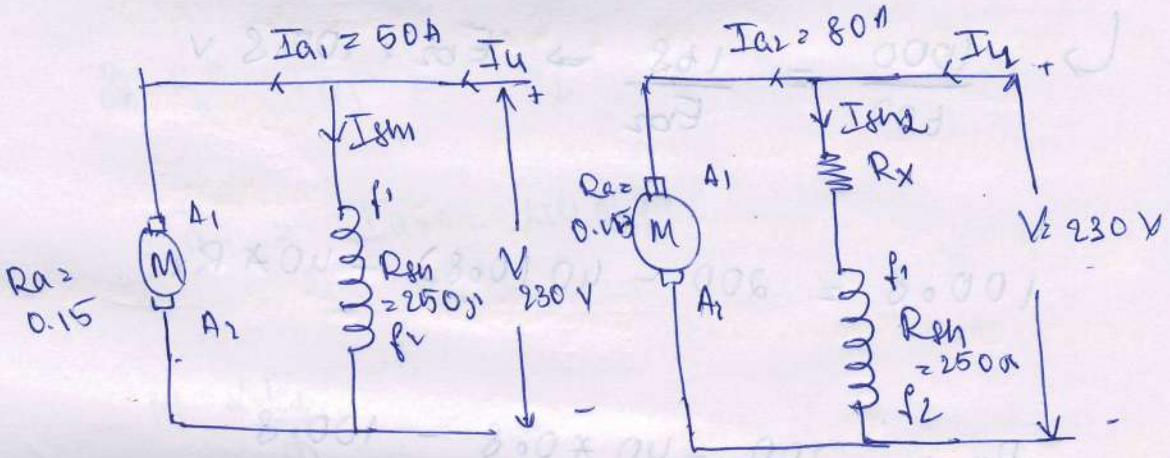
$100.8 = 200 - 40(0.8) - 40 * R_x$

$$R_x = \frac{200 - 40 * 0.8 - 100.8}{40}$$

$R_x = 1.68\ \Omega$

Q3) A 230 volts, DC shunt motor runs at 800 rpm and takes armature current of 50 Amps. Find the resistance to be added in the field circuit to increase the speed from 800 rpm to 1000 rpm, at an armature current of 80 Amps. Assume flux proportion to field current. $R_a = 0.15\Omega$ and $R_{sh} = 250\Omega$

Soln



Given

$V = 230$

$R_a = 0.15\Omega$

$R_{sh} = 250\Omega$

$I_{a_1} = 50A$

$I_{a_2} = 80A$

$N_1 = 800rpm$

$N_2 = 1000rpm$

$\phi \propto I_{sh} \propto I_f$

To find :- $R_x = ?$

$\rightarrow$ ~~$T_a \propto$~~ ϕI_a

$\rightarrow$ ~~$\sqrt{\gamma}$~~

$\rightarrow$ $I_{sh_1} = \dfrac{V}{R_{sh}}$

$I_{sh_1} = \dfrac{250}{230}$

$\underline{I_{sh1} = 0.92A}$

$\rightarrow$ $E_{b1} = V - I_{a1} R_a$

$= 230 - 50 * 0.15$

$\underline{E_{b1} = 222.5\ V}$

$\rightarrow$ $E_{b2} = V - I_{a2} R_a$

$= 230 - 80\ \cancel{Ra} * 0.15$

$\underline{E_{b2} = 218\ V}$

<u>Note</u> :-

As load condition is not given, torque equation cannot be used

$\rightarrow \quad N \propto \dfrac{E_b}{\phi}$

given $[\phi \propto I_{sh} \propto I_f]$

$\rightarrow \quad N \propto \dfrac{E_b}{I_{sh}}$

$\rightarrow \quad N_1 \propto \dfrac{E_{b1}}{I_{sh1}} \rightarrow (1)$

$\rightarrow \quad N_2 \propto \dfrac{E_{b2}}{I_{sh2}} \rightarrow (2)$

(1) $\div$ (2)

$$\frac{N_1}{N_2} = \frac{E_{b1}}{I_{sh1}} * \frac{I_{sh2}}{E_{b2}}$$

$$\frac{800}{1000} = \frac{222.5}{0.92} * \frac{I_{sh2}}{218}$$

$I_{sh2} = 0.72$ Amps

ohms law

$\rightarrow \quad V = I_{sh2}(R_x + R_{sh})$

$\cancel{I_{sh}}$

$230 = 0.72 R_x + 0.72 * 250$

$R_x =$

$$R_x = \frac{230 - 0.72 \times 250}{0.72}$$

$$\underline{R_x = 69.44\ \Omega}$$

⟹ Speed control of DC series motor :-

↳ 1) Flux control

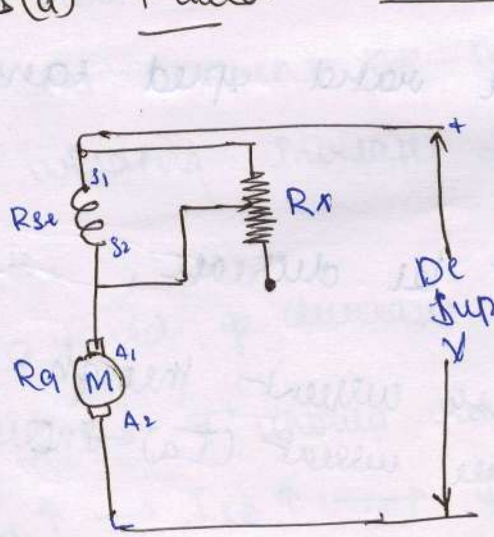
Note :-

The flux produced by a winding (motor) depends on the mmf (magneto motive force) which is a product of current and no. of turns of the winding

$$\boxed{mmf = NI \quad \text{Amp / turn}}$$

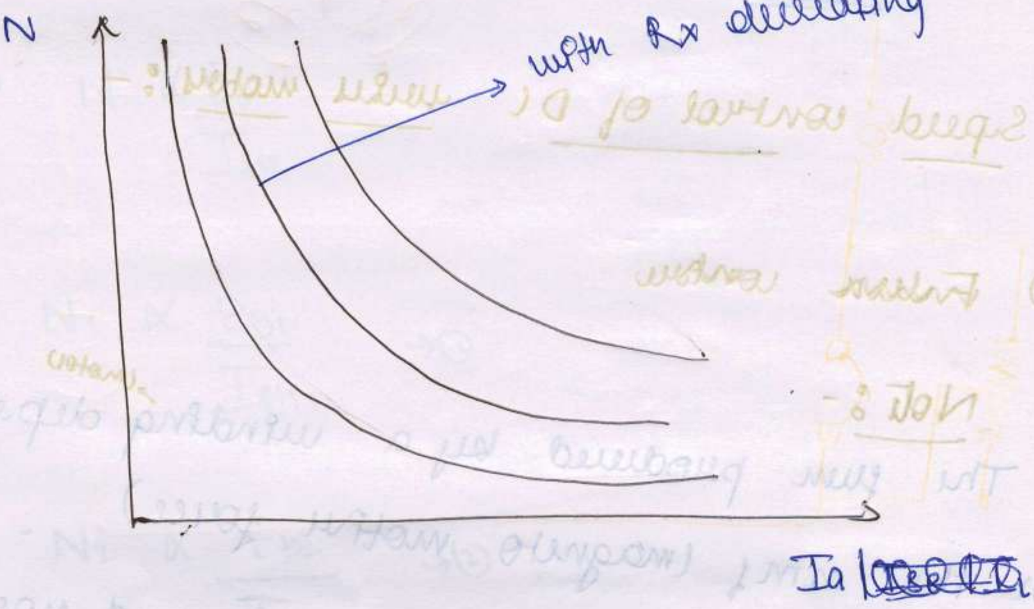
↳ 1) Flux control method

↳ (a) Field diverter method :-



~~Ad~~

→ N Vs Ia (or) Ise (or) I_L



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

as $\phi \uparrow$; Ia ↑ ;

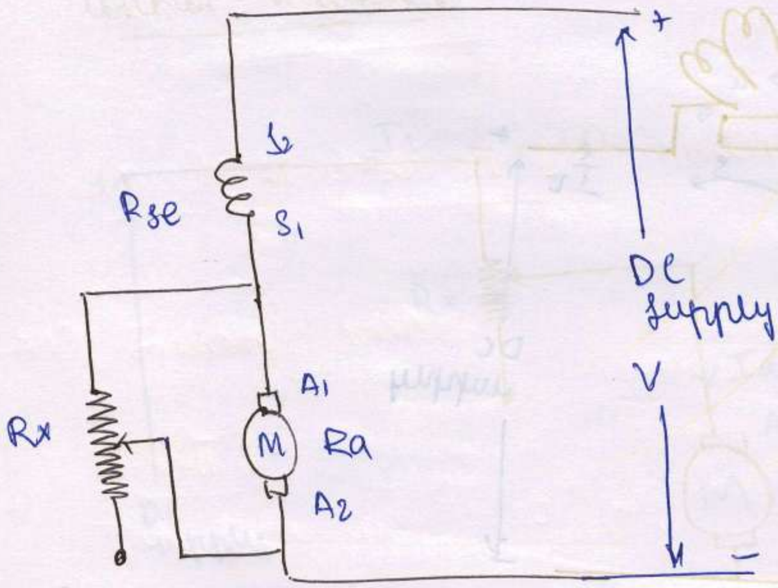
⇒ N ↓

Ise ↓ ⟶ ϕ ↓ ⟶ N ↑

- Speed control above rated speed cannot be done . . .
- As flux cannot be decrease,

As Resistance Rx increase current through Rheostat decreases and ~~the~~ armature current (Ia) increases

→ b) Armature diverter method :-



As → Load ↑ → I_a ↑ → ϕ ↑ → N ↓

→ when the armature current is diverted through R_x thus reducing it.

Now w.K.T

$\boxed{T_a \propto \phi I_a}$ and since the load torque remains constant, the motor draws more current from the supply.

Thus the current ~~to~~ through the series field winding increases → so does the flux increase.

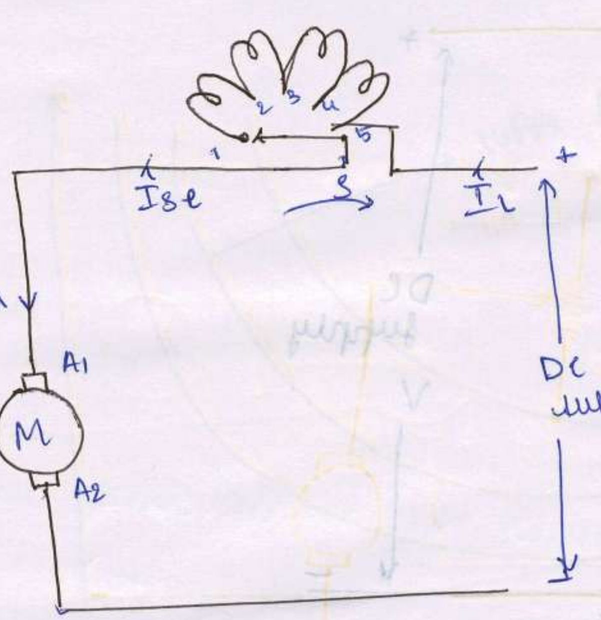
Thus speed ~~of~~ decreases

→ I_a ↓ → T should remain constant →

I_L ↑ → I_{se} ↑ → ϕ ↑ → N ↓

→ I_a decreases due to diverter.

↳ → e) Tapped field method :-



- In this method, the change in flux is achieved by changing the no: of turns of the field winding.
- The field windings is provided with no: of taps and a selector switch 'S' to select the no: of turns (taps) as per requirement

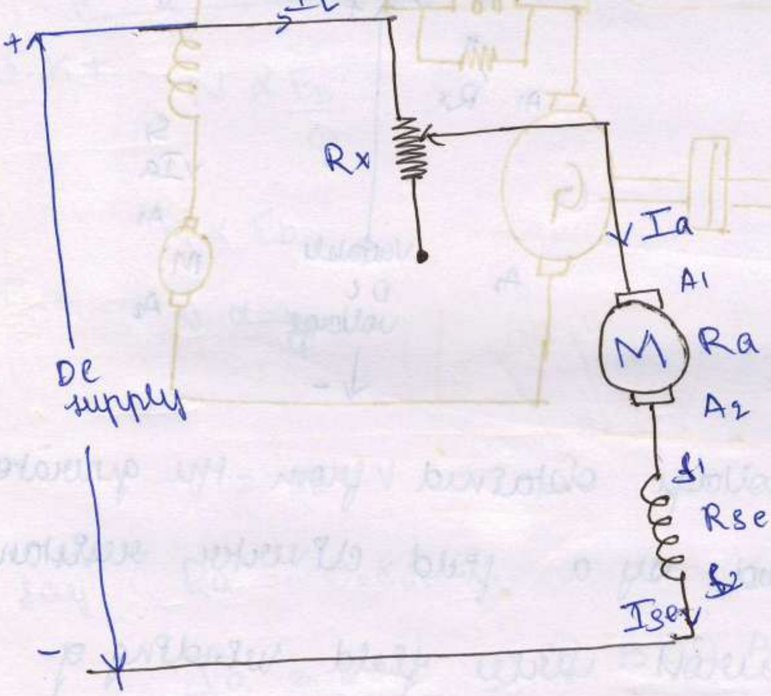
when S is in position 1 → entire winding is included → no: of turns is more → flux is high → speed decreases

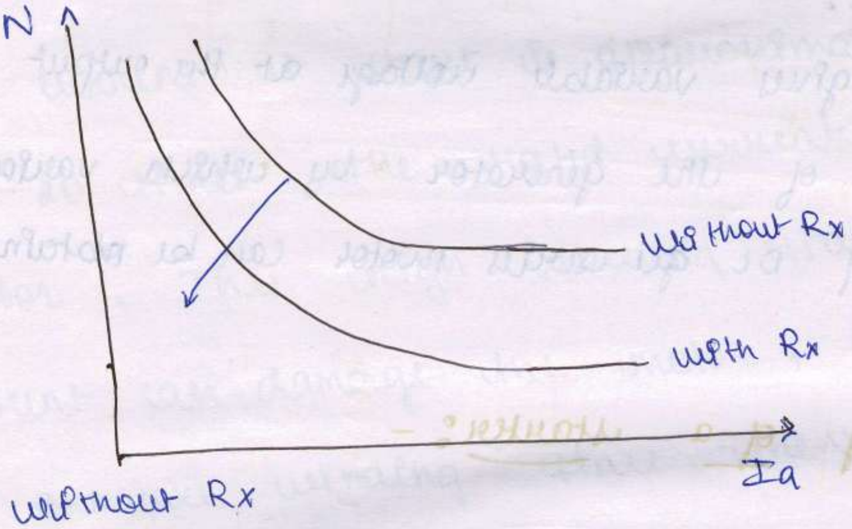
S: → 1 → No: of turns ↑ → ϕ ↑ → N ↓ (↓)

S: → 2 → No: of turns ↓ → ϕ ↓ → N ↑

S: → 3 → No: of turns ↓↓ → ϕ ↓↓ → N ↑↑

↳2) Rheostatic control (or) Armature voltage control method :-





(i) without R_x

$N \propto \frac{1}{\phi}$

$\phi \propto I_{se}$

(ii) with R_x

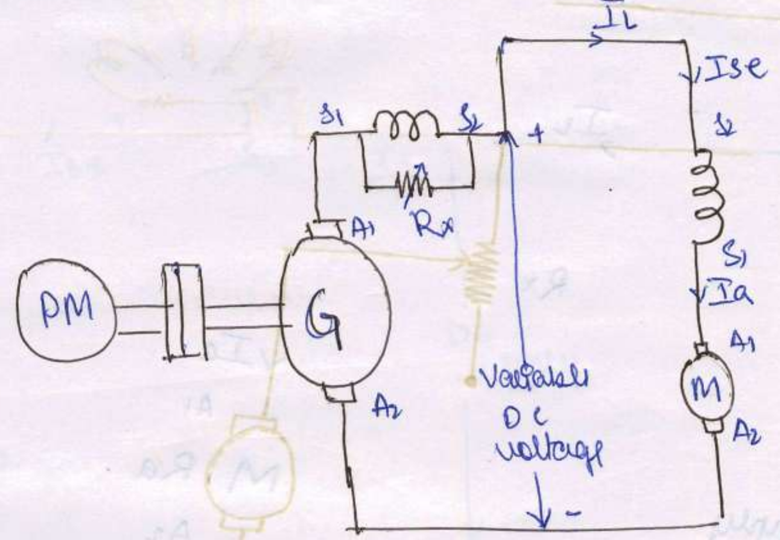
$N \propto V$ $\quad [N \propto E_b/\phi \Rightarrow N \propto \phi]$

$N\downarrow$ as $\rightarrow V\downarrow$ $\quad$ [$V \rightarrow \downarrow \rightarrow$ due to voltage drop]

as R_x is added $I_a\downarrow$

$\therefore V\downarrow$

3) Applied voltage control method:-



→ The voltage obtained from the generator is controlled by a field diverter resistance connected across series field winding of generator.

- This gives variable voltage at the output terminals of the generator by which various speeds of DC series motor can be obtained.

⟹ Necessity of a starter:-

consider a DC shunt motor -

$$V = E_b + I_a R_a$$

At start, $N = 0$

then $E_b = 0$

$$V = 0 + I_a R_a$$

$$V = I_a R_a$$

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

w.k.t

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

$$N \propto E_b$$

$$N \propto \frac{1}{\phi}$$

Eg:-

$V = 220V$

say $R_a = 0.8\Omega$

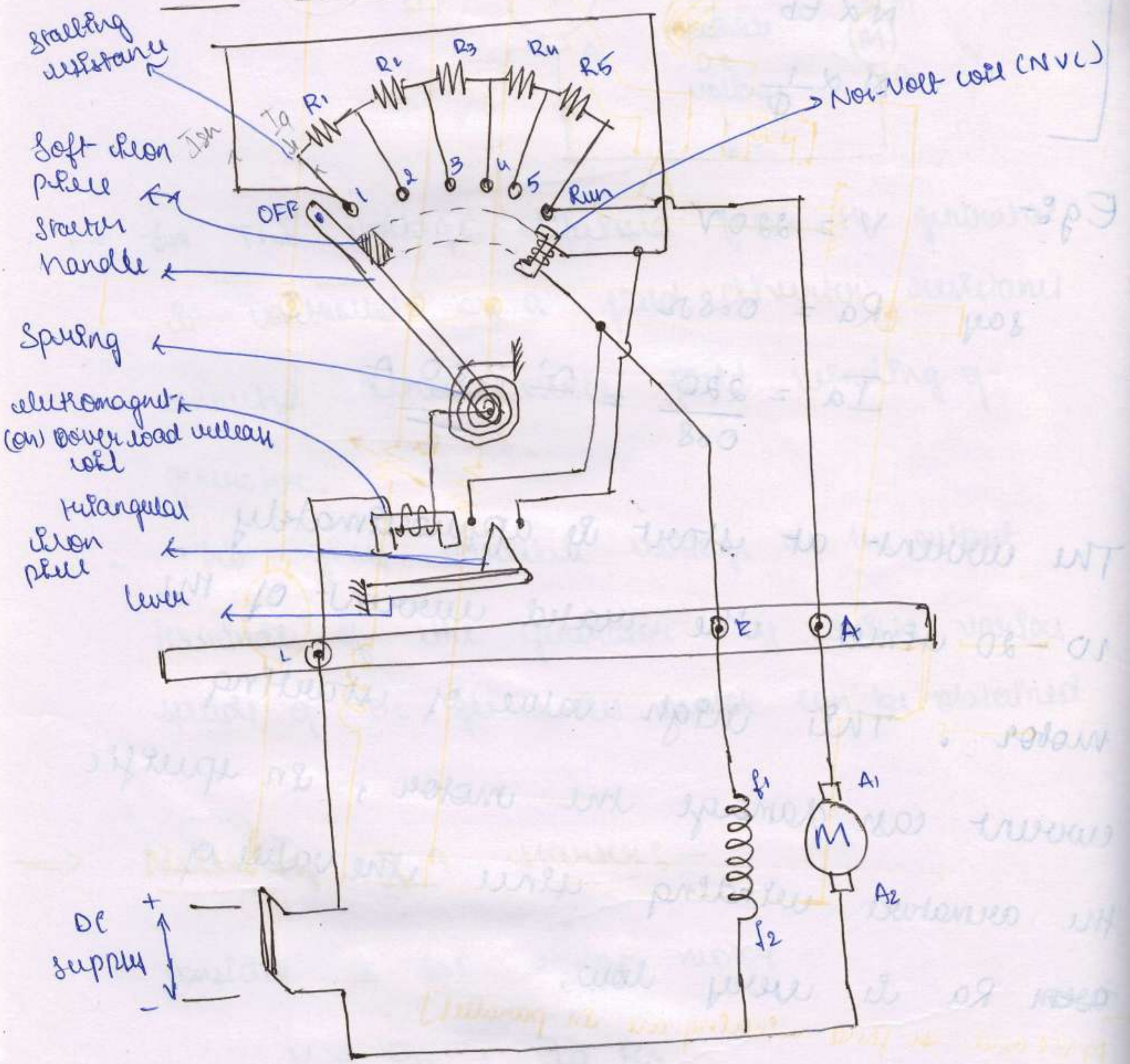
$$I_a = \frac{220}{0.8} = \underline{\underline{\simeq 300\ A}}$$

The current at start is approximately 10 - 20 times the rated current of the motor. This high value of starting current can damage the motor, in specific the armature winding since the value of ~~arm~~ Ra is very low.

⟹ Starter :-

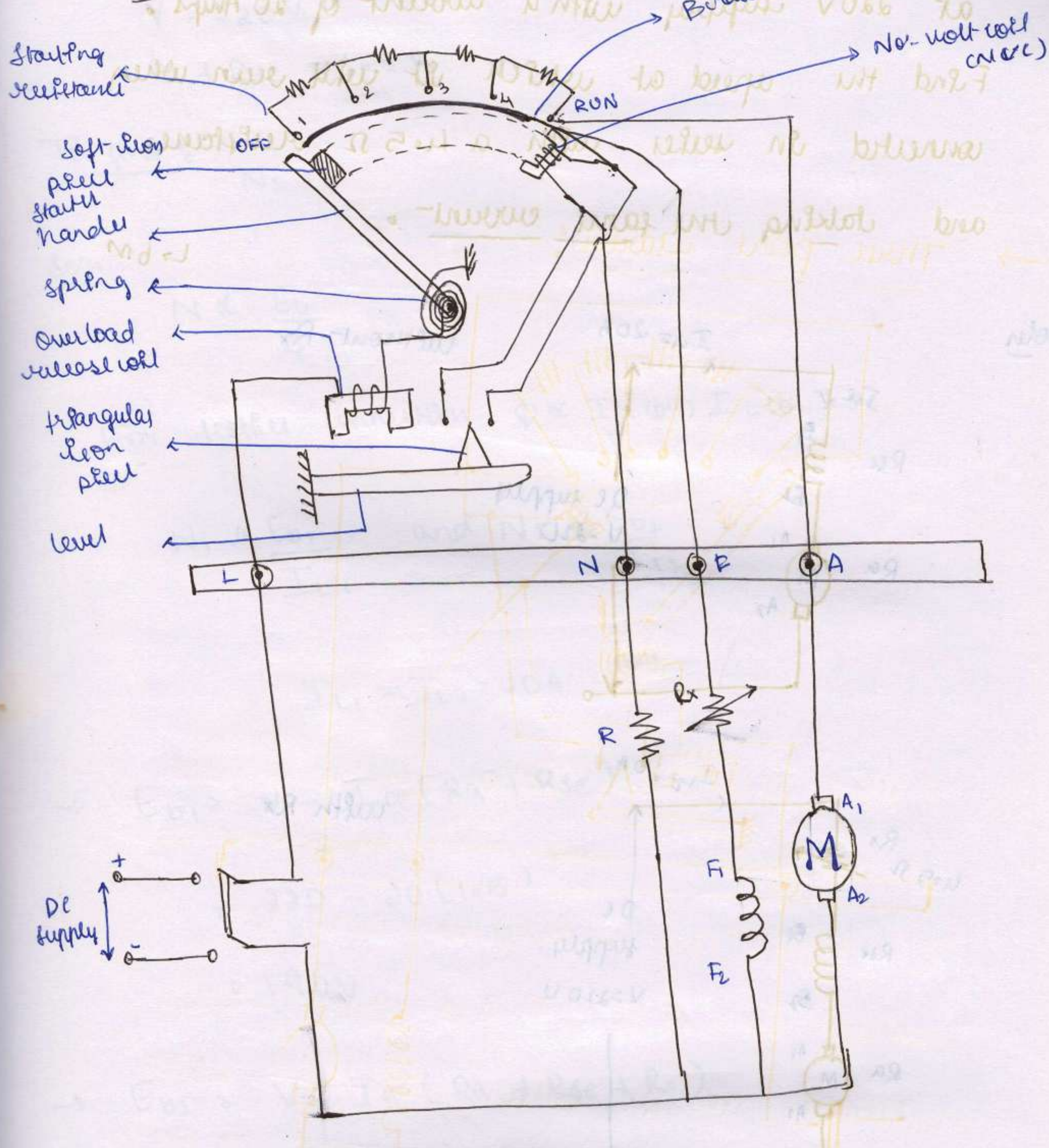
A starter is a safety device which is used to safely star a motor by limiting high starting current.

→ Three point starter :-



28/2/2017

→ Four point starter:-

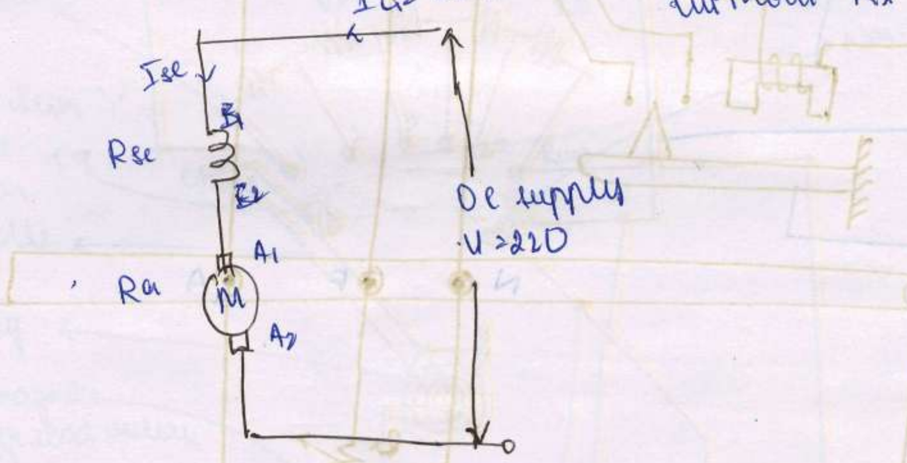


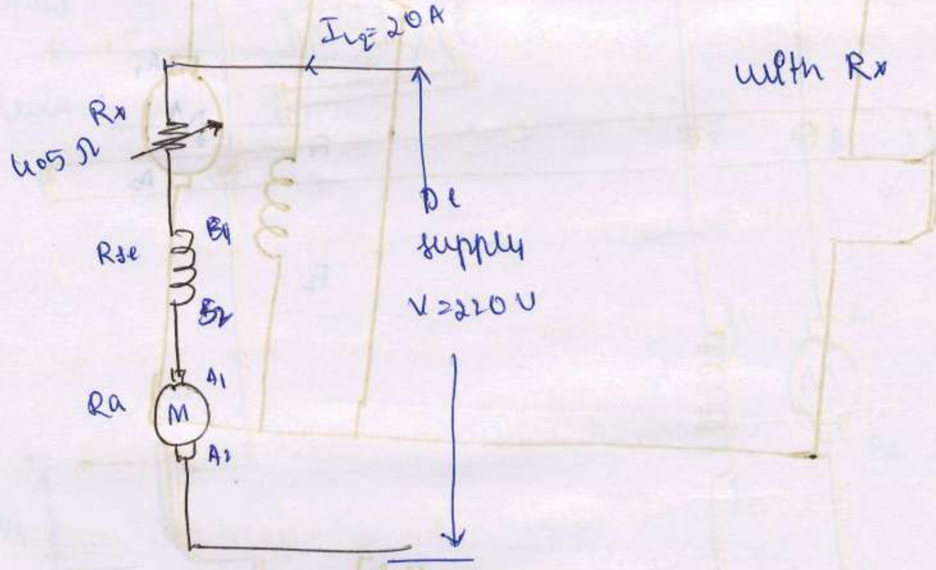
[NVC and field winding are in parallel]

Q1) ~~Aa~~ A DC series motor has a total resistance of 1.5 Ω and runs at 750 rpm at 220V supply with a current of 20 Amps. Find the speed at which it will run when connected in series with a 4.5 Ω resistance and taking the same current.

↳ 6M

Soln





Given

$N_1 = 750$ rpm

$I_{L1} = 20A$

$V = 220V$

$R_a + R_{se} = 1.05\,\Omega$

To find :-

$N_2 = ?$

Soln

$$N \propto \frac{E_b}{\Phi}$$

For series connection $\Phi \propto I_a$ (or) I_L (or) I_{se}

$$N_1 \propto \frac{E_{b1}}{I_{L1}} \quad \text{and} \quad N_2 \propto \frac{E_{b2}}{I_{L2}}$$

$$I_{L1} = I_{L2} = 20A$$

$\rightarrow$ $E_{b1} = V - I_a(R_a + R_{se})$

$= 220 - 20(1.05)$

$= 190V$

$\rightarrow$ $E_{b2} = V - I_a(R_a + R_{se} + R_x)$

$= 220 - 20(1.05 + 4.05)$

$= 100V$

$$N_1 \propto \frac{E_{b1}}{I_{L1}}$$

$$N_2 = \frac{E_b}{I_{L2}}$$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \times \cancel{\frac{I_{L2}}{I_{L1}}}$$

$$= N_2 = \cancel{\frac{750 \times 190}{100}} \quad \frac{N_1 * E_{b2}}{E_{b1}}$$

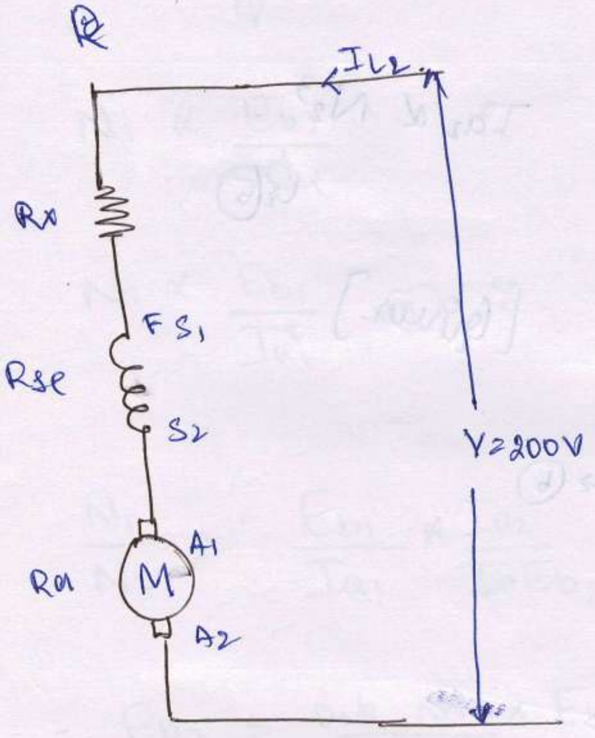
$$N_2 = \frac{750 \times 100}{190}$$

$$= 394.73$$

$$N_2 \simeq 395 \text{ rpm}$$

Q2) A 200 V, DC series motor drives a load at a certain speed and takes a current of 30 Amps. The resistance b/w its terminals is 1.5 Ω. Find the extra resistance to be added in series with motor circuit. To reduce speed to 60% of its original value. Assume torque produced is proportional to cube of speed

Soln



Given

$I_{L1} = I_{a_1} = 30A$

$R_a + R_{se} = 1.5\,\Omega$

$N_2 = 60\% N_1$

$\Rightarrow N_2 = 0.6 N_1$

$T \propto N^3$

reduced by 60%

∴ 60% of N_1

To find:-

$R_x = ?$

Soln

$T_a \propto \phi I_a$

$T_a \propto I_a^2$ → for DC series motors

$T_{a_1} \propto I_{a_1}^2$ ↳ ① ; $T_{a_2} \propto I_{a_2}^2$ ↳ ②

$$\frac{T_{a_1}}{T_{a_2}} = \frac{I_{a_1}^2}{I_{a_2}^2} \rightarrow (3)$$

$T_{a_1} \propto N_1^3$ and $T_{a_2} \propto N_2^3$

$\hookrightarrow (4)$ $\hookrightarrow (5)$

[Given]

$$\frac{T_{a_1}}{T_{a_2}} = \frac{N_1^3}{N_2^3} \rightarrow (6)$$

equati (3) and (6)

$$\frac{I_{a_1}^2}{I_{a_2}^2} = \frac{N_1^3}{N_2^3}$$

$$\frac{I_{a_1}^2}{I_{a_2}^2} = \frac{(\cancel{N_1})^{\cancel{3}}}{(0.6\cancel{N_1})^{\cancel{3}}}$$

$$\frac{(30)^2}{I_a^2} = \frac{1}{0.216}$$

$$I_{a_2}^2 = 194.04$$

$$I_{a_2} = \underline{\underline{13.94 \text{ Amps}}}$$

$$\therefore N \propto \frac{E_b}{\Phi}$$

$$N_1 \propto \frac{E_{b1}}{\Phi_1} \; ; \quad N_2 \propto \frac{E_{b2}}{\Phi_2}$$

$$N_1 \propto \frac{E_{b1}}{I_{a1}} \rightarrow (7) \; ; \quad N_2 \propto \frac{E_{b2}}{I_{a2}} \rightarrow (8)$$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{I_{a1}} * \frac{I_{a2}}{E_{b2}}$$

$$E_{b2} = \frac{0.6\,N_1}{\cancel{0.6}\,N_1} \times \frac{E_{b1} \times I_{a2}}{I_{a1}}$$

$$\rightarrow E_{b1} = V - I_{a1}(R_a + R_{se})$$

$$= 200 - 30(1.5)$$

$$= \cancel{170}\ 155$$

$$\rightarrow E_{b2} = \frac{155 * 13.94 \times 0.6}{\cancel{0.6} * 30}$$

$$= \underline{\underline{43.21\ V}}$$

$$\rightarrow \therefore E_b = V - I_{a2}(R_a + R_{se} + R_x)$$

$$43.21 = 200 - 13.94\,(1.5 + R_x)$$

$$R_x = \frac{200 - 43.21 - 13.94 * 1.5}{13.94} = \underline{\underline{9.74\ \Omega}}$$

→ Losses and efficiency :-

Losses present in a DC motor are

1) Copper losses (or) Variable losses - P_{cu}

2) ~~Friction loss~~

3) Mechanical losses

2) Iron losses

↳1) Copper loss :-

Variable losses

- It is also called I^2R losses where current I is the variable parameter and generally R remains constant.

(It takes place in winding → Cu material)

↳2) Iron losses :-

Constant losses (or) Magnetic losses

Denoted by 'P_i'

(It takes place in core - magnetic material)

↳(i) Hysteresis loss :-

Rapid cycles of magnetisation and demagnetisation

To reduce hysteresis losses used a very good magnetic material with low

↳ iii) Eddy current losses:-

The current flow in the unwanted portions of the core is called eddy currents

~~The~~ To reduce ~~eddy~~ eddy current loss - laminated construction of core is used.

↳ 3) Mechanical losses:-

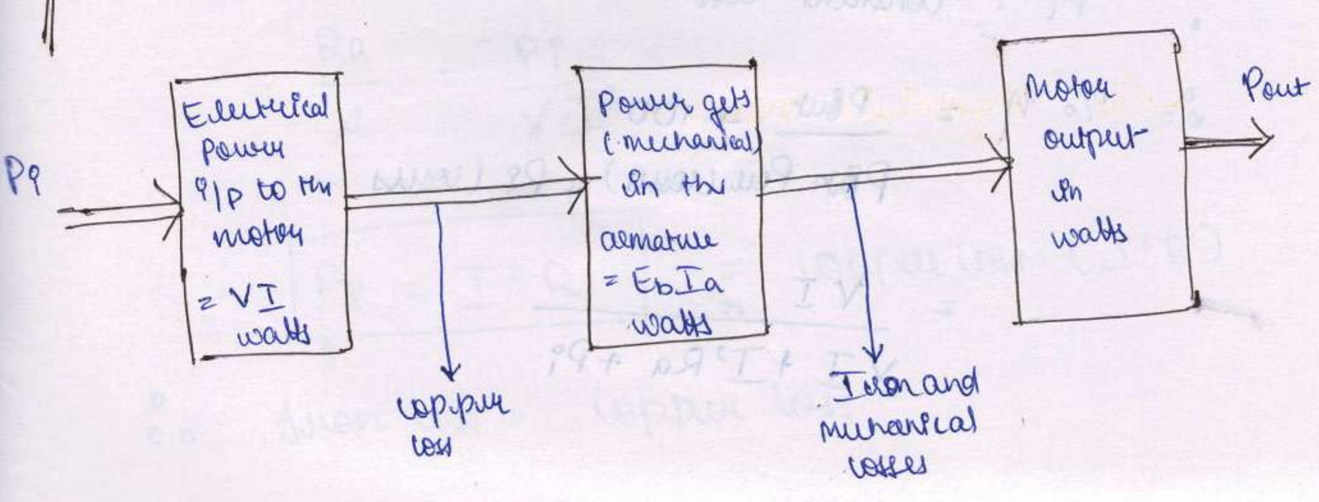
These losses are also called as windage (or) ~~p~~ frictional losses

constant loss (or) Magnetic losses + Mechanic loss → Stray losses
(constant) (constant) (constant)

Total losses:-

Total loss = constant losses + variable losses.

⟹ Power flow diagram:- for (DC motor)



→ Efficiency :-

$$\% \text{ Efficiency} = \frac{P_{out}}{P_{in}} * 100$$

motor electrical i/p power

generator electrical o/p power

for motor

$$\% \eta_m = \frac{P_{in} - \text{total loss}}{P_{in}} * 100$$

for ~~generator~~ generator

$$\% \eta_g = \frac{P_{out}}{P_{out} + \text{losses}} * 100$$

→ Condition for maximum efficiency :-

mechanical is unstable or variable whereas electrical load is stable or constant ∴ using

consider a DC generator

let $P_{out} = VI$

P_{cu} = variable loss $= I_a^2 Ra$ (or) $I^2 Ra$

P_i = constant loss

$$\therefore \% \eta = \frac{P_{out}}{P_{out} + P_{cu}\text{ (losses)} + P_i\text{ (losses)}} * 100$$

$$= \frac{VI}{VI + I^2 Ra + P_i}$$

$\div$ both numerator and denominator by VI

$$\% \eta = \frac{\frac{VI}{VI}}{\frac{VI}{VI} + \frac{I^2 Ra}{VI} + \frac{Pi}{VI}}$$

$$\% \eta = \frac{1}{\left[1 + \frac{IRa}{V} + \frac{Pi}{VI}\right]} * 100$$

For efficiency to be maximum, the denominator should be minimum according to maxima minima theorem

$$\therefore \frac{d}{dI}\left[1 + \frac{IRa}{V} + \frac{Pi}{VI}\right] = 0$$

$$0 + \frac{Ra}{V} - \frac{Pi}{VI^2} = 0$$

$$\frac{Ra}{\cancel{V}} = \frac{Pi}{\cancel{V} I^2}$$

$$\boxed{Pi = I^2 R} = \text{copper loss } (I^2 R)$$

$\therefore$ Iron loss = copper loss

Q1) A 6 pole 500 volts, wave connected DC shunt motor has 1200 armature conductors and flux per pole is 20mWb. The armature and field resistances are 0.5 Ω and 250 Ω respectively. What will be the speed and torque developed by the motor when it draws a current of 20 Amps from the supply? If the magnetic and mechanical losses are 900W. Find

(i) Useful torque

(ii) Efficiency at this load

Soln Given

$P = 6$

$V = 500V$

wave wound $A = 2$

$Z = 1200$

$\phi = 20 \times 10^{-3} Wb$

$R_a = 0.5 \Omega$

$R_{sh} = 250 \Omega$

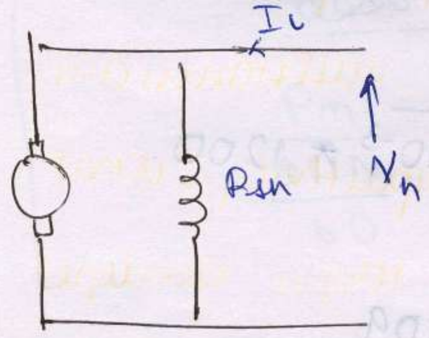
$I_L = 20A$

To find:-

1) $I_{sh} = ?$

2) $\%\eta$

3) N



$$I_{sh} = \frac{V}{R_{sh}}$$

$$= \frac{500}{250} = 2A$$

$$I_L = I_a + I_{sh}$$

$$I_a = I_L - I_{sh}$$

$$= 20 - 2$$

$$= 18A$$

$$E_b = \frac{P\phi NZ}{60A}$$

$$E_b = V - I_a R_a$$

$$= 500 - 18 * 0.5$$

$$= 491V$$

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

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

$$= \frac{491 * 60 * 2}{6 \times 20 * 10^{-3} * 1200}$$

$$= 409$$

$$\boxed{N = \simeq \cancel{600}\ 409 \text{ rpm}}$$

$$T = \frac{P \phi Z i_a}{\cancel{60}\, 2\pi A}$$

$$= \frac{6 \times 20 * 10^{-3} * 1200 * 18}{2\pi * 2}$$

$$\boxed{T = 206.26 \text{ Nm}}$$

Power developed in the armature

$$P_m = E_b * I_a$$

$$= 491 * 18$$

$$P_m = 8838 \text{ watts}$$

$P_m = T_a * \omega = T_a * \omega$ ← Power developed in armature

$T_a = \dfrac{P_m}{\omega}$

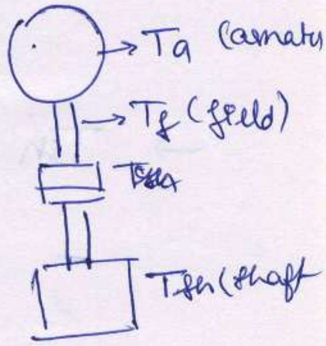
$= \cancel{8838}$

$= \dfrac{P_m}{\frac{2\pi N}{60}}$

same $= \dfrac{P_m * 60}{2\pi N}$

$= \dfrac{8838 * 60}{2 * \pi * 406}$

$T_a = 206.26$ Nm



$\cancel{P_{in} = V I_a}$

$= \cancel{500 * 18}$

$= \cancel{9000 \text{ watts}}$

→ $P_{in} = V I_L$ [electrical parameter i/p in motor]

$= 500 * I_L$

$= 500 * 20$

$P_{in} = 10,000$ watts

$P_{out} = P_m - \text{Mechanical losses}$

$= 8838 - 900$

$P_{out} = 7938 \text{ watts}$

$\rightarrow T_{sh} = \dfrac{P_{out}}{\omega}$

$= \dfrac{7938 * 60}{2 * \pi * 409}$

$T_{sh} = 185.33 \text{ N}$

∴ When T_{sh} will be less than T_a

$\% \eta = \dfrac{P_{out}}{P_{in}} * 100$

$= \dfrac{7938}{100\cancel{00}} * 1\cancel{00}$

$\% \eta = 79.38\%$

MODULE-2

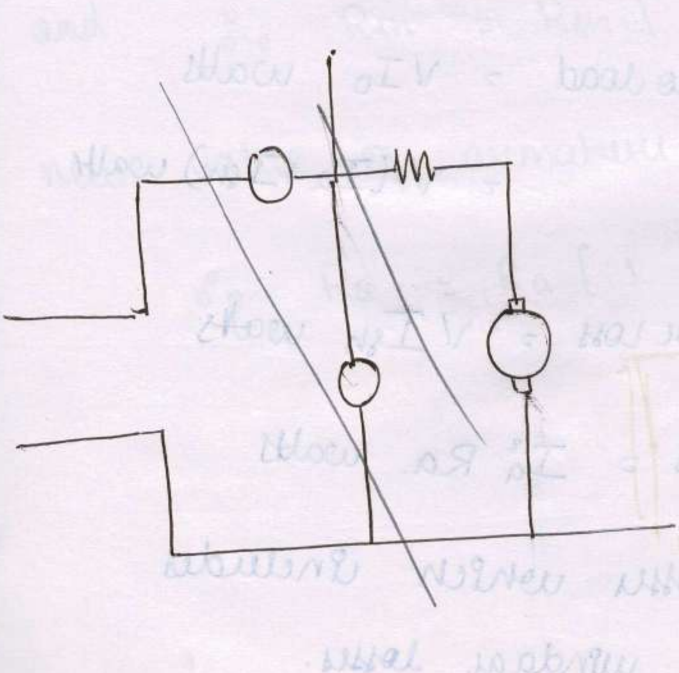
TESTING OF DC MOTORS

⟹ ~~Swinburne's test~~-

↳(i) Direct testing:-

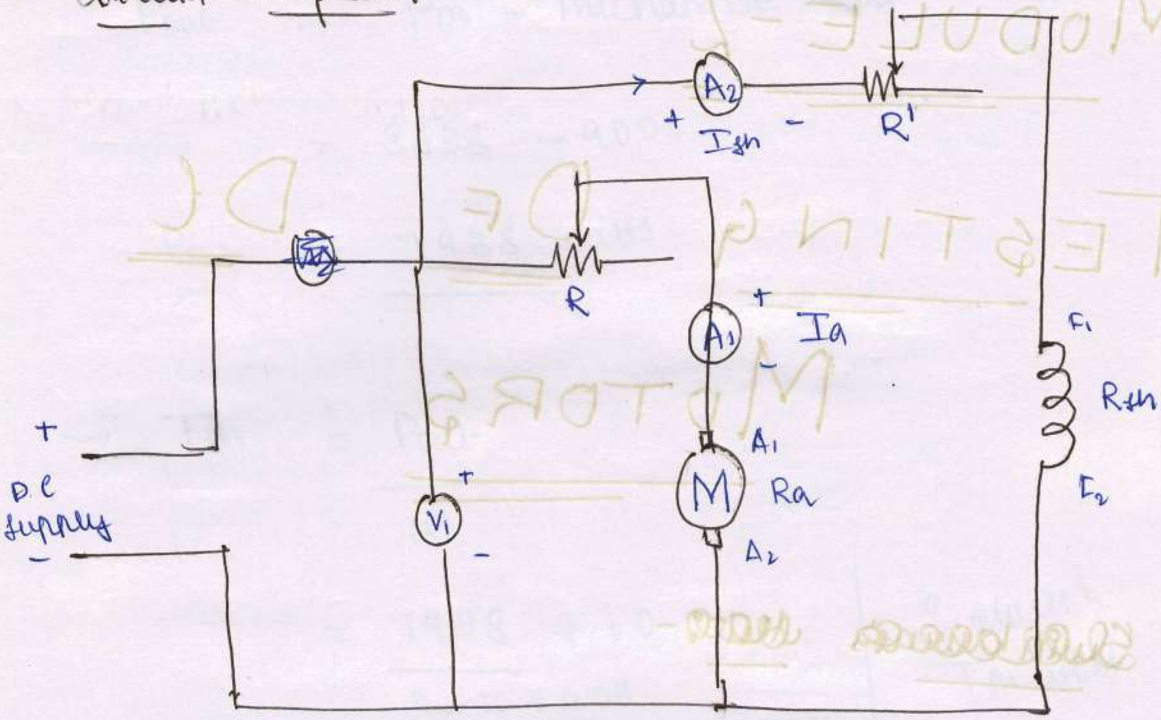
↳(ii) Indirect testing:-

⟹ Swinburne's testing:- [indirect method of testing]



→ Swinburne's test :-

Circuit diagram :-



Tabular colum :-

Sl. No:	V (volts)	Ia (Amps)	Ish (Amps)	$I_0 = I_a + I_{sh}$

Calculation :-

If 'V' is the supply voltage then

then

→ Power i/p on no load $= V I_0$ watts

$= V(I_a + I_{sh})$ watts

Iar -

→ Shunt field copper loss $= V I_{sh}$ watts

→ Armature copper loss $= I_a^2 R_a$ watts

Thus the stray losses which includes iron, friction and windage losses.

Stray → Iron loss + Mechanical loss

→ Iron loss + (friction + windage) losses

can be obtained

Stray losses = No load I/P - field cu loss - Armature cu loss

∴ Stray loss = $V I_0 - V I_{sh} - I_a^2 R_a = W_s$

When current flows through the field and armature windings there will be copper losses (I^2R) in the respective winding which increase the temperature, in turn it affects their resistances

Thus new value of shunt field resistance = R'_{sh}

and ∴ $R'_{sh} = R_{sh}[1 + \alpha_0]$ and

new value of armature resistance = R'_a

∴ $R'_a = R_a[1 + \alpha]$

R'_a and R'_{sh} are temperature dependent

→ To calculate efficiency ~~at~~ of the motor at $1/4^{th}$ load:-

Let I_{FL} = full load current of the motor

W_F = Field copper losses

W_s = Stray losses

Load current at $1/4^{th}$ load

$$= I_{FL} * \frac{1}{4} = \frac{I_{FL}}{4}$$

Motor input at $1/4^{th}$ load

$$= V * \frac{I_{FL}}{4} = \frac{V I_{FL}}{4}$$

Armature current at $1/4^{th}$ load

$$= I_a' = \cancel{I_a - I_{sh}'}$$

$$I_a' = \frac{I_{FL}}{4} - I_{sh}'$$

Armature copper loss at $1/4^{th}$ load $= (I_a')^2 R_a$

$$= (I_a')^2 R_a$$

$$= [I_a']^2 R_a$$

$$= \left[\cancel{\frac{I_{sh}}{4}}\right]^{1}$$

$$= \left[I_a'\right]^2 Ra$$

$$= \left[\frac{I_{FL}}{4} - I_{sh}'\right]^2 Ra$$

Motor output at 1/4th load $= \left(\cancel{\frac{V I_{FL}}{4}}\right) - i/p - \text{loss}$

$$= \left[\frac{V I_{FL}}{4}\right] - \left[\left(\frac{I_{FL}}{4} - I_{sh}'\right)^2 Ra + W_F + W_S\right]$$

% Efficiency $= \dfrac{\cancel{\text{Motor output}}}{\cancel{\text{motor input}}} =$

$$= \cancel{\left[\frac{V I_{FL}}{4}\right] - \left[\left[I\right.\right.}$$

$$= \frac{\text{Input} - \text{loss}}{\text{Input}} * 100$$

$$\%\eta_{1/4} = \frac{\frac{V I_{FL}}{4} - \left[\left(\frac{I_{FL}}{4} - I_{sh}'\right)^2 Ra + W_F + W_S\right]}{\frac{V I_{FL}}{4}} * 100$$

Q1) A 500 volts DC shunt motor takes 4 Amps on no load. The armature resistance including that of the brushes is 0.2 Ω and the field current is 1 Amps. Estimate the output and efficiency when the i/p current is

(i) 20 Amps

(ii) 100 Amps

Soln Given :-

$V = 500\ V$

$I_0 = 4$ Amps

$R_a = 0.2\ \Omega$

$I_{sh} = 1$ Amps

To find :- o/p efficiency

at $I_{L1} = 20\ A$, $I_{L2} = 100\ A$

Soln

$\longrightarrow I_{a0} = I_0 - I_{sh}$

$= (4 - 1)$

$I_{a0} = 3$ Amps

$\longrightarrow$ No load armature copper loss =

$= I_{a0}^2 R_a = (3)^2 (0.2) = 1.8$ watts

$\rightarrow$ No load i/p = $V I_0$

$500 * 4 = 2000$ watts

→ constant losses $= V I_a - I_{a0}^2 R_a$

$= 2000 - 1.8$

$= 1998.2$ watts

↳ (i) when $I_{L1} = 20$ Amps

$I_{a1} = I_{L1} - I_{sh}$

$= 20 - 1 = 19$ Amps

New value of cu loss $= I_{a1}^2 R_a = 19^2 * 0.2$

$= 72.2$ watts

New load o/p $= V I_{L1}$

$= 500 * 20$

$= 10000$ watts

$\%\eta = \frac{i/p - loss}{i/p} * 100$

$= \frac{10{,}000 - [72.2 + 1998.2]}{10{,}000} * 100$

$= 79.29\ \%$

↳ (ii) when $I_{L2} = 100$ Amps

$I_{a2} = 100 - 1$

$= 99$ Amps

New cu loss $= I_{a2}^2 R_a = (99)^2\ 0.2 = 1960.2$ W

New load o/p $= V I_{L2} = 500 * 100$

$= 50000$

$$\%\eta = \frac{50{,}000 - [1960.2 + 1998.2]}{50{,}000} * 100$$

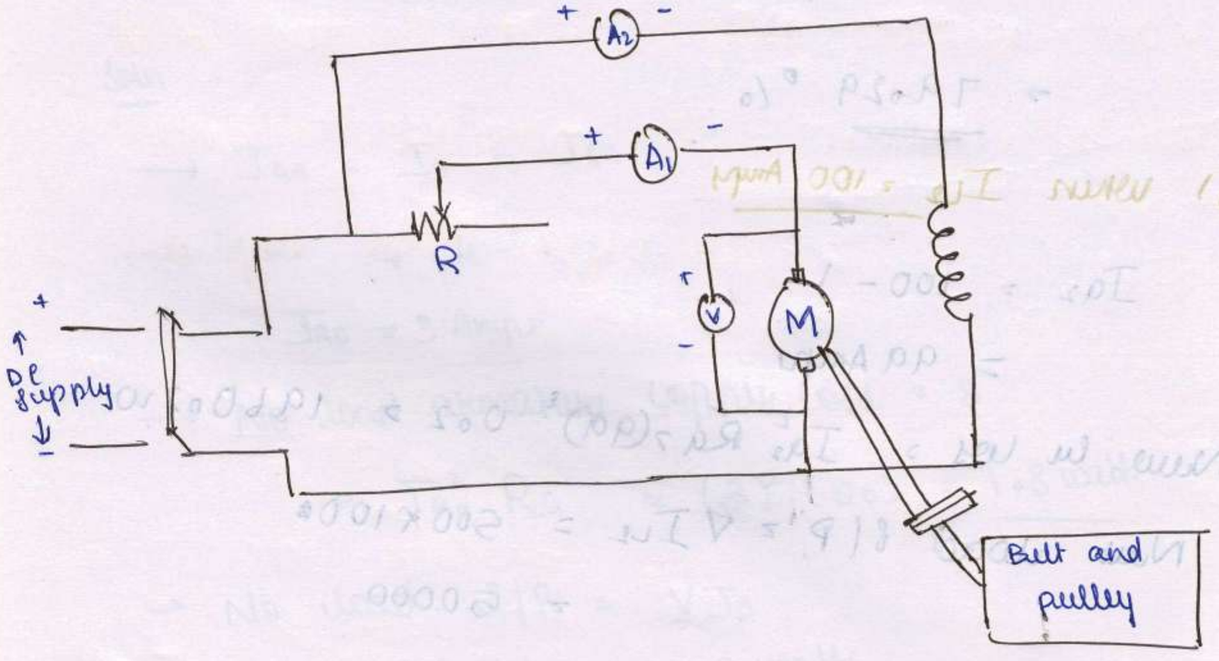
$$\%\eta = 92.08\%$$

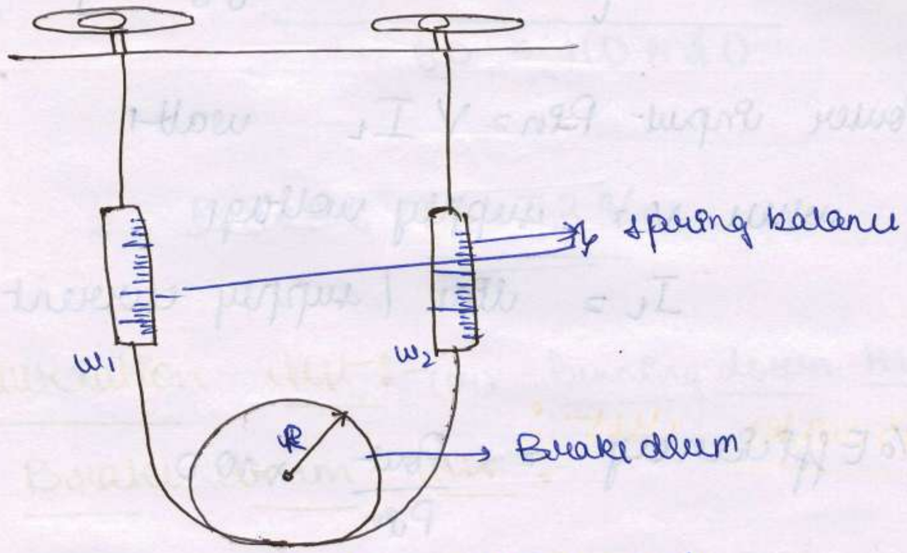
⇒ Brake test :-

This is direct method of testing a DC motor by means of a belt and pully arrangment (brake drum).

By adjusting the tension of the belt, the load is adjusted to give various values of current.

Circuit diagram :-





Belt and pulley arrangement

Let R = radius of brake drum in metres

N = speed in rpm

w_1 = spring balance reading on tight side in Kg

w_2 = spring balance reading on slag side

∴ Net pull on the belt due to friction is given by = $(w_1 - w_2)$ Kgs

Net pull = $9.81 (w_1 - w_2)$ ~~Newton~~ Newton

As the speed N and radius R is known, the shaft torque developed is given by

T_{sh} = ~~Net~~ Net pull * R

$= 9.81 (w_1 - w_2) * R$ N-m

The power O/P is given by

$P_{out} = T_{sh} * \omega$ watts

$$P_{out} = \left[\frac{9.81\,(W_1 - W_2) * 2\pi N R}{60}\right] \text{ watts}$$

Power input $P_{in} = V I_L$ watts

where V = supply voltage

I_L = line / supply current

$$\% \text{Efficiency} = \frac{P_{out}}{P_{in}} * 100$$

$$\% \eta = \frac{9.81\,(W_1 - W_2) * 2\pi N R}{60 * VI} * 100$$

Q1) In a brake test conducted on a DC shunt motor, the full load reading are observed as - tension of tight side = 9.1 Kg, tension of slag side = 0.8 Kg, total current = 10A, supply voltage = 110V, speed = 1320 rpm, R = 7.5 cm. Calculate its full load efficiency.

Soln

Given

W_1 = 9.1 Kg

W_2 = 0.8 Kg

N = 1320 rpm

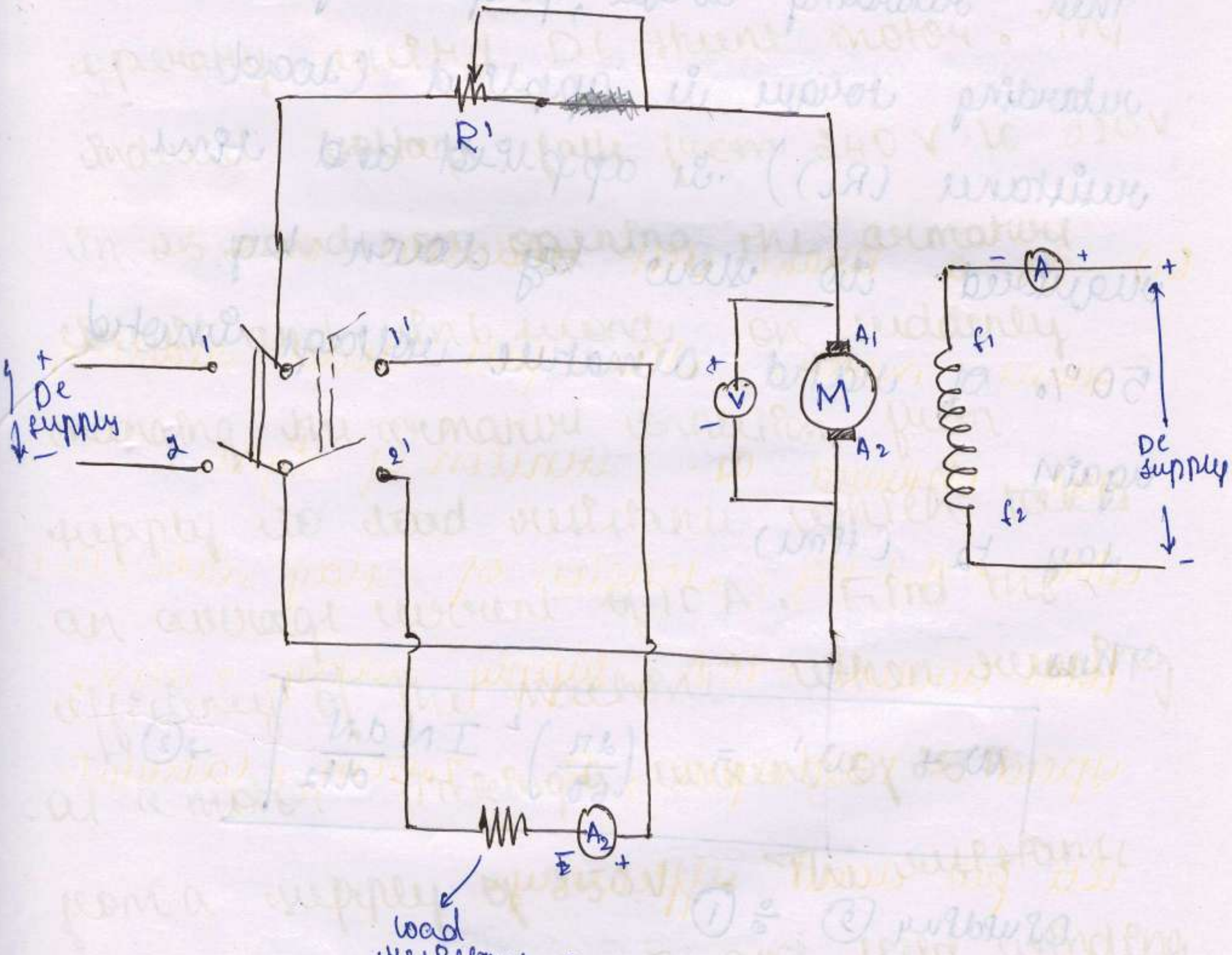
I_L = 10 A

R = 7.5 cm = 0.075 m

$$\% \eta = \frac{9.81\,(9.81 - 0.8) * 2\pi * 1320 * 0.075 * 100}{60 * 110 * 10}$$

$= \cancel{30.8826}\ \underline{76.73\%}$

⇒ **Retardation test :-** (or) **Running down test :-** (or) **Brake drum test :-**



From this method we can get stray losses.

It is generally employed for DC shunt machines.

If I is the moment of inertia of the

then

$$\boxed{W = \left(\frac{2\pi}{60}\right)^2 I N \frac{dN}{dt_1}} \rightarrow (1)$$

In this method the time is noted for the machine to slow down by 50% of the rated armature voltage alone. say t_1 (time)

Then retarding torque, preferably electrical retarding torque is applied (load resistance (R_L)) is applied and time required to slow ~~by~~ down by 50% of rated armature voltage is noted again say t_2 (time)

Thus

$$\boxed{W + W' = \left(\frac{2\pi}{60}\right)^2 I N \frac{dN}{dt_2}} \rightarrow (2)$$

Dividing (2) ÷ (1)

$$\frac{W + W'}{W} = \frac{d\cancel{N}}{dt_2} * \frac{dt_1}{d\cancel{N}} = \frac{dt_1}{dt_2}$$

$$W dt_2 + W' dt_2 = W dt_1$$

$$W' dt_2 = W dt_1 - W dt_2$$

$$w\,[dt_1 - dt_2] = w' dt_2$$

$$\boxed{w = \frac{w' dt_2}{(dt_1 - dt_2)}}$$

$$\Rightarrow \quad \boxed{w = \frac{w' t_2}{t_1 - t_2}}$$

Q1) A retardation test is conducted on a seperately excited DC shunt motor. The induced voltage falls from 240 V to 220 V in 25 seconds on opening the armature circuit and in 6 seconds on suddenly changing the armature connection from supply to load resistance which takes an average current of 10 A. Find the efficiency of the machine when running as a motor taking a current of 25 A from a supply of 250 V. The resistance of its armature is 0.3 Ω and field winding is 200 Ω.

soln Given :- $R_a = 0.6\Omega$, $R_{sh} = 200\Omega$

$I_{avg} = 10 A$

$t_1 = 25 sec = 25 sec$

$t_2 = 6 sec = 6 sec$

$V_1 = 240 V$

$V_2 = 220 V$

$V_{avg} = \frac{V_1 + V_2}{2} = \frac{240 + 220}{2} = \underline{\underline{230 V}}$

Power absorbed by the load = W' =

$W' = V_{avg} * I_{avg}$

$= 230 * 10$

$= \underline{\underline{2300 \text{ watts}}}$

$W = \frac{W' \times t_2}{t_1 - t_2}$

$= \frac{2300 \times 6}{25 - 6}$

$= \underline{\underline{726.31 \text{ watts}}}$ = stray losses (constant)

Power i/p to the motor = VI_a

$P = 250 * 25$

$= 6250$ watts

→ Copper loss $= I_a^2 R_a$

$= \cancel{(250)^2 \times 0.3}$

$I_a = I_L - I_{sh}$

$= I_L - \frac{V}{R_{sh}}$

$= 25 - \frac{250}{200}$

$I_a = 23.75$

Armature copper loss $= I_a^2 R_a$

$= (23.75)^2 \, 0.3$

$= \cancel{338.43 \text{ watts}} = 169.21$ watts

Field copper loss $= V I_{sh}$

(or) $I_{sh}^2 R_{sh}$

$= \left(\frac{250}{200}\right)^2 \times 200$

$= 312.5$ watts

total loss = Armature loss + Field cu loss + Stray loss

$= 169.21 + 312.5 + 726.31$

$= 1208.02$ watts

$\% \eta_m = \frac{i/p - \text{loss}}{i/p} \times 100 = \frac{6250 - 1208.02}{6250} \times 100$

$= 80.67 \%$

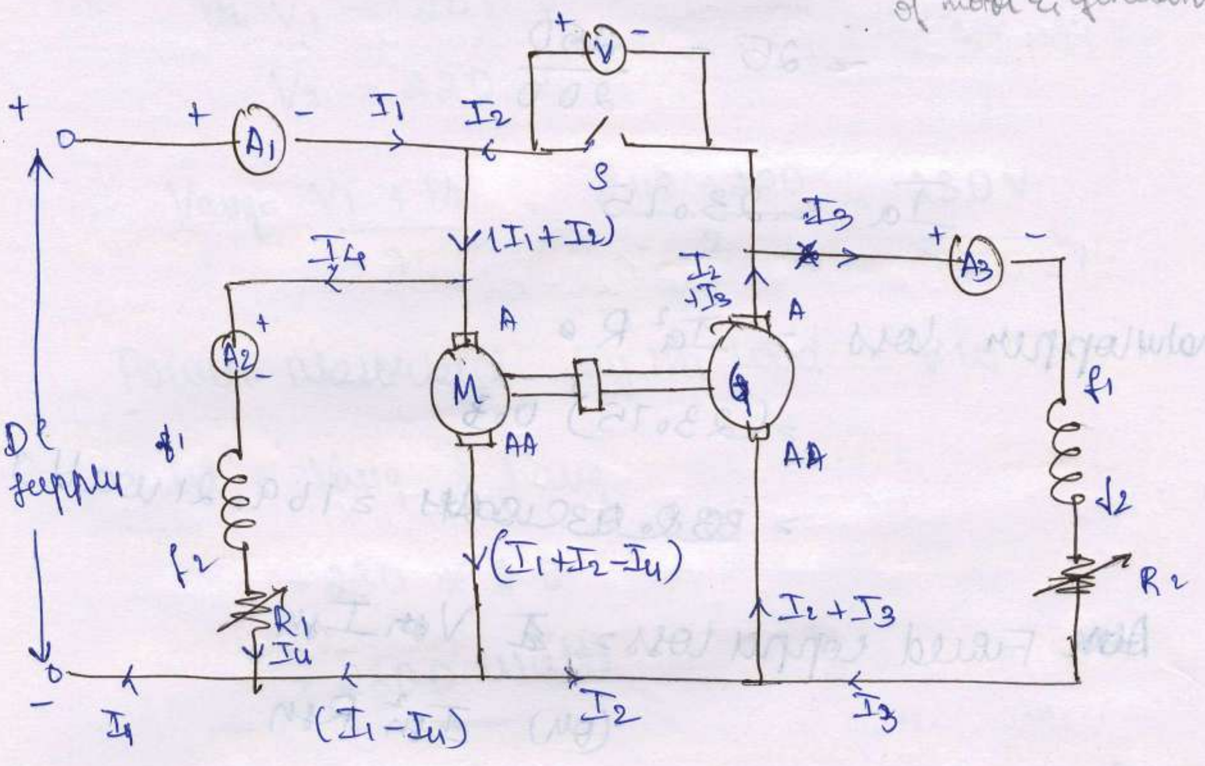
⟹ Hopkinson's test :-

(or) Regenerative test :-

(or) back to back test :-

without show (M) (G) current of Generat doesnot have path for flowing

(V) made zero to avoid circulating currents and allow synchronizat of motor & generator



M: motor i/p electric through generator

G: Generator i/p mechanic through motor

∴ Back to back test

over exciting - Generator } through
under exciting - Motor } rheostat

Let V = supply voltage

I_1 = current drawn from the supply

I_2 = current supplied by the generator

I_3 = Exciting / field current of the generator field current = Exciting current

I_4 = Exciting ~~of~~ or field current of motor

R_a = Resistance of each armature of each machine

→ Armature copper loss in the generator

$= (I_2 + I_3)^2 R_a$ watts

→ Field copper loss in the generator

$= V I_3$ watts

→ Armature copper loss the motor $= (I_1 + I_2 - I_4)^2 R_a$ w

Field copper loss in the motor $= V I_4$ watts

The total losses in the generator and motor are equal to power supplied by the mains

∴ Power drawn from the supply $= V I_1$ watts

∴ Total stray losses = Power i/p − Total cu losses

$$W_s = V I_1 - \left[(I_2 + I_3)^2 R_a + V I_3 + (I_1 + I_2 - I_4)^2 R_a + V I_4 \right]$$

∴ Stray loss per machine $= W_s/2$

(iii) Ans

(i) Motor efficiency :-

$$\% \eta_m = \frac{i/p - losses}{i/p} * 100$$

→ Power i/p to the motor = $V(I_1 + I_2)$ watts

Total loss of the motor =

$$= (I_1 + I_2 - I_4)^2 Ra + V I_4 + Ws/2$$

$$\% \eta_m = \frac{V(I_1+I_2) - [(I_1+I_2-I_4)^2 Ra + V I_4 + Ws/2]}{V(I_1+I_2)} * 100$$

(ii) Generator efficiency :-

consider electric parameters

motor - i/p - electric

generator = o/p - electric

∴ η_m = i/p

$\%\eta_g$ = o/p

$$\% \eta_g = \frac{o/p}{o/p + losses} * 100$$

Power o/p of the generator = $V I_2$ watts

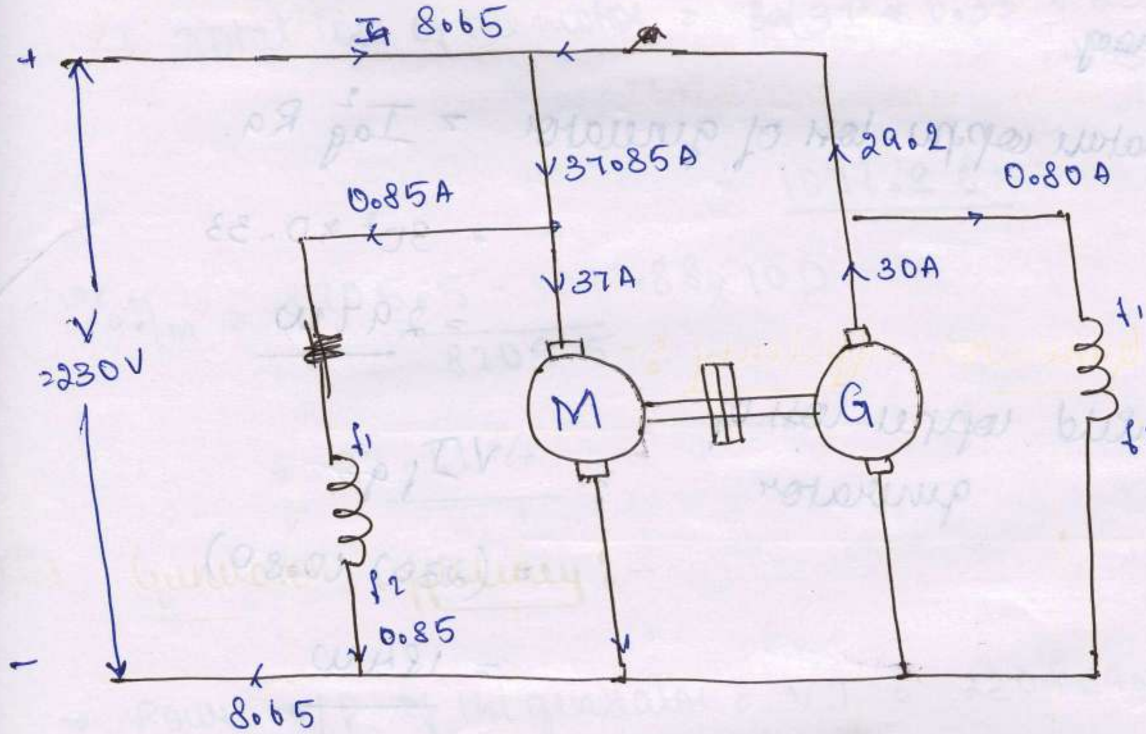
Total losses of generator

$$= (I_2 + I_3)^2 Ra + V I_3 + Ws/2 \text{ watt}$$

$$\% \eta_g = \frac{V I_2}{[(I_2+I_3)^2 Ra + V I_3 + Ws/2] + [V I_2]} * 100$$

Q1) Following results were obtained during Hopkinson's on two similar DC shunt machines of 230V, Armature currents 37A and 30A, field current 0.85A and 0.80A respectively calculate the efficiencies of the machines if each has armature resistance of 0.33 ohms

Soln



Given

Armature current = 37 A, 30A

field current = 0.85A, 0.80A

$R_a = 0.33\,\Omega$

Soln // (method - 1 - Solve using)

For motor - generator set

→ Armature copper loss of ~~generator~~ motor $= I_{am}^2 R_a$

$= 37^2 * 0.33$

$= 451.77\ W$

→ Field copper loss of motor $= V I_{fm}$

$= 220 * 0.85$

$= 195.5\ W$

Step

→ Armature copper loss of generator $= I_{ag}^2 R_a$

$= 30^2 * 0.33$

$= 297\ W$

→ Field copper loss of generator $= V I_{fg}$

$= (230)(0.80)$

$= 184\ W$

Step

→ Total power I/P $= VI$

$= 230 * 8.65$

$= 1989.5\ W$

→ Stray loss = W_s = i/p − total cu losses

$= 1989.5 - (451.77 + 195.5 + 297 + 184)$

$= \underline{861.23 \text{ W}}$

→ Stray loss per machine = 430.615 W

(i) Motor efficiency :-

→ Power i/p to the motor = 230×37.5

$= \underline{8705.5 \text{ W}}$

→ Total loss of the motor = $(37^2 \times 0.33 + 230 \times 0.85) + 430.615$

↳ $W_s/2$

$= \underline{1077.88 \text{ W}}$

$$\% \eta_m = \frac{8705.5 - 1077.88}{8705.5} \times 100$$

$= \underline{87.61\%}$

(ii) Generator efficiency :-

→ Power o/p of the generator = VI = 230×29.2

$= \underline{6716 \text{ W}}$

→ Total loss = ~~30×230~~ +

$= 30^2 \times 0.33 + 0.8 \times 230 + 430.615$

$= \underline{911.61}$

$$\% \eta_g = \frac{6716}{6716 + 911.61} \times 100 = \underline{88.04\%}$$

Q2) Two identical DC shunt machines when test by Hopkinson's method gave the following results

(i) line voltage 230 V

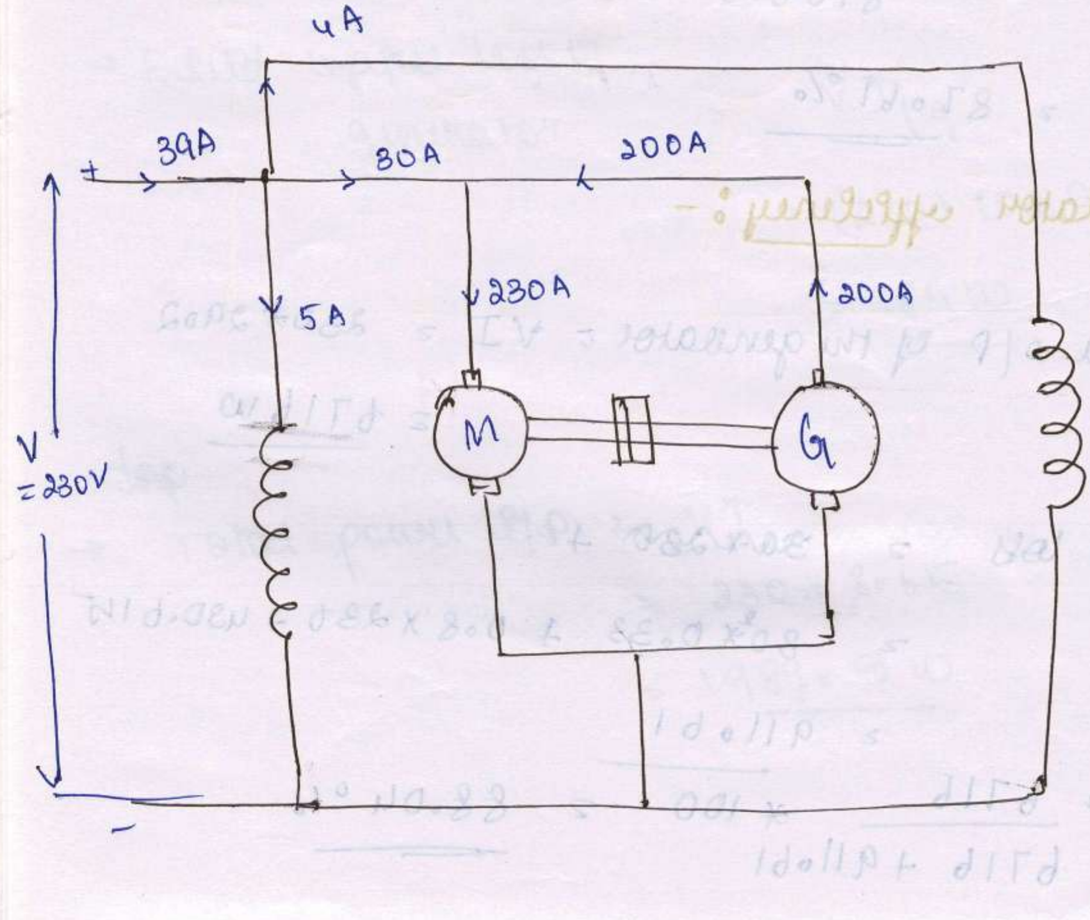
(ii) line current including field current = 30 A

(iii) Motor armature current as 230A

Soln (iv) Field current 5A & 4A respectively

(v) The armature resistance of each machine 0.025 Ω. Calculate the efficiency of both the machines

// (Method-2) → solve using)



Soln

For motor generator set

→ Armature cu loss of motor $= I_{am}^2 R_a$

$= (230)^2\, 0.025$

$= 1322.5\ W$

→ Field cu loss motor $= V I_{fm}$

$= 230 * 5$

$= 1150 W$

→ Armature cu loss of generator $= I_{ag}^2 R_a$

$= (200)^2\, 0.025$

$= 1000\ W$

→ Field cu loss of generator $= 230 * 4$

$= 920\ W$

→ Total power i/P $= VI =$

$230 * 39$

$= 8970$

$W_s = i/P - \text{loss}$

$= 8970 - (132205 + 1150 + 1000 + 920)$

$= 4577.5\ W$

$W_s/2 = 2288.77\ W$

(ii) Motor efficiency

armature + field

→ Power i/p $= 230 * (230 + 5)$

$= ~~52900w~~ \; 54050\,w$

→ Total loss $= (230^2 * 0.025) + (230 * 5) + 2288.75$

$= 4761.25\,w$

$\% \eta_m = \dfrac{54050 - 4761.25}{54050} * 100$

$= ~~92.92\%~~ \; 91.19\%$

→ (iii) Generator efficiency

→ power o/p $= 230 * 200$

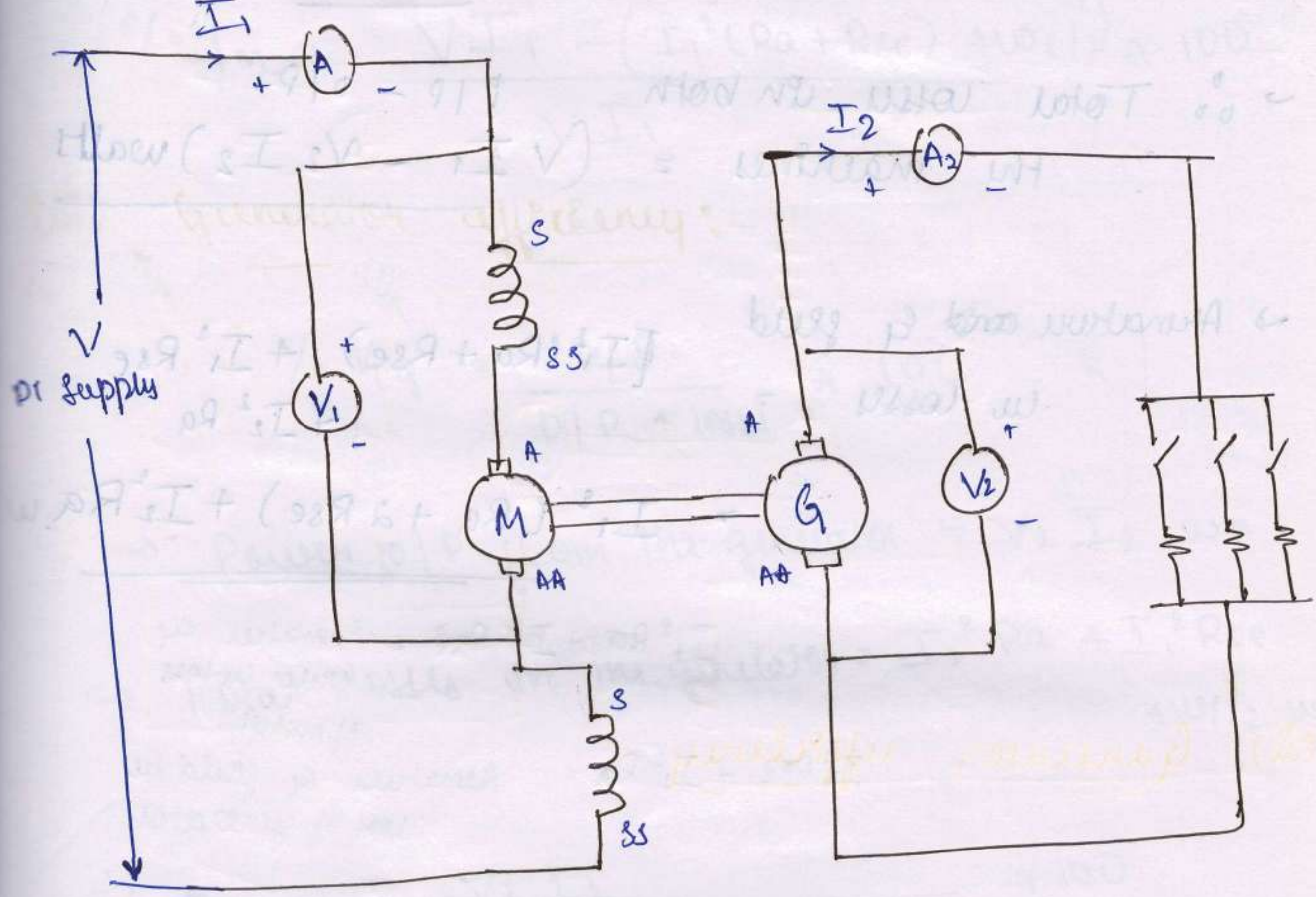
$= 46000\,w$

→ Total loss $= (200^2 * 0.025) + (230 * 4) + 2288.75$

$= 4208.75\,w$

$\% \eta_g = \dfrac{46000}{46000 + 4208.75} = 91.61\%$

⇒ Field test on DC series machines :-



Let V = supply voltage

I_1 = current drawn by the motor

I_2 = current supplied by the generator

V_1 = voltage drop across motor

V_2 = voltage drop across generator

R_a & R_{se} = Armature and series field resistance of each machine.

→ Power drawn from the supply = $V I_1$ watts

→ output of the generator = $V_2 I_2$ watts

→ ∴ Total loss in both the machines = i/p − o/p = $(V I_1 - V_2 I_2)$ watts

→ Armature & field cu losses = $[I_1^2 (Ra + Rse)$ + $I_1^2 Rse$ + $I_2^2 Ra$

(i) (iii)

= $I_1^2 (Ra + 2Rse) + I_2^2 Ra$ w

$I_1^2 Ra + I_1^2 Rse$ = Armature & field cu loss of motor

$I_1^2 Rse + I_2^2 Ra$ = Armature & field cu loss of generator

→ Stray loss = Total loss − cu loss

$$W_s = (V I_1 - V_2 I_2) - [I_1^2 (Ra + 2Rse) + I_2^2 Ra]$$

Stray loss per machine = $W_s/2$

(i) Motor efficiency :-

$$\% \eta_m = \frac{i/p - losses}{i/p} * 100$$

→ Power i/p to the motor = $V I_1$ watts

→ Total losses in the motor $= I_1^2 Ra + I_1^2 Rse + W_s/2$

$= I_1^2 (Ra + Rse) + W_s/2$ watt

$$\% \eta_m = \frac{V I_1 - \left(I_1^2 (Ra + Rse) + W_s/2\right)}{V I_1} \times 100$$

(iii) Generator efficiency:-

$$\% \eta_g = \frac{O/P}{O/P + \text{losses}} \times 100$$

→ Power O/P from the generator $= V_2 I_2$ watt

→ Total losses in the generator $= I_2^2 Ra + I_1^2 Rse + W_s/2$ watt

$$\% \eta_g = \frac{V_2 I_2}{V_2 I_2 + I_2^2 Ra + I_1^2 Rse + W_s/2} \times 100$$

Q1) A test on two coupled similar tramway motors, with their field connected in series, gave the following result when one machine acted as a motor and the other as a generator.

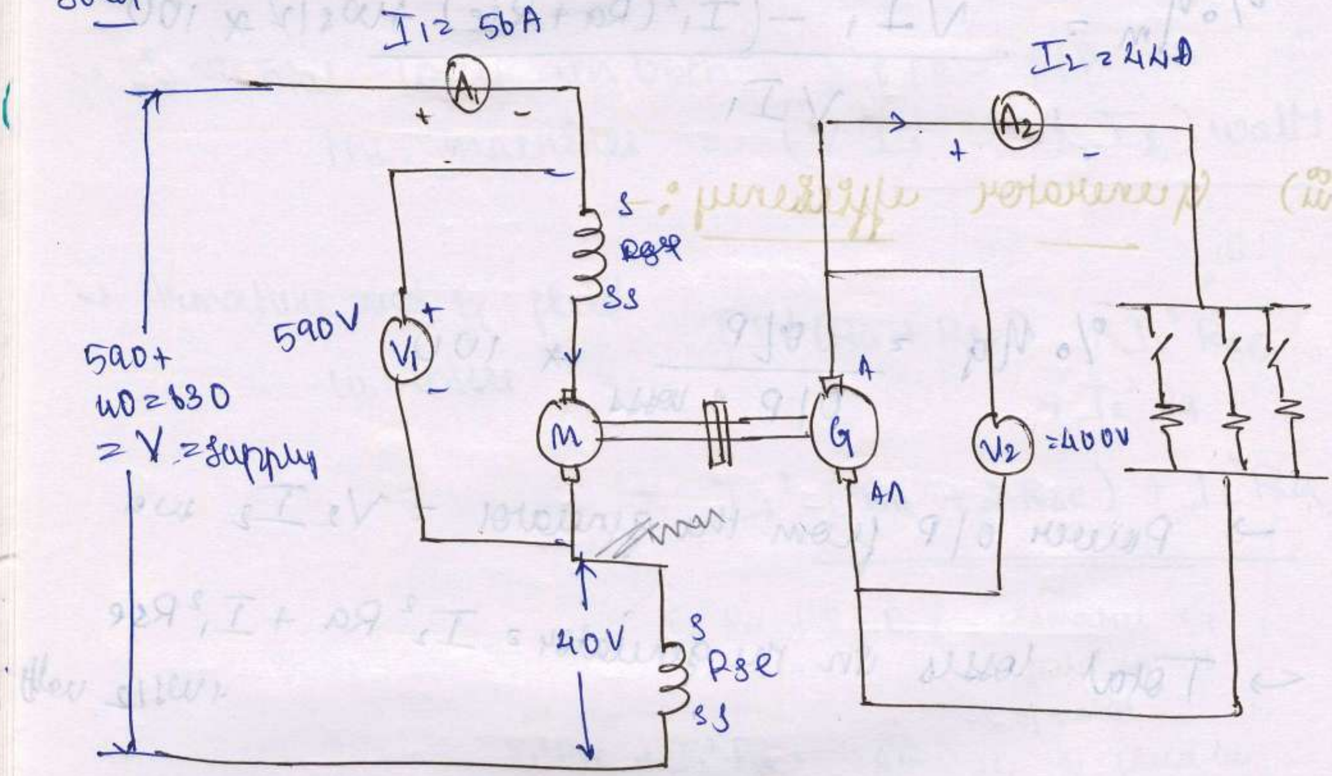
(a) Motor:- $I_a = 56$ A, Armature voltage = 590 V, Voltage drop across field winding = 40 V

(b) Generator:- $I_a = 44$ A, Armature voltage = 400 V, voltage drop across field = 40 V

→ Resistance of each armature = 0.03 Ω

Calculate the efficiency of the motor and the generator.

Soln



Armature voltage = M + M
(both include)
↳ not single armature

→ Total supply voltage $= V_g = 590 + 40 = 630$

→ Supply current $= I_1 = 56A$

→ Total power i/p $= VI_1 = 630 * 56 = 35280\ W$

→ o/p of generator, $V_2 * I_2 = 400 * 44 =$
$= 17600\ W$

→ Total loss = i/p − o/p = 35280 − 17600
$= 17680\ W$

→ cu loss = $[I_1^2 (Ra + 2Rse) + I_2^2 Ra]$

$= \cancel{(56)^2 (0.3 + 2(0.3))}]$

$Rse = \frac{V_{al}}{I_1} = \frac{\cancel{5990}}{\cancel{590}} = \frac{40}{56} = 0.714$

Rse = $\frac{\text{Voltage drop across field winding}}{\text{current}}$

cu loss = $(56)^2 (0.3 + 2(0.714)) + (44)^2 (0.3)$

$= 5999.80$

Stray loss = $17680 - 5999.8$ W

$= \underline{11680.2 \text{ W}}$

$W_s/2 = \underline{5840.1 \text{ W}}$

(i) Motor efficiency :-

$\% \eta_m = \frac{I/P - \text{loss}}{I/P} \times 100$

only for mo :: 590 not (630V)

→ Power I/P to motor = $V I_1 = 590 \times 56$

$= \underline{33040 \text{ W}}$

→ losses $= I_1^2 Ra + I_1^2 Rse + W_s/2$

$= 56^2 (0.3) + 56^2 \times (0.714) + 5840.1$

$= \underline{9020.00 \text{ W}}$

$$\% \eta = \frac{33040 - 9020}{33040} * 100$$

$= 72.07\%$

Sync m/c → synchronous speed

$N_s = \frac{120f}{P}$

→ Induction m/c (motor) → sub sync speed $\neq N_s$

RMF → rotates at N_s ↳ in 3φ m/c ... ↓ rotates at N_s

→ (iii) Generator efficiency :-

$$\eta_g = \frac{O/P}{O/P + i/P} * 100$$

RMF → flux produced by stator winding

→ Power O/P $= V_2 I_2 = 400 * 44$

$= 17600\ W$

→ Total loss $= I_2^2 R_a + I_1^2 R_{se} + W_s/2$

$= (44^2(0.3)) + (56)^2(0.714) + 5839.3$

$= 8659.10$

$$\% \eta = \frac{17600}{17600 + 8659.10} * 100$$

$= 67.02\%$

AC machine
- 1-φ AC
  - Transf
  - Generat or motor
- 3φ AC
  - Transfr
  - Generator or motor

DC supply = ±220 V

1φ AC → 230 V, 50 Hz

3φ AC → 415/430/440, 50 Hz

→ $V_{ph} = \frac{V_L}{\sqrt{3}}$; $I_L = I_{ph}$

D.C machine → physical pole
AC mach → imaginary pole
Im → Imaginary pole

⟹ Three - phase induction motor:-

Stator → 3 ϕ (compulsory / always) → Y or Δ conn
↓ same type of winding Y or Δ
Rotor →

RMF creates the effect of imaginary pole
↓
rotates at synchronous speed.

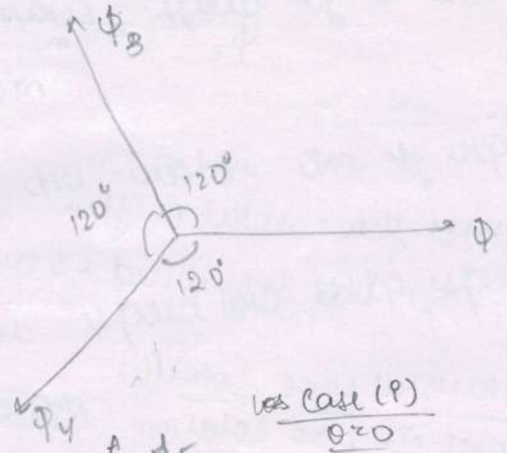
$\phi_R = \phi \sin\theta$ → sequence
$\phi_Y = \phi_m \sin(\theta - 120)$
$\phi_B = \phi_m \sin(\theta - 240)$
By instantaneous sine wave eqns

// works on electromagnetic induction

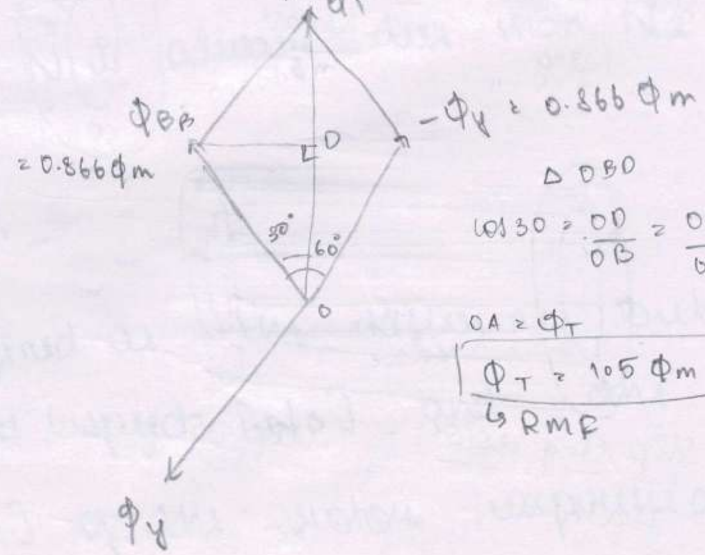
RMF
stator -
zero crossing at $\theta = 0°, 60°, 120°, 180°$

$\phi_R = \sin\theta = 0$
$\phi_Y = \phi_m \sin(-120) = -0.866\phi_m$
$\phi_B = \phi_m \sin(-240) = +0.866\phi_m$

Assumed +ve direction phasor diagram →



case (i) $\theta = 0$



Δ OBD

$\cos 30 = \frac{OD}{OB} = \frac{OA/2}{0.866\phi_m}$

$OA = \phi_T$

$\boxed{\phi_T = 1.5\,\phi_m}$
↳ RMF

||ly

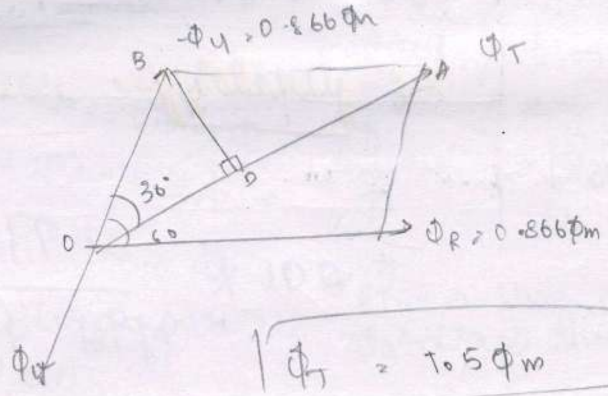
case 2 $\theta = 60°$

$$\boxed{\phi_T = \bar{\phi}_R + \bar{\phi}_Y + \bar{\phi}_B}$$

$\phi_R = \phi_m \sin 60 = 0.866\,\phi_m$

$\phi_Y = \phi_m \sin(60-120) = -0.866\,\phi_m$

$\phi_B = \phi_m \sin(60-240) = 0$



$\cos 30 = \frac{OD}{OB} = \frac{\phi_T/2}{0.866\,\phi_m}$

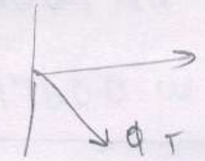
$\phi_T = 1.5\,\phi_m$

$$\boxed{\phi_T = 1.5\,\phi_m}$$

||ly

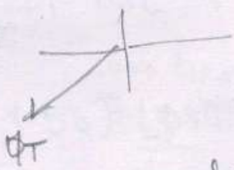
case (3) $\theta = 120°$

$\phi_T = 1.5\,\phi_m$



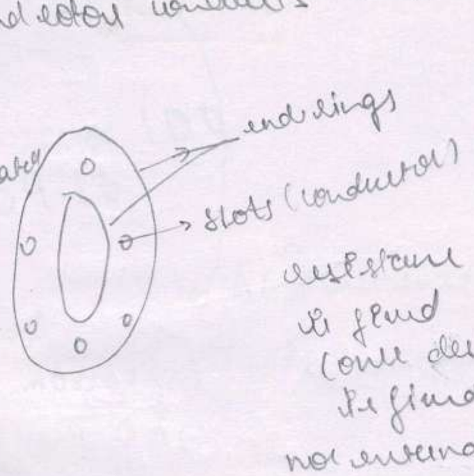
|| case (iv) $\theta = 180°$

$\phi_T = 1.5\,\phi_m$

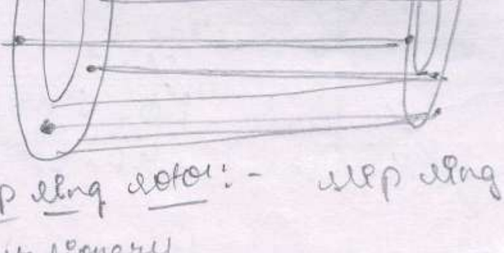


|| Stator flux + rotator flux interact to produce force starts rotating and emf is produced => and rotor conductors

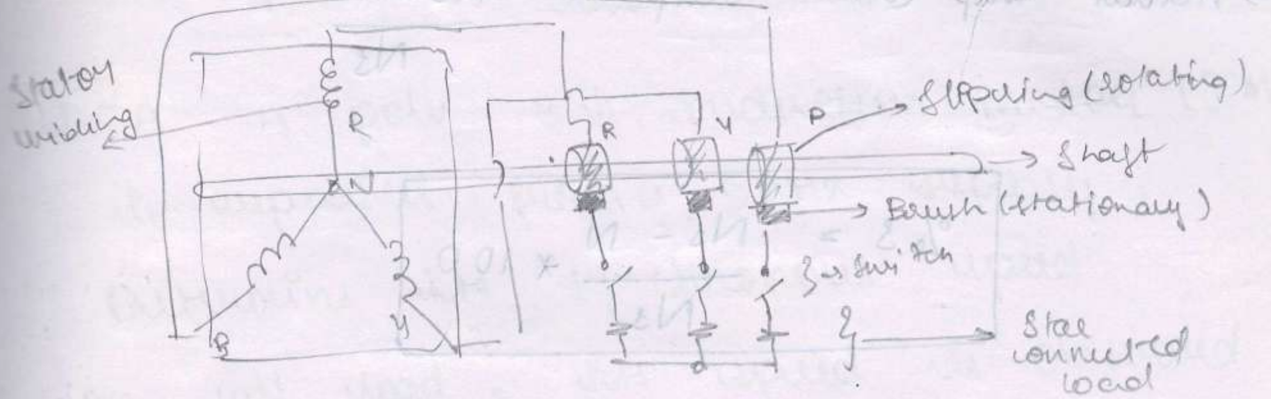
(i) squirrel cage rotor (or) short circuited rotor (or) uninsulated Cu or Al bars (ring



resistance value is fixed (once designed it is fixed) no external resistance can be added



(ii) slip ring rotor:- slip ring and brush assembly is stationary



* External resistance can be added to external rotor
* Frequent maintainance is necessary

Stator flux + Rotor flux → emf
(RMF)

emf gets induced in rotor
↳ Frequency is off

→ Slip of an induction motor:- (S) :-
(or) (Absolute slip)

→ Let N_s = synchronous speed of the RMF in rpm

N = speed of the motor in rpm

$N_s - N$ = Relative speed (or) slip speed in rpm

$N < N_s$ = N is always less than N_s

Definition :-

It is defined as the difference between the synchronous speed $[N_s]$ and the actual speed $[N]$ of the rotor expressed as a fraction of synchronous speed N_s

→ Actual slip (or) $Slip = \frac{N_s - N}{N_s}$

$$\boxed{\% S = \frac{N_s - N}{N_s} * 100}$$

⟹ Actual speed (N) in terms of Ns :-

$$(S * N_s) = (N_s - N)$$

$$SN_s - N_s = -N$$

$$N_s (S-1) = -N$$

$$\boxed{N = N_s (1-S)}$$

* At start

$$N = 0$$

$$0 = N_s (1-S)$$

$$1 - S = 1$$

$$S = 1$$

[maximum value that the induction motor can attain } i.e., S = 1]

[S is maximum at start]

- The value of slip is maximum i.e, S = 1 only at start, and goes on reducing as the rotor starts rotating

- Slip can never be zero

Q1) A 4 pole 3 ϕ induction motor (IM) is supplied from a 50Hz supply, Determine its synchronous speed on full load, its speed is observed to be 1410 rpm calculate its full load slip.

Soln $P = 4$

$f = 50Hz$

$N = 1410$ rpm

To find = $S = ?$

$$N_s = \frac{120f}{P}$$

$$= \frac{120 * 50}{4}$$

$$= 1500$$

$$S = \frac{N_s - N}{N_s}$$

$$= \frac{1500 - 1410}{1500} * 100$$

$$S = 0.06$$

(or) $S(\%) = 6\%$

[It can't go more than 1 and cannot be zero]

and [values from (10 - 15%)]

→ Effect of slip on the rotor parameters:-

- slip affects ~~some~~ the frequency of the rotor induced emf and hence some rotor parameters also gets affected.

→ the following rotor parameters gets affected due to slip:-

(i) Rotor frequency
(ii) Magnitude of rotor induced emf
(iii) Rotor reactance
(iv) Rotor powerfactor
(v) Rotor current

(i) Effect on rotor frequency:- (f_r):-

f_r = rotor frequency

WKT

speed of rpm = $\frac{120f}{P} = N_s$ → (1) (at start)

f = frequency of supply

At start $N = 0$, $S = 1$

- Thus stationary rotor has maximum relative motion w.r.t RMF

- Hence maximum emf gets induced at start and frequency of this induced emf is same as supply

- As the motor (rotor) starts running with a speed of 'N' rpm, the relative motion between the rotor w.r.t 'RMF' decreases and becomes equal to the slip speed $[N_s - N]$

- Hence in running condition, the magnitude of induced emf decreases and so does the frequency (decrease)

- If f_r = frequency of rotor induced emf in running condition at slip speed $N_s - N$ then

$$N_s - N = \frac{120 f_r}{P} \rightarrow (2)$$

→ in running condition

Dividing eqn (2) by eqn (1)

$$\frac{N_s - N}{N_s} = \frac{120 f_r / \cancel{P}}{\cancel{120} f / \cancel{P}}$$

$$S = \frac{f_r}{f}$$

$\therefore$ $\boxed{f_r = Sf}$

At start $S = 1$, $N = 0$ [slip is max at start]

$\therefore$ $\boxed{f_r = f_{rotor}}$

→ ↳ (iii) Effect on magnitude of rotor induced emf :- (E_{2r})

- W.K.T at start $N = 0$, $S = 1$ and relative speed is maximum (or) motion

$\therefore$ Induced emf is also maximum

let this emf be E_2

i.e., E_2 = rotor induced emf per phase at stand still

- As the rotates starts running relative speed decreases, the induced emf in the rotor also decreases proportional to the ~~sp~~ slip speed $[N_s - N]$

$E_2 \propto N_s \rightarrow ①$

$E_{2r} \propto [N_s - N] \rightarrow ②$

E_{2r} = induced emf in rotor at running condition

∴ dividing ② / ①

$$\frac{E_{2r}}{E_2} = \frac{N_s - N}{N_s}$$

$$\frac{E_{2r}}{E_2} = s$$

$$\boxed{E_{2r} = sE_2}$$

At start $s = 1$, $N = 0$

$$\boxed{E_{2r} = E_2}$$

→ (iii) Effect on rotor reactance :- (X_{2r})

(It will not no effect ~~on~~ on resistance, // only on reactance)

$(\underbrace{R}_{\text{constant}} + j\underbrace{X_L}_{\text{varies}})$

∴ Resistance is independent frequency

$X_L = 2\pi f L$ — f change, L const

∴ X_L changes as frequency change

Let R_2 = rotor resistance per phase on standstill

X_2 = rotor reactance per phase on standstill

→ At standstill, $N = 0$, $s = 1$

WKT → $f_r = s f$

at standstill
$f_r = f$ $[s = 1]$

If L_2 is the rotor inductance per phase

then
$$\boxed{\begin{aligned} \overset{(X_2)}{X_2} &= 2\pi f_r L_2 \quad \Omega/\text{phase} \\ &= 2\pi f L_2 \quad \Omega/\text{phase} \end{aligned}} \quad \Bigg\} \quad (1)$$

In running condition

$$X_{2r} = 2\pi f_r L_2$$

w.k.t
$f_r = s f$, in running condition

$$\therefore \boxed{X_{2r} = 2\pi s f L_2} \quad \Omega/\text{phase} \longrightarrow (2)$$

when X_{2r} is rotor reactance per phase in running condition

$\therefore$ ~~by~~

$\therefore$ ~~$X_{2r} = s X_2$~~

$$X_{2r} = (\underbrace{2\pi f L_2}_{X_2}) s$$

from ean (1)

$$\boxed{X_{2r} = s X_2}$$

The rotor resistance per phase remains unchanged because it is independent of frequency

→ Thus the rotor impedance per phase is Z_2 at standstill is

$$\boxed{Z_2 = R_2 + jX_2} \ \Omega \,/\, \text{phase}$$

→ Thus the rotor impedance per phase under running condition is

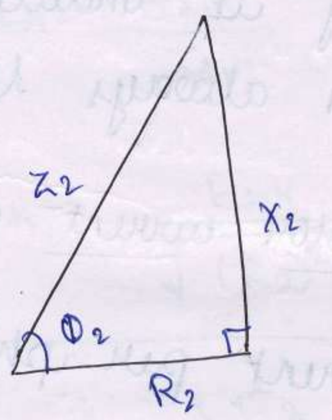
$$\boxed{Z_{2r} = R_2 + jX_{2r}} \ \Omega \,/\, \text{pha}$$

$$\therefore \boxed{Z_{2r} = R_2 + jsX_2}$$

→ iv) <u>Effect on rotor power factor</u>:-

<u>At standstill</u>

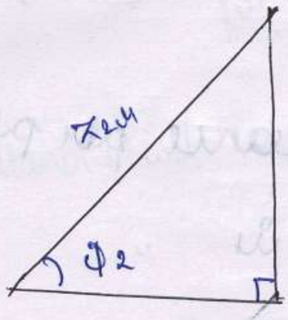
[impedance triangle]



$$\cos\phi_2 = \frac{R_2}{Z_2}$$

$$\cos\phi_2 = \frac{R_2}{R_2 + jX_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$

At running condition



$$\cos \phi_{2r} = \frac{R_2}{Z_{2r}}$$

$$= \frac{R_2}{R_2 + j X_{2r}}$$

$$= \frac{R_2}{R_2 + j(s X_2)}$$

$$= \frac{R_2}{\sqrt{R_2^2 + (s X_2)^2}}$$

As the rotor winding is inductive, the rotor powerfactor is always lagging

→ ↳ (ii) Effect on rotor current :-

Let I_2 = rotor current per phase on standstill

I_2 depends on the magnitude of E_2 and Z_2

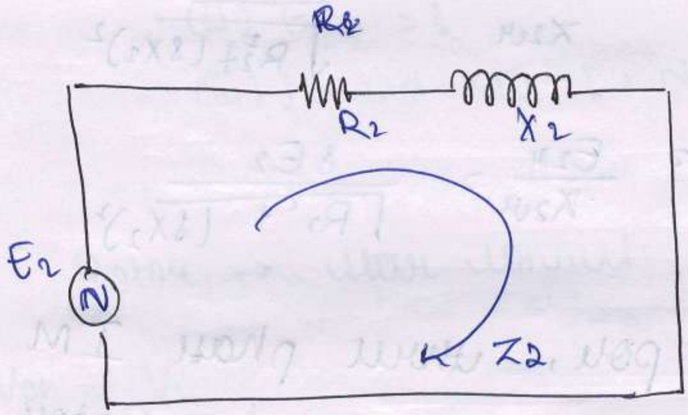
Z_2 is a impedance at standstill

where E_2 = rotor induced emf per phase on standstill

$\therefore \quad I_2 = \frac{E_2}{Z_2}$ per phase

$$\boxed{I_2 = \frac{E_2}{\sqrt{R_2^2 + (X_2)^2}}}$$ per phase

→ The equivalent rotor circuit on standstill is as shown

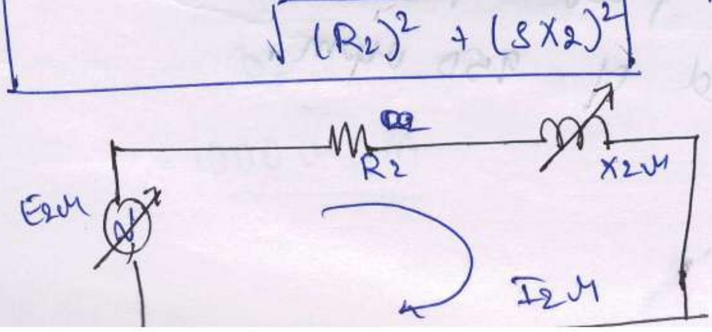


Let I_{2r} = rotor current per phase under running condition.

$I_{2r} = \frac{E_{2r}}{Z_{2r}}$ per phase

$I_{2r} = \frac{E_{2r}}{\sqrt{(R_2)^2 + (X_{2r})^2}}$ per phase

$$\boxed{I_2 = \frac{s\,E_2}{\sqrt{(R_2)^2 + (sX_2)^2}}}$$ per phase



→ Effect of slip on rotor parameters :-

(i) $f_r = s f$

(ii) $E_{2r} = s E_2$

(iii) $X_{2r} = s X_2$

and

$Z_{2r} = \sqrt{R_2^2 + (s X_2)^2}$

(iv) $\cos\phi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (s X_2)^2}}$

(v) $I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{s E_2}{\sqrt{R_2^2 + (s X_2)^2}}$

Q1) In a ~~...~~ 6 pole, three phase IM 50 Hz with star connected motor, the rotor resistance per phase is 0.3 ohm the reactance at standstill is 1.5 Ω per phase an emf b/w the sliprings on open circuit is 175 V. Calculate

(i) Slip at a speed of 960 rpm

(ii) Rotor emf per phase

(iii) Rotor frequency and reactance at a speed of 950 rpm.

Soln Given :-

$P = 6$

$f = 50\,Hz$

$R_2 = 0.3\,\Omega$ /phase

$X_2 = 1.5\,\Omega$ /phase

$E_{2(line)} = 175\,V$

To find :-

(i) $s = ?$ → $N = 960$ rpm

(ii) $E_{2r} = ?$

(iii) f_r and $X_{2r} = ?$ → $N = 950$ rpm

Soln

Rotor → star connect

$$V_{ph} = \frac{V_L}{\sqrt{3}}$$

$$E_{ph} = \frac{E_L}{\sqrt{3}}$$

$$= \frac{175}{\sqrt{3}}$$

$$= 101.036\ V$$

$$\Rightarrow N_s = \frac{120f}{P}$$

$$= \frac{120 * 50}{6}$$

$$= \underline{1000\ rpm}$$

$N = 960\ rpm$

Always E should in phase

→ $s = \dfrac{N_s - N}{N_s}$

$= \dfrac{1000-960}{1000}$

$s = 0.04$

→ $E_{2ph} = 101.036\ V$

$E_{2r} = s * E_2$

$= 0.04 * 101.036$

$E_{2r} = 4.041\ V/phase$

→ * .

→ $f_r = s f$

$f_r = 0.05 * 50$

$f_r = 2.5$

→ $X_{2r} = s X_2$

$= 0.05 * 0.15$

$= 0.075 \Omega / phase$

→ New value of speed $N = 950\ rpm$

$s = \dfrac{1000-950}{1000} = 0.05$

→ Induction motor as a rotating transformer:-

	Transformer	Induction machine
1)	~~Roto~~ Alternating flux is produced	Rotating flux (RMF)
2)	There is no air gap between the windings	There is air gap between winding (stator and rotor)
3)	Frequency of induced emf and current in primary and secondary is same	The frequency of ~~viemain~~ rotor emf and current depends on slip and slip depends load on motor except starting condition
4)	The entire energy present in the secondary circuit is in electrical form	Some minor part of the energy in the rotor circuit is electrical form and major part of the energy is in mechanical form

⟹ Transformation ratio in 3Φ I M :-

⟶ At start $N = 0$, $S = 1$

where $\frac{E_2}{E_1} = K$

where E_2 = rotor induced emf at stand still (or) start

E_1 = stator induced emf per phase

$$\boxed{\frac{E_2}{E_1} = \frac{\text{Rotor emf / phase}}{\text{Stator emf / phase}} = K} = \frac{\text{Rotor turns / phase}}{\text{Stator turns / phase}}$$

Q1) A 1000 V, 50 Hz, 3Φ induction motor has star connected stator. The ~~st~~ ratio of stator to rotor turns is 3.6. The standstill impedance of rotor per phase is $0.01 + j0.02\,\Omega$. Calculate

(i) Rotor current at start

(ii) Rotor power factor at start

(iii) Rotor current at a slip of 3%

Soln

Given :- $V_L = 1000V$

$\hookrightarrow V_{ph} = 577.35V$

$f = 50Hz$

$$\frac{\text{Stator turns}}{\text{Rotor turns}} = 3.6$$

$$K = \frac{\text{Rotor turns}}{\text{Stator turns}} = \frac{1}{3.6} = 0.277$$

$Z_2 = R_2 + jX_2 = 0.1 + j0.2$ = Standstill value

To find :-

(i) I_2

(ii) $\cos\phi_2$

(iii) I_{2r} at $s = 3\%$

Soln

$$I_2 = \frac{E_2}{Z_2}$$

$E_{1(L)} = 1000V$

$E_{1(ph)} = 577.35V$

$E_{2(ph)} = K * E_1$

$= 0.277 * 577.35$

$= \cancel{155.88V}$ $160.375V$

$\rightarrow$ $I_2 = \dfrac{E_2}{Z_2}$

$= \dfrac{\cancel{155.88}\ \cancel{39.99}\ 160.375}{0.01 + j0.2}$

$= \cancel{778.92 \angle -1.52}$

$= 39.99 - j799.87$

$I_2 = 800.87 \angle -1.52$ A

$\rightarrow$ $\cos\phi_2 = \dfrac{R_2}{Z_2}$

$= \dfrac{0.01}{0.01 + j0.2}$

$= 0.0499 \angle -1.52$

$\rightarrow$ $s = 0.03$

$I_{2r} = \dfrac{E_{2r}}{Z_{2r}}$

$= \dfrac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

$= \dfrac{0.03 * \cancel{39.99}\ 160.375}{\sqrt{(0.01)^2 + (0.03 * 0.2)^2}}$

$= 412.056$ A

→ Torque equation of 3φ Induction motor:-

The torque produced in an IM depends on

(i) The RMF which is responsible for inducing emf in the rotor (φ)

(ii) The magnitude of rotor current in running condition (I_{2r})

(iii) The power factor of the rotor in running condition ($\cos\phi_{2r}$)

Mathematically it is expressed as torque

$$T \propto \phi \, I_{2r} \cos\phi_{2r}$$

The flux (or) RMF φ produced by stator winding is proportional to E_1 (stator voltage (or) induced emf)

WKT

E_1 and E_2 are related by the turns ratio i.e., K

$$K = \frac{\text{Rotor turns / phase}}{\text{Stator turns / phase}} = \frac{E_2}{E_1}$$

$$\therefore K = \frac{E_2}{E_1}$$

$\therefore E_2 = K E_1$

Assuming constant of proportionality

$K = 1$

$$E_2 = E_1$$

If

$\phi \propto E_1$

$$E_2 = E_1$$

$\therefore \phi \propto E_2$

$\therefore$ sub in torque expression

$$T \propto E_2 I_{2r} \cos\phi_{2r}$$

$$T = K E_2 I_{2r} \cos\phi_{2r}$$

where K = constant of proportionality

for 3-ϕ IM $\Rightarrow K = \dfrac{3}{2\pi n_s} = \dfrac{3}{2\pi n_s}$

where $n_s = \dfrac{N_s}{60}$ rps.

$$T = \frac{3}{2\pi n_s} E_2 * \frac{E_{2r}}{Z_{2r}} * \frac{R_2}{Z_{2r}}$$

$$T = \frac{3E_2}{2\pi n_s} \times \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$\boxed{T = \frac{3sE_2^2 R_2}{2\pi n_s (R_2^2 + (sX_2)^2)}} \text{ N-m}$$

⟹ **Starting torque**

at start $s = 1$

$$\boxed{T = \frac{3E_2^2 R_2}{2\pi n_s (R_2^2 + (X_2)^2)}} \text{ N-m}$$

Q1) A 3Φ, 400V 50Hz, 4 pole IM has star connected stator winding. The rotor resistance and reactance are 0.1Ω and 1Ω respectively at standstill. The full load speed is 1440 rpm calculate the torque developed on full load by the motor. Assume stator to rotor ratio as 2 : 1

Soln :- Given :-

$E_{1(L)} = 400\,V$

$E_{1\,ph} = 230.94$ (star connected system)

$f = 50\,Hz$

$P = 4$

$R_2 = 0.1\,\Omega$

$X_2 = 1\,\Omega$

$N = 1440$ rpm

$\dfrac{\text{stator } \cancel{\text{to}}\text{ turn/phase}}{\text{rotor turn/ph}} = \dfrac{2}{1}$

$K = \dfrac{1}{2} = 0.5$

To find :- ?

$$T = \frac{3\,S\,E_2^2\,R_2}{2\pi n_s (R_2^2 + (S X_2)^2)}$$

$$N_s = \frac{120 f}{P}$$

$$= \cancel{120} = \frac{120 \times 50}{4}$$

$N_s = 1500$

$$n_s = \frac{N_s}{60} = \frac{1500}{60} \text{ rps}$$

$$n_s = 25 \text{ rps}$$

$T_e \propto$

$$\rightarrow s = \frac{N_s - N}{N_s}$$

$$= \frac{1500 - 1440}{1500}$$

$$= 0.04$$

$T_e \propto$

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

$$E_2 = 230.94 * 0.5$$

$$= 115.47 \text{ V}$$

$$= \frac{3 * 0.04 * (115.47)^2 * 0.1}{2 * \pi * 25\left((0.1)^2 + (0.04 * 1)^2\right)}$$

$$= \underline{87.77 \text{ N-m}}$$

verify

→ Condition for maximum torque (T_m) :-

W.K.T

the torque depends on slip at which the motor is running

$$T = \frac{K\, S\, E_2^2\, R_2}{(R_2^2 + (S X_2)^2)} \quad N\text{-}m \qquad K = \frac{3}{2\pi N_s}$$

where K_1, E_2, R_2 and X_2 are constants

To find the condition for maximum torque using maxima, minima theorem -

$$\frac{dT}{ds} = 0$$

where $T = \frac{K\, S\, E_2^2\, R_2}{(R_2^2 + (S X_2)^2)}$ Nm

$$\cancel{\frac{dT}{ds} = \frac{(R_2^2 + (S(X_2))^2)(K E_2^2 R_2) - K S E_2^2 R_2 (2 S X_2^2)}{(R}}$$

Differentiate w.r.t 'S'

$$\frac{dT}{ds} = \frac{(R_2^2 + (S X_2)^2)(K E_2^2 R_2) - K S E_2^2 R_2 (2 S X_2^2)}{(R_2^2 + (S X_2)^2)} = 0$$

$$(R_2^2 + (S X_2)^2)(\cancel{K E_2^2 R_2}) = \cancel{K} \check{S} \cancel{E_2^2} R_2 (2 S X_2^2$$

$$R_2^2 + (S X_2)^2 = 2 S^2 X_2^2$$

$$R_2^2 = 2 S^2 X_2^2 - S^2 X_2^2$$

$$R_2^2 = S^2 X_2^2$$

$$S^2 = \frac{R_2^2}{X_2^2}$$

$$\boxed{S = \frac{R_2}{X_2}}$$

$$\Rightarrow \boxed{S_m = \frac{R_2}{X_2}} = \text{slip at maximum torque}$$

⇒ Magnitude of maximum torque :-

WKT

$$T = \frac{K S E_2^2 N_s}{R_2^2 + (S X_2)^2} \text{ N-m}$$

Replacing S by Sm in the above equation we get magnitude of maximum torque

~~Tm = K Sm E2² R2~~

$$\boxed{T_m = \frac{K S_m E_2^2 R_2}{R_2^2 + (S_m X_2)^2}} = \boxed{\frac{K E_2^2}{2 X_2}} = T_m$$

N-m

where $S_m = R_2 / X_2$

Q1) Calculate the torque exerted by an 8 pole, 50 Hz, 3ϕ - IM operating with a 4% slip which develops a maximum torque of 150 kg-m at a speed of 660 rpm. The resistance per phase of the motor is 0.5 Ω

Soln:- Given

$P = 8$

$f = 50 Hz$

$s = 0.04$

$T = 150 kg\text{-}m = 1470\ N\text{-}m$ $(150 * 9.8 = 1470\ N\text{-}m)$

$N_m = 660 rpm$ (at maximum torque speed is also maximum N_m)

$R_2 = 0.5 \Omega$

To find:-

$$T = \frac{3}{2\pi n_s} * \frac{s E_2^2 R_2}{(R_2^2 + (sX_2)^2)}$$

$$N_s = \frac{120f}{P}$$

$$= \frac{120 * 50}{8}$$

$$= 750 rpm$$

$$n_s = \frac{N_s}{60} = \frac{750}{60} = 12.8 rps$$

$\rightarrow \quad S_m = \dfrac{R_2}{X_2}$

$\rightarrow \quad S_m = \dfrac{N_s - N_m}{N_s}$

$= \dfrac{750 - 660}{750}$

$= \underline{0.12}$

$\rightarrow \quad X_2 = \dfrac{0.5}{0.12}$

$= \underline{4.16\,\Omega}$

$T_m = \dfrac{K E_2^2}{2X_2}$

$E_2 = \sqrt{\dfrac{T_m \times X_2}{K}}$

$= \sqrt{1470 \times}$

$K E_2^2 = T_m \, 2X_2$

$= 1470 \times 2 \times 4.16$

$K E_2^2 = \underline{12242.88 \ V}$

$$T = \frac{K S E^2 R_2}{R_2^2 + (S X_2)^2}$$

$$= \frac{K E^2 S R_2}{R_2^2 + (S X_2)^2}$$

$$= \frac{12242.88 * 0.04 * 0.5}{(0.5)^2 + (0.04 * 4.16)}$$

$$\underline{T = 881.76 \text{ -Nm}}$$

Q2) A 3 ϕ IM having 6 poles star connected stator winding runs on 240 V, 50 Hz supply. The rotor resistance & reactance on standstill are 0.12 Ω and 0.85 Ω per phase respectively. The ratio of stator to rotor turns is 1.8 and full load slip is 4%. Calculate the torque developed at full load, maximum torque and the speed at maximum torque.

Soln E_1

Given :-

$E_{1(L)} = 240 = E_{1(ph)} = 138.56\,V$

$f = 50\,Hz$

$R_2 = 0.12\,\Omega$

$X_2 = 0.85\,\Omega$

$$\frac{\text{stator turns / phase}}{\text{rotor turns / phase}} = 1.8$$

$$K = \frac{1}{1.8} = 0.56$$

$s_m = 0.04$

To find :- (i) T
(ii) T_m
(iii) N_m

Soln :-

$$T = \frac{K\, s\, E_2^2 R_2}{(R_2^2 + (sX_2)^2)}$$

$E_2 = KE_1 = 0.56 * 138.56$

$= \cancel{4358.4} \quad 77.59$

$$K = \frac{3}{2\pi N_s} = \frac{3}{2\pi * 16.66} = 0.028$$

$$N_s = \frac{120 f}{P}$$

$$= \frac{120 * 50}{6} = 1000$$

$$n_s = \frac{1000}{60} = 16.66$$

$$T = \frac{0.028 * (77.59)^2 * 0.04 * 0.12}{\left((0.12)^2 + (0.04 * 0.85)^2\right)}$$

$$= \underline{52.01 \text{ N-m}}$$

(iii) → $T_m = \dfrac{K \, s_m \, E_2^2 \, R_2}{R_2^2 + (s_m X_2)^2}$

$$s_m = \frac{R_2}{X_2} = \frac{0.12}{0.85} = 0.141$$

$$= \frac{0.028 \times 0.141 \times (77.59)^2 \times 0.12}{(0.12)^2 + (0.141 \times 0.85)^2}$$

$$= \underline{99.15 \text{ N-m}}$$

(iiii) N_m

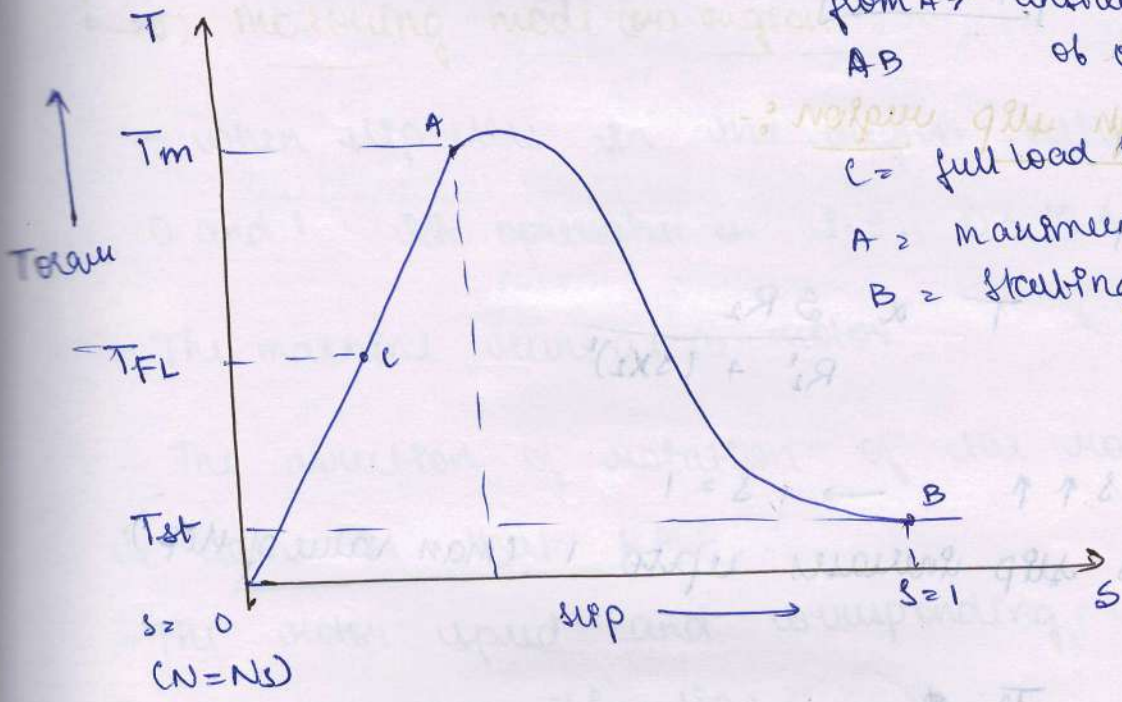
$$N = N_s (1 - s)$$

$$N_m = N_s (1 - s_m)$$

$$= 1000 (1 - 0.141)$$

$$N_m = \underline{859 \text{ rpm}}$$

→ Torque slip characteristics :-



OA = stable region

from A-> AB unstable region of operation

C= full load torque

A = maximum torque

B = starting torque.

↳ It consists of

- low slip region
- High slip region

↳(i) Low slip region :-

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (sX_2)^2}$$

if supply voltage Vg remains constant then E_2 is also constant

$$T \propto \frac{s R_2}{R_2^2 + (sX_2)^2}$$

slip ↓↓↓ ⟶ $(sX_2)^2$ ↓↓

if slip is low ⟶ then $(sX_2)^2$ will be

∴ Neglecting $(sX_2)^2$ term from denominator

$$T \propto \frac{sR_2}{R_2^2} \propto \frac{s}{R_2}$$

R remains constant

$$\boxed{T \propto s}$$

↳ (ii) <u>High</u> <u>slip</u> <u>region</u> :-

WKT

$$T \propto \frac{sR_2}{R_2^2 + (sX_2)^2}$$

as $s \uparrow\uparrow \longrightarrow s = 1$

as slip increases upto 1 (max value of slip)

R_2 remains constant

$$T \propto \frac{s}{s^2 X_2^2}$$

$$\boxed{T \propto \frac{1}{s}}$$

X_2 = constant at standstill

$$\boxed{T_{FL} < T_m}$$

Full load torque will be always less than maximum torque.

motoring,

⇒ Generating and braking regions of modes of operation:-

↳ (i) Motoring mode (or) normal region:-

- when slip lies in the region between 0 and 1 its operation in i.e., $0 \leq S \leq 1$

- The machine runs as a motor

- The direction of rotation of the rotor is same as that RMF.

- The rotor speed and corresponding torque is in the same direction

↳ (ii) Braking mode:-

- when the slip is greater 1 the machines works in braking mode.

- The rotor is rotated in opposite direction to that of RMF

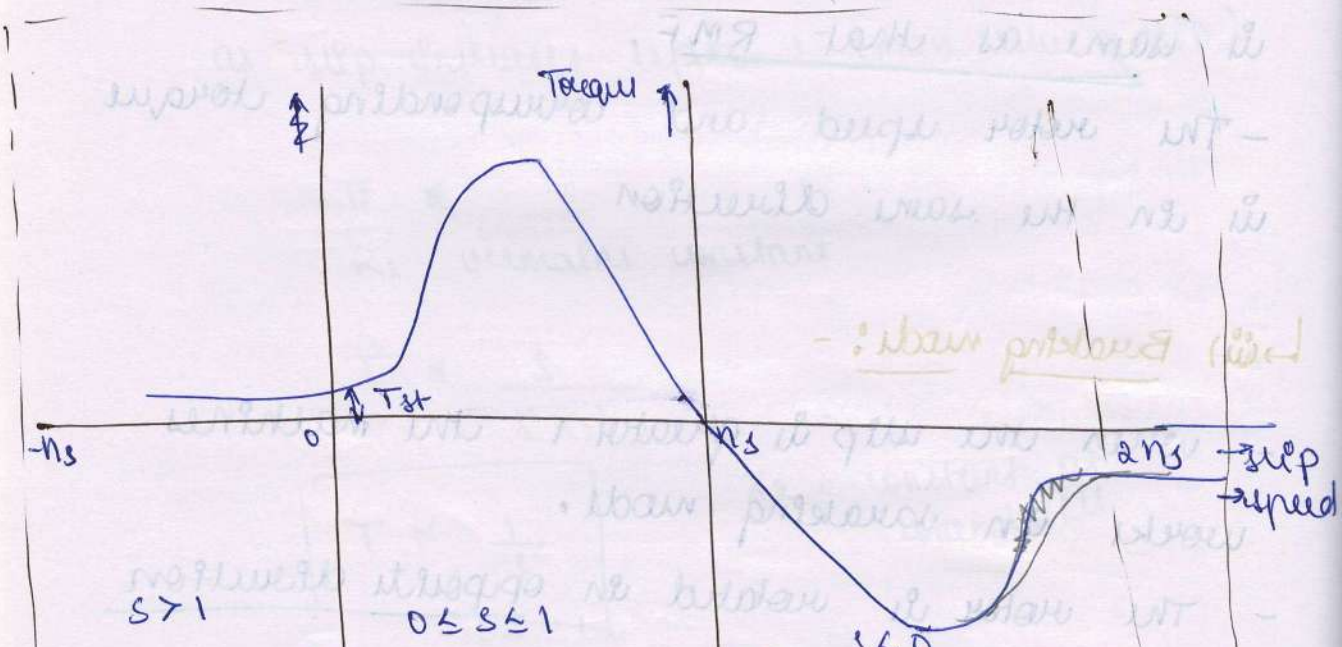
- The motor comes to a quick stop under the influence of counter torque. which

* produces braking action

- The method is also known as plugging

↳ (iii) Generating mode

- The value of the slip must be less than zero, (negative slip) which indicates that the rotor is rotating at a speed above synchronous speed
- The nature of torque slip characteristics reverses in generating mode



(Both curves should be identical)

⟹ Torque ratios:-

→ Torque ratios:-

↳(i) Full load and max torque ratios:-

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2}$$

→ For full load $s = S_F$

$$T_{FL} \propto \frac{S_F E_2^2 R_2}{(R_2)^2 + (S_F X_2)^2}$$

→ For maximum load $S = S_m$

$$T_m \propto \frac{S_m E_2^2 R_2}{(R_2)^2 + (S_m X_2)^2}$$

$$\therefore \frac{T_{FL}}{T_m} = \frac{S_F \cancel{E_2^2 R_2}}{R_2^2 + (S_F X_2)^2} * \frac{R_2^2 + (S_m X_2)^2}{S_m \cancel{E_2^2 R_2}}$$

$$\frac{T_{FL}}{T_m} \propto \frac{S_F}{S_m} * \frac{(R_2^2 + (S_m X_2)^2)}{(R_2^2 + (S_F X_2)^2)}$$

Dividing both Nu & Dr by X_2^2

$$\frac{T_{FL}}{T_m} \propto \frac{S_F (R_2^2 / X_2^2 + S_m^2)}{S_m (R_2^2 / X_2^2 + S_F^2)}$$

$$\therefore \text{W.K.T} = \frac{R_2}{X_2} = S_m$$

$$\frac{R^2}{X_2^2} = S_m^2$$

$$\frac{T_{FL}}{T_m} \propto \frac{s_F}{s_m} \times \frac{(s_m^2 + s_m^2)}{(s_m^2 + s_F^2)}$$

$$\propto \frac{s_F}{s_m} \times \frac{2 s_m^2}{(s_m^2 + s_F^2)}$$

$$\frac{T_{FL}}{T_m} \propto \frac{2 s_F s_m}{s_m^2 + s_F^2}$$

$$\frac{T_{FL}}{T_m} = K \frac{2 s_F s_m}{s_m^2 + s_F^2}$$

if $K = 1$

$$\boxed{\frac{T_{FL}}{T_m} = \frac{2 s_F s_m}{s_m^2 + s_F^2}}$$

↳ iii) Starting torque and maximum torque ratios:-

HW

$$T \propto \frac{s E_2^2 R_2}{R_2^2 + (s X_2)^2} \rightarrow ①$$

At start $s = 1$

$$T_{st} \propto \frac{E_2^2 R_2}{R_2^2 + X_2^2} \rightarrow ②$$

If $s = s_m$

then

$$T_m \propto \frac{s_m E_2^2 R_2}{R_2^2 + (s_m X_2)^2} \rightarrow ③$$

Dividing ② and ③

$$\frac{T_{st}}{T_m} = \frac{\cancel{E_2^2} R_2}{(R_2^2 + X_2^2)} \times \frac{(R_2^2 + (S_m X_2)^2)}{S_m \cancel{E_2^2 R_2}}$$

$$\frac{T_{st}}{T_m} = \frac{R_2^2 + S_m^2 X_2^2}{S_m [R_2^2 + X_2^2]}$$

Dividing both Nr and Dr by X_2^2

$$= \frac{\frac{R_2^2}{X_2^2} + S_m^2}{S_m \left[\frac{R_2^2}{X_2^2} + 1\right]}$$

Substitute $R_2 / X_2 = S_m$

$$\frac{T_{st}}{T_m} = \frac{S_m^2 + S_m^2}{S_m (S_m^2 + 1)}$$

$$= \frac{2 S_m^{\cancel{2}}}{\cancel{S_m} (1 + S_m^2)}$$

$$\boxed{\frac{T_{st}}{T_m} = \frac{2 S_m}{1 + S_m^2}}$$

Q1) A six pole, 3 φ 50 Hz IM runs on full load with a slip of 4%. The rotor standstill impedance per phase 0.0 + j 0.05 Ω calculate the available maximum torque in terms of full load torque. Also determine speed at which maximum torque occurs.

Soln Given :-

$S\% = 4\%$

$s = 0.04 = S_f = 0.04$

$P = 6$

$f = 50\,Hz$

$Z_2 = (0.01 + j0.05)\ \Omega/ph$

$R_2 = 0.01\ \Omega/ph$

$X_2 = 0.05\ \Omega/ph$

To find :-

T_m interms of T_{st}

and N_m at T_m

Soln

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (X_2 S)^2}$$

R E_2 remains constant if the supply voltage remains constant

$$T \propto \frac{S R_2}{R_2^2 + (S X_2)^2}$$

$$\rightarrow \cancel{T}\ T_{FL} \propto \frac{S_F R_2}{R_2^2 + (S_F X_2)^2}$$

$$\rightarrow T_m \propto \frac{S_m R_2}{R_2^2 + (S_m X_2)^2}$$

$$S_m = \frac{R_2}{X_2}$$

$$= \frac{0.01}{0.05} = 0.2$$

$$\rightarrow T_m = \frac{(0.2)(0.01)}{(0.01)^2 + (0.2)^2(0.05)^2} \quad [K=1]$$

$$T_m = 10$$

$$\rightarrow T_{FL} = \frac{(0.04)(0.01)}{(0.01)^2 + (0.04 \times 0.05)^2}$$

$$T_{FL} = 3.84$$

$$\therefore \frac{T_{FL}}{T_m} = \frac{3.84}{10} = \underline{0.384}$$

$$T_m = \frac{T_{FL}}{0.384} = 2.6\,T_{FL}$$

$$\therefore \boxed{T_m = 2.6\,T_{FL}}$$

$$\rightarrow N = N_s(1-S)$$

$$\rightarrow \cancel{N = N_m(1 - S_m)}$$

$$\cancel{N_m = \frac{N}{1 - S_m}}$$

$\rightarrow$ $N = N_s(1-s)$

at max

$\rightarrow$ $N_m = N_s(1-s_m)$

$N_s = \frac{120f}{P}$

$= \frac{120 \times 50}{\cancel{50}6}$

$= 1000$

$\rightarrow$ $N_m = 1000(1-0.2)$

$\underline{N_m = 800 rpm}$

Q2) A 746 KW, 3 ϕ, 50 Hz, 16 Pole IM has a rotor impedance of $0.02 + j0.15\ \Omega$ at standstill. The full load torque is obtained at 360 rpm. Calculate

(i) Speed at which maximum torque occurs

(ii) Ratio of maximum to full load torque

(iii) The external resistance / phase to be inserted in the rotor circuit to get maximum torque at start

Soln

$P = 16$

$f = 50Hz$

$Z_2 = 0.02 + j0.015$

$P_{out} = 746 KW$ = O/P power

~~At~~ $R_2 = 0.02\ \Omega/ph$

$X_2 = 0.015\ \Omega/ph$

$N_{f.L} = 360 rpm$

~~Soln~~ To find :-

(i) $N_m = ?$

(ii) $T_m / T_{fL} = ?$

(iii) $R_{ext}/ph = ?$

Soln

(i) $N_m = N_s(1 - s_m)$

$N_s = \frac{120f}{P}$

$= \frac{120 * 50}{16}$

$= 375\ rpm$

$s_m = \frac{R_2}{X_2} = \frac{0.02}{0.015} = 0.133$

$N_m = 375(1 - 0.133)$

$= 325\ rpm$

(ii)

$$\rightarrow \quad T_m \propto \frac{s_m R_2}{R_2^2 + (s_m X_2)^2}$$

$$= \frac{(0.133)(0.02)}{(0.02)^2 + ((0.133)(0.15))^2}$$

$$T_m = 3.33$$

$\rightarrow$ ~~s_0 =~~

~~To find~~ ~~$s = \frac{N_s - N_s}{N_s}$~~

~~360 - 3~~

$\rightarrow$ To find s_{fL} $\Rightarrow$ $N = N_s(1 - s_f)$

$$360 = 375(1 - s_f)$$

$$s_f = 0.04$$

WKT

~~T~~

$$T_{sf} = \frac{T_m \times 2 s_m s_f}{s_m^2 + s_f^2}$$

$$= \frac{3.33 \times 2 \times 0.133 \times 0.04}{(0.133)^2 + (0.04)^2}$$

$$= \underline{\underline{1.812}}$$

(iii)

for Tm at start $S_m = 1 = \frac{R_2}{X_2}$

$\therefore$ $R_2 = X_2$

$R_2 = X_2 = 0.15\,\Omega$ → (new value of resistance)

Rex ~~at~~ that needs to be added

is

$R_{ex} = 0.15 - 0.02 = 0.13\,\Omega$ / ph

(0.02 = old value of resistance)

Q3) A six pole 3ϕ, 50 Hz IM develops a maximum torque of 30 N m at 960 rpm. Determine the torque exerted by the motor at 5% slip. The rotor resistance per phase is $0.6\,\Omega$

Soln Given

$P = 6$

$f = 50\,Hz$

$T_m = 30\,N\text{-}m$

$N_m = 960$

$R_2 = 0.6\,\Omega$ / ph

~~T~~ $S = 0.05$

To find

~~Tfull~~ $T = ?$

(iii)

$\rightarrow$ $N_m = N_s(1 - s_m)$

$\cancel{s_m} = \cancel{\frac{R_2}{X_2}}$

$N_s = \frac{120f}{P} = \frac{120 \times 50}{6} = 1000 rpm$

$960 = 1000(1 - s_m)$

$0.96 = 1 - s_m$

$s_m = 0.04$

$\rightarrow$ $\cancel{T_m = \frac{s_m R_2}{R_2^2 + (s_m^2}}$

$s_m = \frac{R_2}{X_2}$

$X_2 = \frac{0.6}{0.005} = 15 \Omega / ph$

$\rightarrow$ $T \propto \frac{sE^2 R_2}{R_2^2 + (sX_2)^2}$

$E_2 = constant$

$T \propto \frac{sR_2}{R_2^2 + (sX_2)^2}$ $(K = 1)$

$= \frac{0.05 * 0.6}{(0.6)^2 + (0.05 * 05)^2}$

$T = 0.0325$ Nm

$$\frac{T_m}{T} = \frac{30}{T}$$

$$= \frac{30}{sR_2} \times \frac{(R_1^2 + (sX_2))^2}{1}$$

$$\frac{\cancel{Tm}30}{T} = \frac{30}{(0.005 \times 6)} \times \left((0.6)^2 + (0.05 \times 15)^2\right)$$

$\boxed{\text{Using } (T_m)}$

$$\frac{T_m}{T} = \frac{s_m R_2/2}{R_2^2 + (s_m X_2)^2} \times \frac{R_2^2 + (sX_2)^2}{s R_2/2}$$

$$\frac{30}{T} = \frac{0.04}{0.05} \times \left[\frac{(0.6)^2 + (0.05 \times 15)^2}{(0.6)^2 + (0.04 \times 15)^2}\right]$$

$$T = \underline{\underline{29.26 \text{ Nm}}}$$

MODULE-4

SINGLE PHASE INDUCTION MOTORS

Construction

1) Stator
2) Rotor → squirrel cage (or) short-circuited rotor

3ϕ IM	1ϕ IM
1) Self starting	1) Not self starting
2) Flux produced in rotating flux (or) (field)	2) Flux produced in alternating (or) (field)
3)	

Sing → stato → altor → cuts rotor → emf → current flows → flux is pr. → stato & rotor flux interact to

→ To understand why single phase induction motors are not self starting,

let us consider Double revolving field theory

* According to this theory, any alternating quantity (referring to flux) but can be resolved into two rotating components which rotate in opposite directions and each having magnitude half of the maximum magnitude of the alternating quantity.

- In case of single phase induction motors the stator winding produces an alternating magnetic field say ϕ_s

- According to double revolving theory consider the two rotating components of the stator flux say ϕ_f and ϕ_b

where $\phi_f = \frac{\phi_s}{2} = \phi_b$

(or) $\phi_f = \phi_b = \frac{\phi_s}{2}$

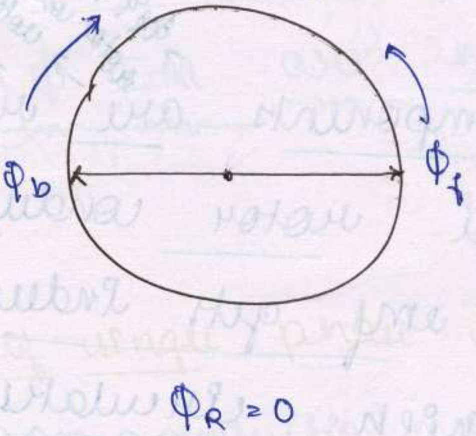
- ϕ_f is the forward component rotating in anticlockwise direction and

ϕ_b is the backward component rotating in clockwise direction

- The resultant of these two components gives the originating stator flux

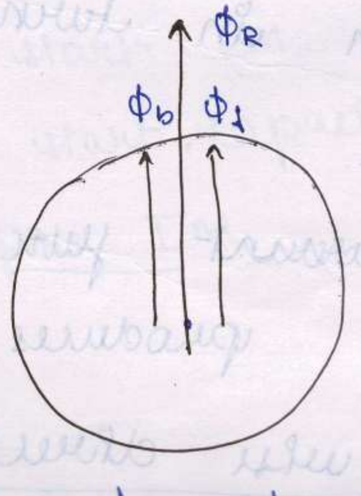
At start :-

$\phi_f = \phi_b = \frac{\phi_s}{2}$



$\phi_R = 0$

After $\theta = 90^\circ$



$\phi_R = \phi_b + \phi_f = \phi_s$

- (i) At start both the components are opposite to each other

Thus $\phi_R = 0$

- (ii) After $\theta = 90^\circ$ both the components are pointing in the same direction hence ϕ_R is the algebraic sum of two components

- continous rotating of these two components gives the original alternating stator flux

ϕ_f & ϕ_b → cuts → rotor conductor → rotor current → rotor flux is produced

- Both the components are rotating and cut the rotor conductor and hence emf gets induced in the rotor which circulates rotor current which in turn produces rotor flux

R(emf) ↓ R(I) ↓ R(ϕ)

- This rotor current flux interacts with ϕ_f and produces "torque in anticlock wise direction" and

rotor flux ↓ ϕ_f and rotor flux ↓

the same rotor flux interacts with ϕ_b and produces "torque in clockwise direction." (say -ve torque)

- At start when two torques are also in opposite direction with equal magnitudes → Each torque tries to rotate the rotor in its own respective direction

- "The net torque experienced or resultant torque experienced by the rotor at start is zero".
Hence 1ϕ IM are not self starting.

→ Types of single phase induction motor:-

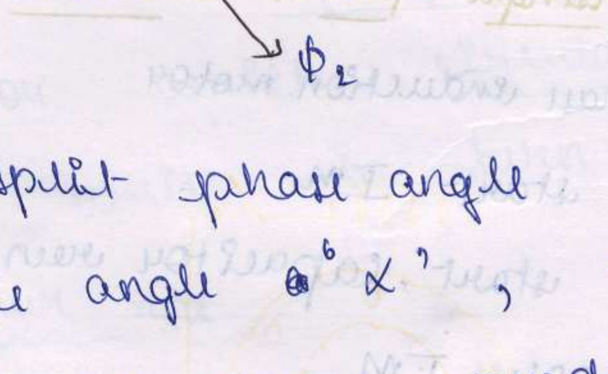
1) Split phase induction motor
2) Capacitor start IM
3) Capacitor start, capacitor run IM
4) Shaded pole IM

winding → Stator / main
→ Auxiliary / Starting
→ Starting
→ running

b,1) Split phase induction motor:-

To produce RMF, it is necessary to have minimum two alternating fluxes having a phase difference b/w the two.

The interaction of these two fluxes produce a resultant flux which is rotating in space at a speed of synchronous speed $(N_s = 120f/P)$



α = split phase angle

more the angle 'α', more is the starting torque produced rotor in 1φ IM rotates in same direction as that of RMF

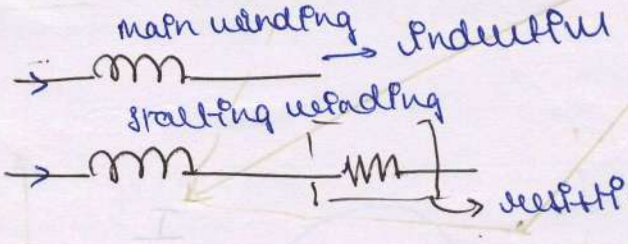
↳ i) Split phase induction motor -

This type of motor has single phase stator winding called the main winding.

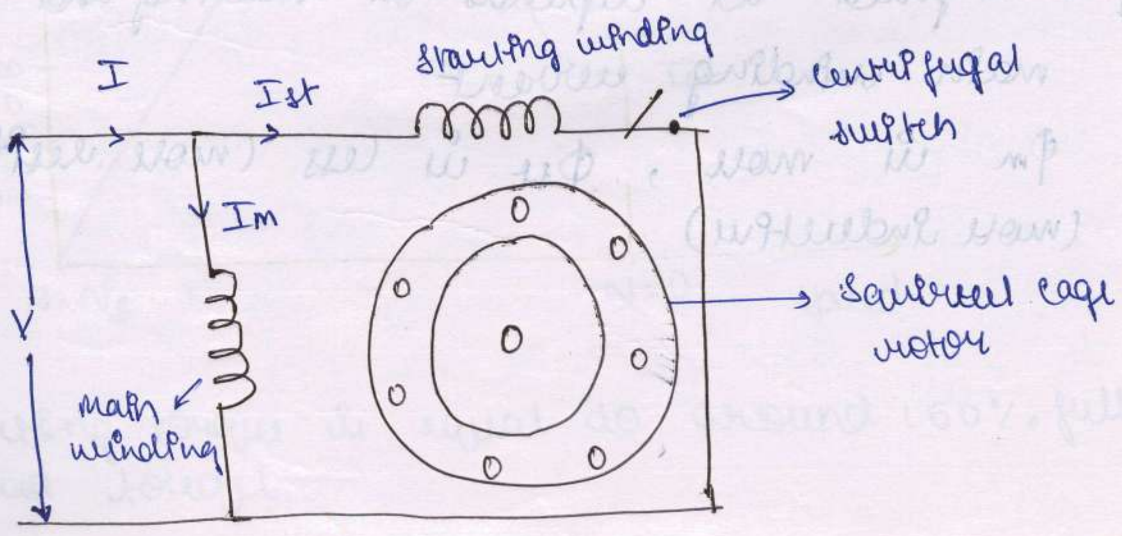
In addition to this stator carries one more winding called auxillary winding or starting winding.

Stator winding → (or) main winding → more inductive in nature

Auxillary winding → (or) starting winding → more resistive in nature



Circuit diagram



Let

I_m = current through the main winding

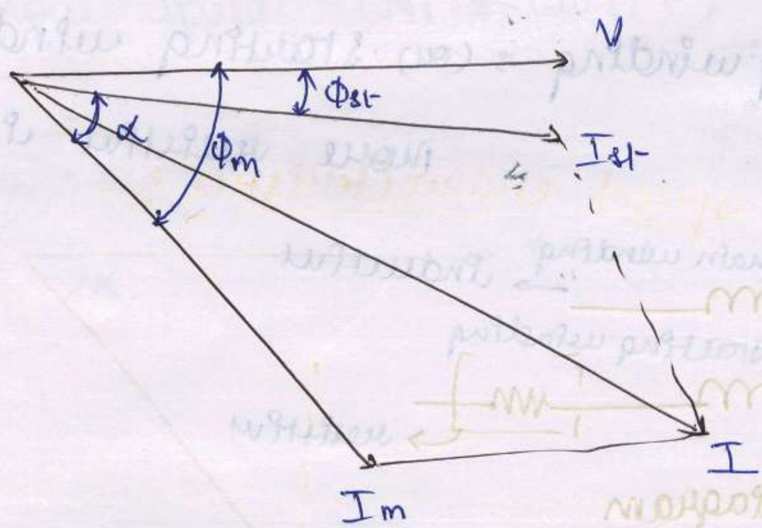
I_{st} = current through the starting winding

V = ~~Main~~ supply voltage

Once the speed of rotor reaches 75-80% of synchronous speed centrifugal switch opens

To start the rotor RMF is realized.

<u>Phasor</u> <u>diagram</u> :-



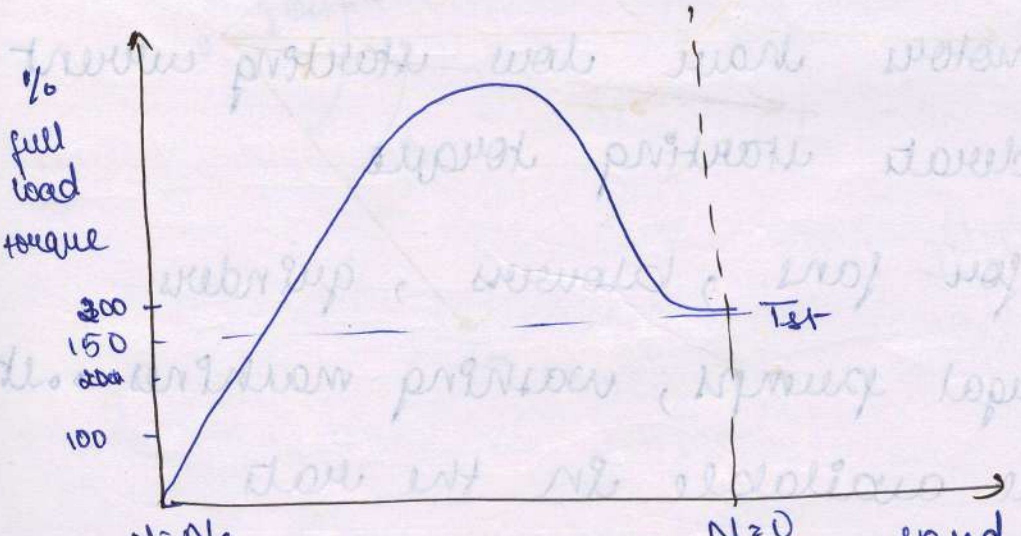
α is fixed it depends on starting and main winding current

ϕ_m is more, ϕ_{st} is less (more resistive)
(more inductive)

starting winding ~~it~~ has a centrifugal switch in series with it ~~volte~~ when the motor attains the speed of 75 – 80% of synchronous speed, the centrifugal switch gets opened mechanically and then in running condition the starting winding gets removed ~~in~~ from the circuit.

As current I_m and I_{st} are splitted from each other by an angle α at start, the motor is called split phase I motor.

Torque speed characteristics :-



starting torque is equal to around 150% full load torque

$$\boxed{T_{st} \propto \alpha}$$

α - split phase angle or
phase difference angle

- Split phase IM have poor starting torque which is 125-150% of full load torque

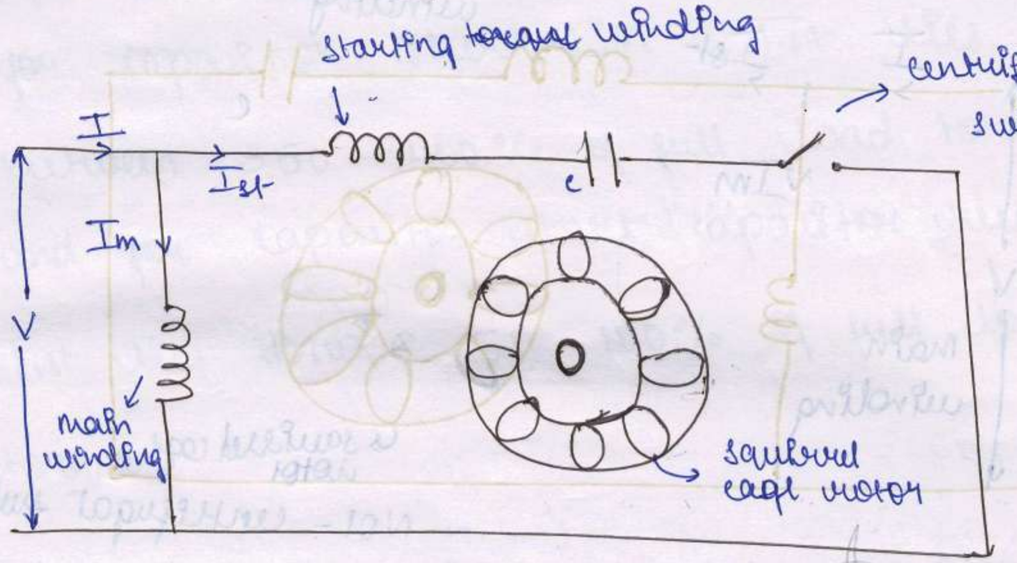
- Direction of rotation of the motor can be reversed by reversing the terminals of either main winding or auxillary winding

Applications

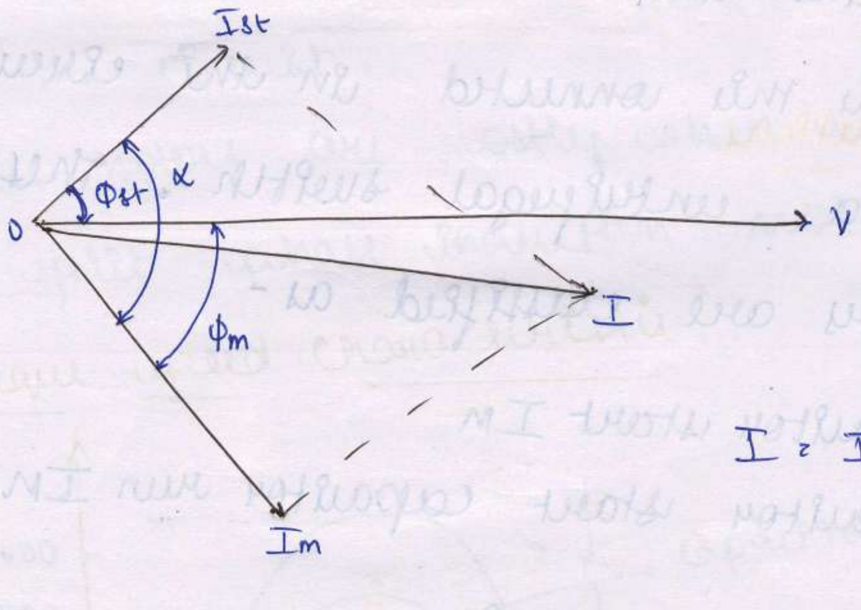
- These motors have low starting current and moderate starting torque
- Used for fans, blowers, grinders centrifugal pumps, washing machines ...etc.
- They are available in the rate of $\frac{1}{20}$ to $\frac{1}{2}$ kW

↳ iii) Capacitor start induction motor :-

→ Circuit diagram

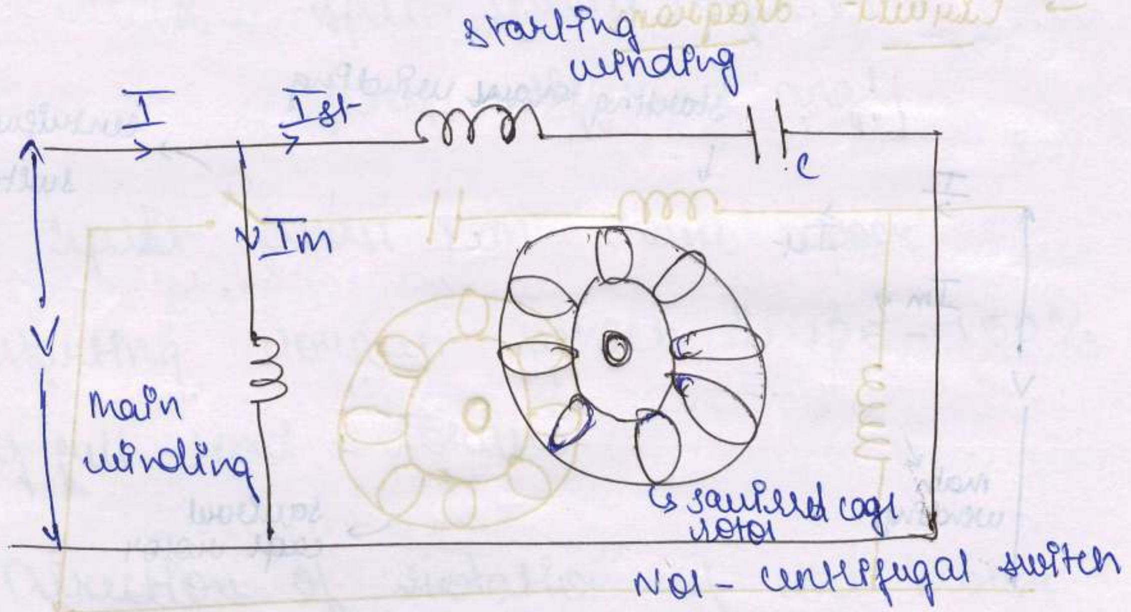


→ Phasor diagram :-



$I = I_m + I_{st}$

↳ (iii) Capacitor start capacitor run induction motor:-



→ Depending whether the capacitor remains in the circuit permanently or is the connected in the circuit using a centrifugal switch. These motors are classified as-

(i) Capacitor start IM
(ii) Capacitor start capacitor run IM

Due to the capacitor the current I_{st} leads the voltage by an angle ϕ_{st} hence there exists a large phase difference b/w I_m and I_{st} which is

W.K.T

- ~~T~~ $T_{st} \propto (\alpha)$

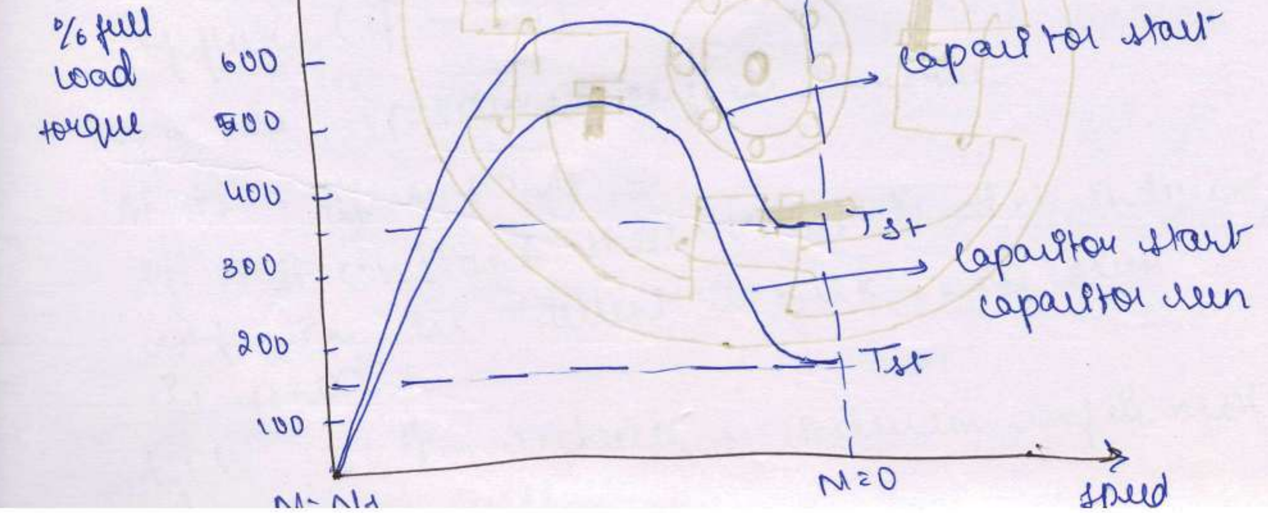
Hence such motors produce a very high starting torque i.e.,

for capacitor start IM - T_{st} lies between 350 - 400% of full load torque and for capacitor start capacitor run IM T_{st} lies b/w 50 - 100% of full load torque.

In case of capacitor start capacitor run IM there is no centrifugal switch and the capacitor remains permanently in the circuit.

These motors are costly when compared to split phase induction motors

→ Torque speed characteristics

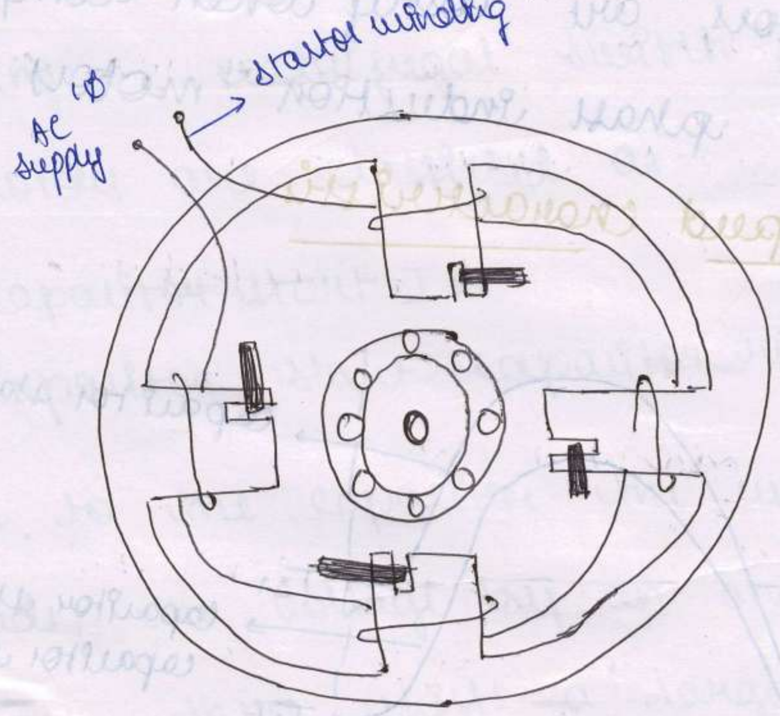


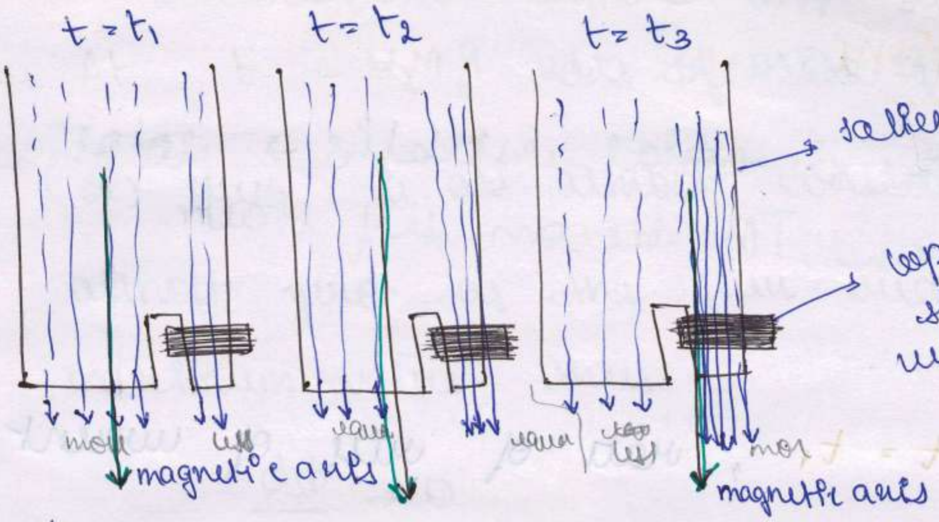
Applications

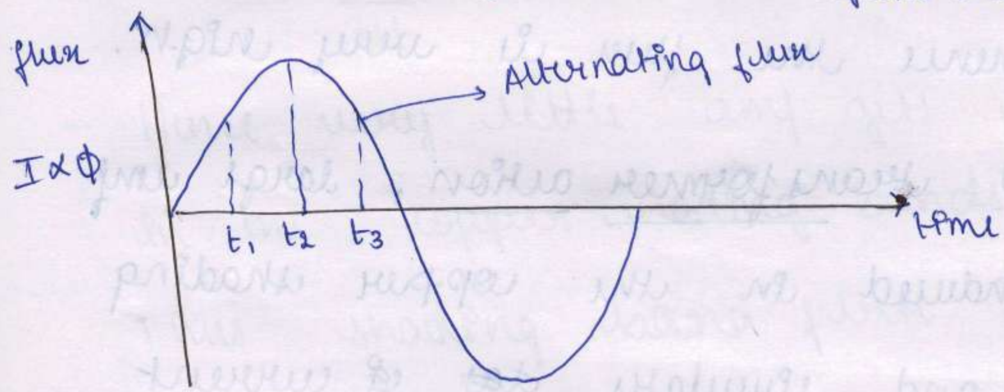
- These motors have high starting torque
- Used for compressors, conveyors, grinders, fans, refrigerators, air conditioners .. etc..
  → capacitor start
- Used for ceiling fans, blowers, air circulators - ...etc..
  → capacitor start-capacitor run
- These motors are available upto 6 kW

iv) Shaded pole induction motor:-

(only this consists of physical poles)







Stator - ~~all~~ has salient poles
copper shading bands are mounted on their pole
↳ convert alternating flux to RMF

As I flow → ϕ flow → when ϕ cuts Cu shading bands → current starts
→ emf gets induced in Cu shading → it produces
flowing in Cu shading band
ϕ of its → this Cu produced ϕ opposes main
ϕ (Lenz's law) (ϕ_{cu} less)
↳ Due to this there will be subtraction
of flux ($\phi - \phi_{cu}$)

when Cu → produced emf is maximum

At t_2 → ϕ_m constant → since there is ~~not~~ no induced
If ϕ is constant then current is zero → no flux
emf in Cu
is prod

$t = t_3$ → ϕ_m reduces → induced emf is not
... is small

due to this sequen alternating flux is converted to RMF

If RMF is ~~rotal~~ establis → rotor rotates and IM becom self starts

15|4|2017

• ↳ At $t = t_1$, rate of rise of current and hence the flux is very high.

- Due to transformer action, large emf gets induced in the copper shading bands and circulates ~~cur~~ a current through the copper shading bands producing its own flux to

- By Lenz's law, the shading band flux opposes main stator flux.

- Hence there is crowding / gathering / accumulation of flux under the non shaded part while there is weakening of flux under the shadded part

- Overall magnetic axis shifts to the non shaded part shown.

- ↳ At $t = t_2$, rate of rise of current (or) flux is ~~at~~ almost constant i.e., almost zero as the flux reaches maximum value thus

$$\frac{d\phi}{dt} = 0$$

- Hence very little emf gets induced in the copper shading bands. Thus shading band flux is almost negligible.
- Thus it does not affect the distribution of main stator flux, ~~&~~ hence ~~a~~ the main stator flux gets equally under both shaded and non shaded part of pole

- ↳ At $t = t_3$, the current ~~and~~ (or) flux is reducing, the rate of decrease is high and thus a large emf gets induced in the copper shading band.
- This shading band flux is in the same

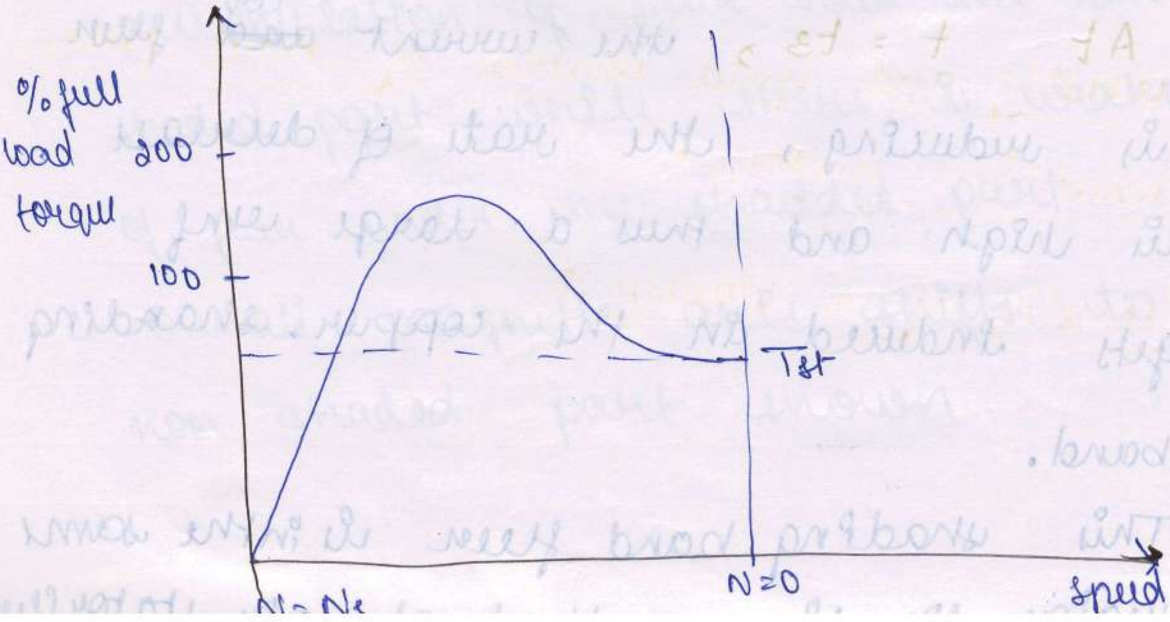
- Thus there is more flux under the shaded part when compared to non shaded part.
- Thus magnetic axis lies under the shaded part of the pole.

→ During -ve half cycle

This sequence keeps on repeating for -ve half cycle also and produces the effect of rotating magnetic field which is from the non shaded part of the pole to shaded part of the pole.

[+ve → shaded to non shaded part

⟹ Torque speed characteristics:-



- Starting torque is low which is about 40 - 50% of % full load torque

-

→ Limitations :-

- Starting torque is low.
- Power factor is also low.
- Due to I^2R losses (copper losses) in the shading band, the efficiency is very low
- Speed reversal is very difficult
- Size and power rating of these motor is very small. These motor are available in the range of 1/300 to 1/20 KW

— Applications :-

- ~~was~~ Used for small fans, toy motors advertising display, film projectors, hair driers, photo copying machines ... etc.
- Available in the range of $\frac{1}{300}$ to $\frac{1}{20}$ KW

⇒ Starting and speed control of three phase induction motors :-

- Necessity of a starter :-

WKT

$$I_{2r} = \frac{s E_2}{\sqrt{R_2^2 + (sX_2)^2}} \text{ Amps}$$

I_{2r} = rotor current under running condition

But at start $s = 1$, $N = 0$

$$I_{2r} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

Thus the magnitude of rotor induced emf is very large at start

$$E_{2r} = s E_2$$

$$E_{2r} = E_2 \quad [s = 1]$$

As the rotor conductors are short circuited, large emf gets induced in the rotor which circulates very high current in the rotor at start.

- When the rotor current is high, consequently the stator draws a very high current from the supplies. This current can be of the order of ~~5 - 10 times~~ 5 - 8 times the full load current at start.

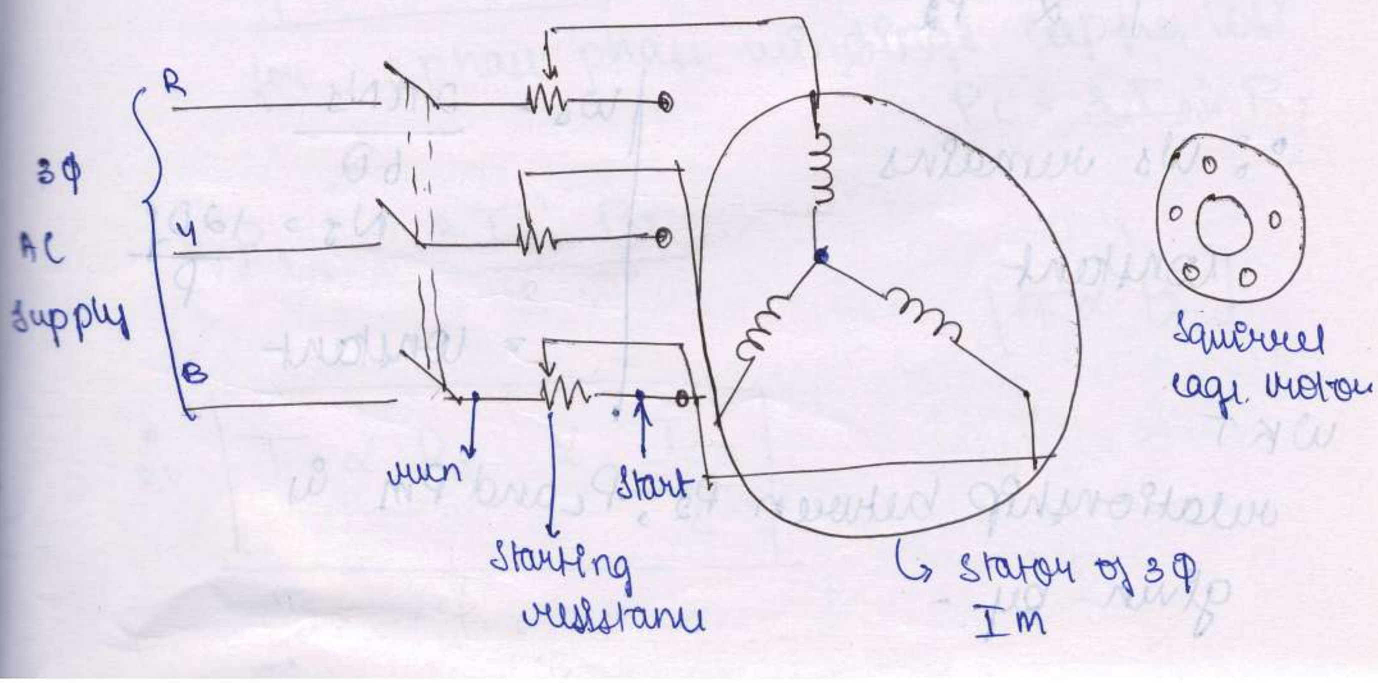
- rotor winding terminals are available only at slipring rotor
- not and not for induction motor (as internal resistance cannot be added

- To limit the high starting current, a starter is used for a three phase induction motor.

- Types of starters used for three phase induction motors:-

1) Stator resistance starter
2) Auto-transformer starter
3) Star delta starter
4) Rotor resistance starter
5) Direct ON line starter

1) Stator resistance starter:-

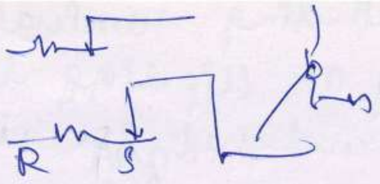


(i) At start

arrow at start position

resistance is added (max)

∴ less current flows at start



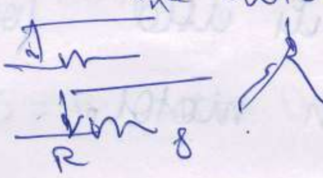
→ supply volt → in stator reduces

i.e rotor emf reduces

(ii) In run

arrow at run position

resistance is bypassed



When the motor picks up 70-80% of speed arrow comes to run position [I ↓ → induced emf in stator ↓ → flux ↓ → rotor induced emf ↓]

→ Relationship between starting torque T_{st} and full load torque T_{FL} :-

$P_2 = T * \omega_s$

P_2 = Rotor input power at N_s

T = torque produced

$T \propto P_2$

∵ ω_s remains constant

$\omega_s = \frac{2\pi N_s}{60}$

$N_s = \frac{120f}{P}$

= constant

WKT

relationship between P_2, P_c and P_m is given by -

$P_2 : P_c : P_m$ is $1 : S : 1-S$

$$\left[\frac{P_2}{P_c} = \frac{1}{S} ; \frac{P_c}{P_m} = \frac{S}{1-S}\right]$$

where P_2 = rotor i/p power at N_s in watts

P_c = rotor copper loss in watts

P_m = ~~gro~~ gross mechanical power developed in the motor

[electrical equivalent of gross mechanical power developed $= P_m = E_0 I_a$]

$$\therefore \frac{P_2}{P_c} = \frac{1}{S}$$

$$\boxed{P_2 = \frac{P_c}{S}}$$

$\frac{P_2}{P_c} = \frac{P_1}{S}$

$P_2 = \frac{3 I_{2i}^2 R_2}{S}$

$P_2 \propto \frac{I_1^2}{S}$

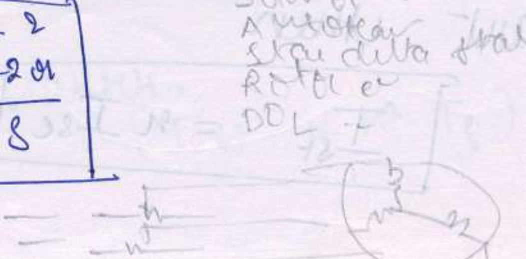
for 3 phase phase windings copper loss $P_c = 3 I_{2r}^2 R_2$

$$P_2 = \frac{3 I_{2r}^2 R_2}{S}$$

$[T \propto P_2]$

Stator resist starter
Autotransformer starter
Star delta starter
[illegible]
DOL

$$\therefore \boxed{T \propto P_2 \propto \frac{I_{2r}^2}{S}}$$



Note :-

The rotor current I_{2r} and the stator current are related to each other through transformer action.

$$T \propto \frac{I_1^2}{S} \rightarrow ①$$

where I_1^2 is stator current

$S=1$, $I_1 = I_{st} = x I_{sc}$

$\therefore I_{2r}^2 \propto I_1^2$

At start $S = 1$, $T = T_{st}$ and $I_1 = I_{st}$

The stator voltage reduces by a factor "x" which is always ~~....~~ less than 1

i.e., $\boxed{x < 1}$

and starting current proportional to this factor "x" ~~i.e~~

If I_{sc} is the normal current drawn under full rated voltage condition at start then

$$\boxed{I_{st} = x I_{sc}}$$

∴ eqn ① ⇒ becomes

$$T_{st} \propto \frac{(I_{st})^2}{1} \propto \frac{(x I_{sc})^2}{1} \quad \rightarrow ② \quad s = 1$$

↳ Under full load condition

$$S = S_f, \quad T = T_{fl} \text{ and } I_1 = I_{FL}$$

① ⇒ becomes

$$\therefore \quad T_{fl} = \frac{(I_{fl})^2}{S_f} \quad \rightarrow ③$$

∴ Dividing ② by ③

$$\frac{T_{st}}{T_{fl}} = \frac{(x I_{sc})^2}{\frac{(I_{fl})^2}{S_f}},$$

$$\frac{T_{st}}{T_{fl}} = \left(\frac{x I_{sc}}{I_{fl}}\right)^2 * S_f$$

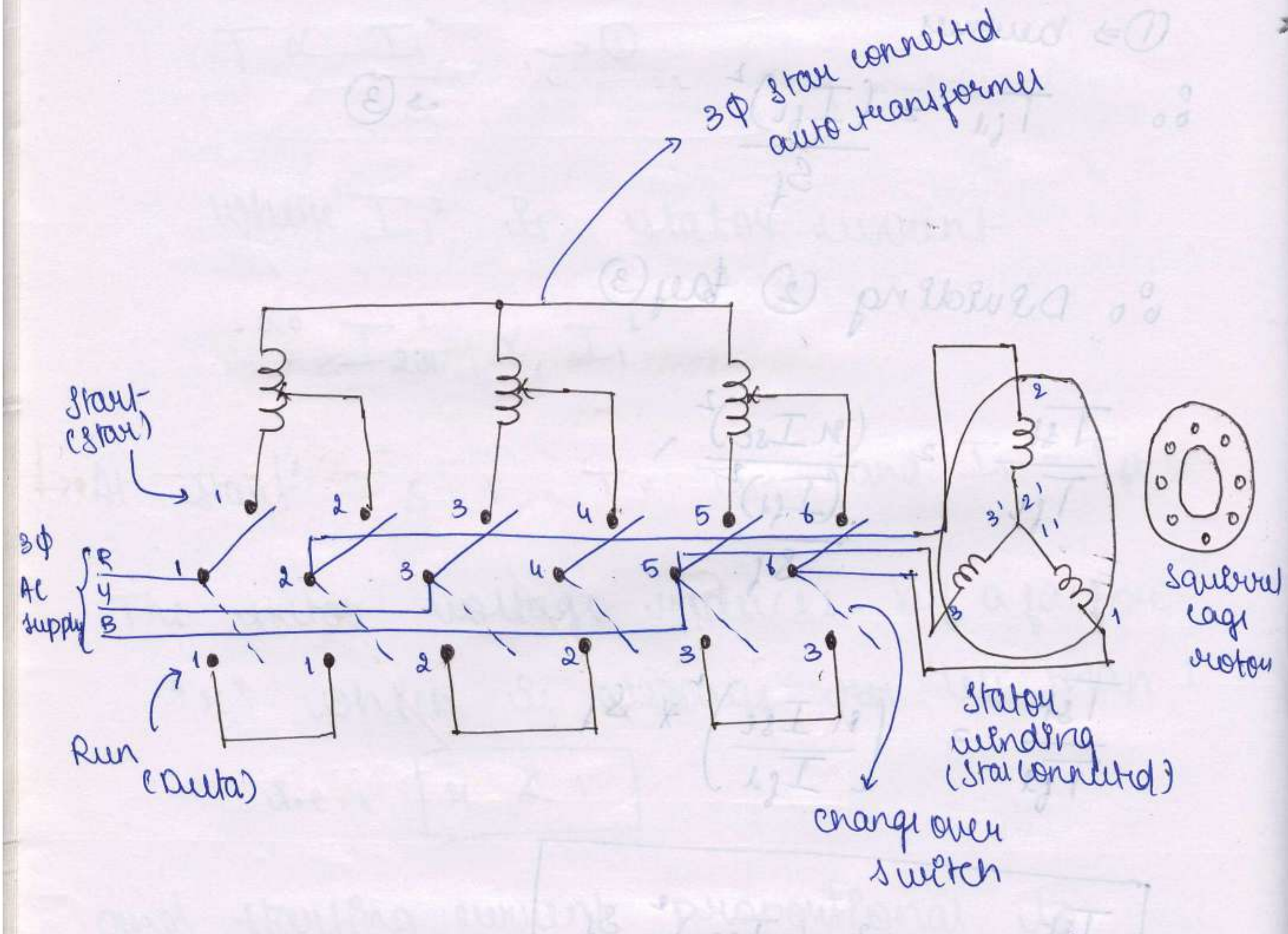
$$\boxed{\frac{T_{st}}{T_f} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 S_f}$$

Note :-

As $x < 1$, the starting reduces by a fraction x^2 due to stator resistance starter. $(T_{st} \propto x^2 T_f)$

↳ 2) Auto transformer starter :-

A three phase star connected auto-transformer is used to reduce the voltage applied to the stator



At start - switch → Auto tran ~~Hed~~ side
(0 - 400) V can be varied
∴ current is reduced
reduced voltage is applied by varying auto tr from 0 to 400 V
∴ (change over switch in start condition)

- It consists of a suitable change over switch

- when the switch is in start position, the winding is supplied with reduced voltage.
- This can be controlled by tapping provided in the autotransformer
- when motor gathers 80% of normal speed, change over switch is thrown into run position and the rated voltage gets applied to stator winding

→ Relationship b/w T_{st} and T_{FL} :-

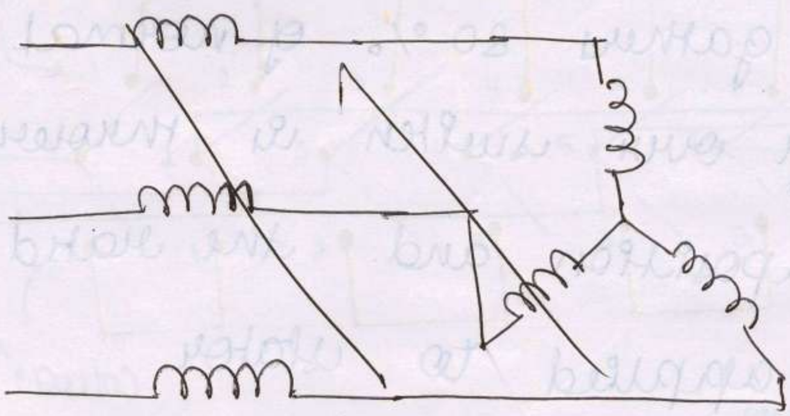
Let "x" be the fractional ~~per~~ percentage tapping used for the autotransformer if I_{sc} = starting motor current at rated voltage

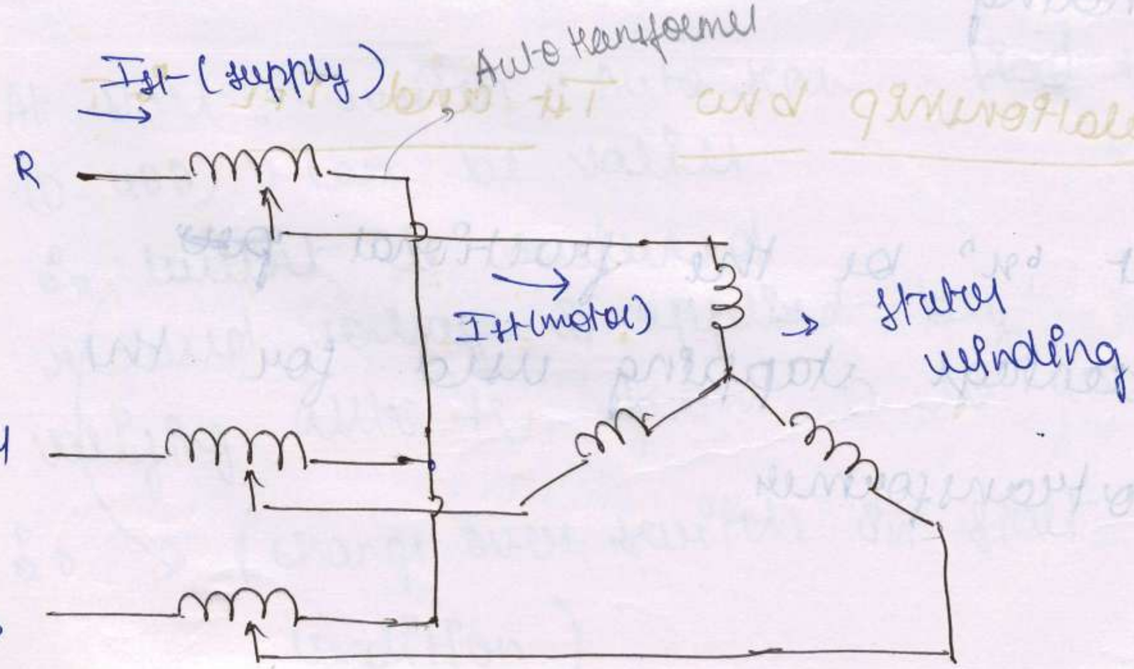
I_{st} = starting motor current with the starter

then

$$\boxed{I_{st} = x I_{sc}} \rightarrow ①$$

x = fraction





There exists a fixed ratio ~~ration~~ between I_{st} (supply) and I_{st} (motor) due to auto transformer

$$\boxed{I_{st}\,(\text{supply}) = x\, I_{st}\,(\text{motor})} \rightarrow (2)$$

→ At start $s = 1$, $T = T_{st}$, $N = 0$

$$T_{st} \propto I_{st}^2\ (\text{motor})$$

$$T_{st} \propto x^2 I_{sc}^2 \rightarrow (3)$$

$$T_{fl} \propto \frac{I_{fl}^2}{S_f} \rightarrow (4)$$

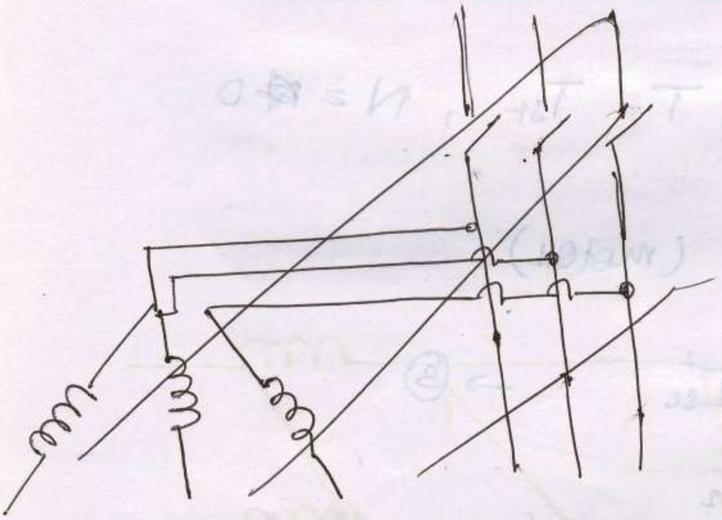
$$\frac{T_{st}}{T_{fl}} = \frac{x^2 I_{sc}^2}{\frac{I_{fl}^2}{s_f}}$$

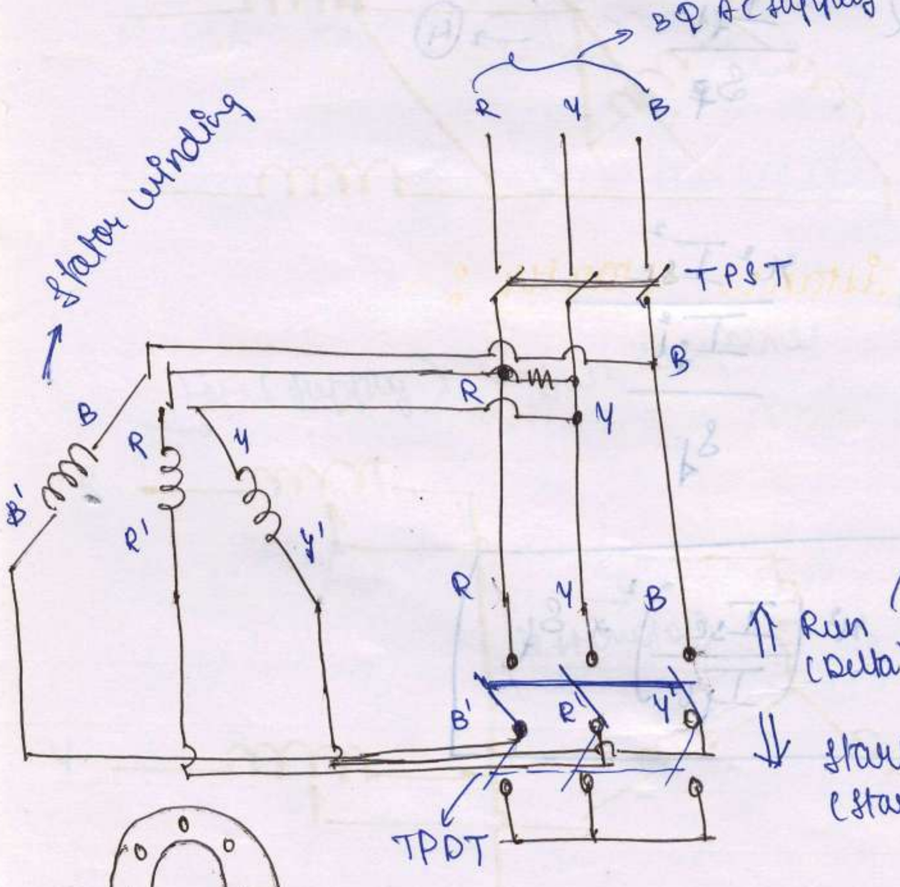
$$\boxed{\frac{T_{st}}{T_{fl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 \times S_f}$$

Note
|| Starting torque reduced by x^2

↳ 3) Star - delta starter :-

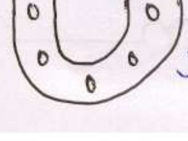
Star	Delta
$V_{ph} = \frac{V_L}{\sqrt{3}}$	$I_{ph} = \frac{I_L}{\sqrt{3}}$
$I_{ph} = I_{Ln}$	$V_L = V_{ph}$





It gets normal rated ~~delta~~ voltage connected when motor gather sufficient speed

Due to this at start per phase voltage is limited & hence starting current is reduced



squirrel cage rotor

V_{ccr}.

- Ratio of T_{st} and T_{FL}

→ Relationship between T_{st} and T_{fl} :-

W.K.T in case of autotransformer starter

$$\frac{T_{st}}{T_{fl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 S_f$$

Now the factor "x" for star-delta starter is $\frac{1}{\sqrt{3}}$

$\{ x = 1/3$

$$\therefore \frac{T_{st}}{T_{fl}} = \left(\frac{1}{3}\right)\left(\frac{I_{sc}}{I_{fl}}\right)^2 S_f$$

↳4) Rotor resistance starter :-

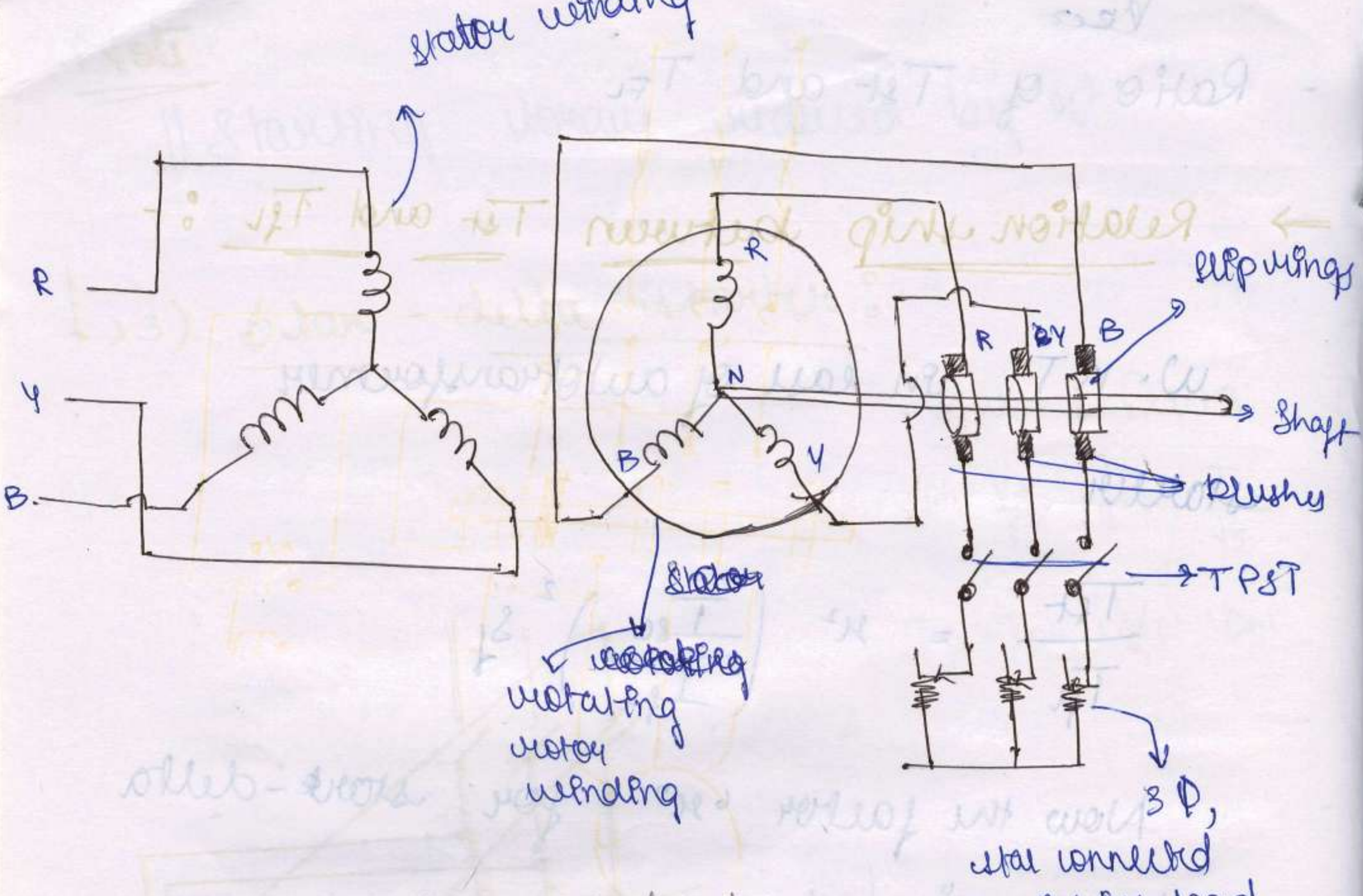
- This type of starter is applicable only for slip ring induction motor.

Initially max resistance as motor gathers speed resistance is removed

$T \propto \frac{I_{2r} R}{s} \Rightarrow T_{st} \propto I_{st}^2 R$

as $R \uparrow \Rightarrow T_{st}$ improves

Not applicable for squirrel cage motor



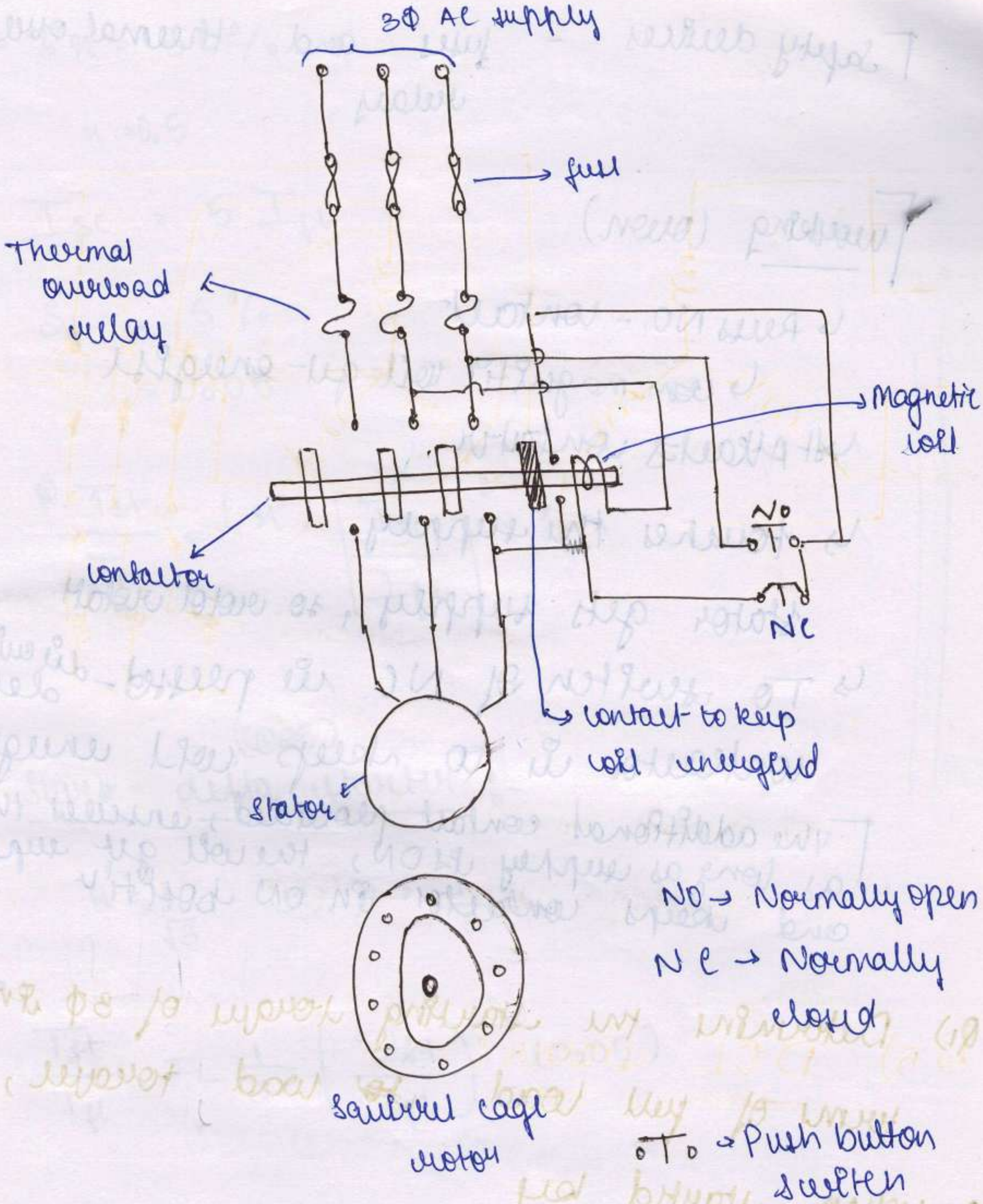
At start station we should be stationary resistive load
max
care on internal resistance is reduced

20/4/2017

↳ 5) DOL starter :-

|| It does not reduce the supply voltage.

[Direct on line starter]



[~~relay~~ relay - sensor → senses any abnormality]
- Protective device

thermal overload relay - senses change in high current using temperature variation

→ motor below 5HP - DOL starter

i.e., small rating motor - higher starting is present in motor for only less duration of time so does not affect the motor

→ contactor - switch gear arrangement

2 push button switches - NO & NC

Safety devices - fuses and thermal overload relay

Working (on)

↳ Press NO - contact
↳ ~~Elem~~ magnetic coil get energised
↳ Attracts contactor
↳ touches the supply

stator gets supply, so rotor rotates
↳ To switch of NC is pressed - circuit deenergised
contactor is to keep coil energised

The additional contact provided, ensures that as long as supply is ON, the coil get supply and keeps contactor in ON position

Q1) Determine the starting torque of 3ϕ in terms of full load ~~to~~ load torque, when started by

(i) star delta starter

(ii) auto transformer with 50% tapping.

- The short circuit current of the motor is 5 times the full load current and full load slip is 5%

Soln :- $\% x = 50\%$

$x = 0.5$

$I_{sc} = 5\, I_{fl}$

$S_f = 5\%$
$= 0.05$

$\rightarrow \frac{T_{st}}{T_{fl}} = (x^2)\left[\frac{I_{sc}}{I_{fl}}\right]^2 * S_f$

↳ (i) Star - delta starter :-

$x = \frac{1}{\sqrt{3}}$ (or) $x = \frac{1}{3}$

$\frac{T_{st}}{T_{fl}} = \frac{1}{3}\left(\frac{5\, I_{fl}}{\cancel{I_{fl}}}\right)^2 (0.05)$

$T_{st} = 0.416\, T_{fl}$

$T_{st} = 41.66\,\%\; T_{fl}$

↳ (iii) Auto transformer starter

$x = 0.5$

$\frac{T_{st}}{T_{fl}} = (0.5)^2\left(\frac{5\, I_{fl}}{I_{fl}}\right)^2 (0.05)$

$T_{st} = 0.3125\; T_{fl}$

$T_{st} = 31.25\% \, T_{fl}$

Q2) A three phase 6 pole, 50 Hz induction motor takes 60 Amperes at full load speed of 940 rpm and develops a torque of 150 Nm. The starting current at rated voltage is 300 Amper. What is the starting torque? If a star delta starter is used, determine the starting torque and starting current.

Soln:- (i) In case (i) starter is mention x^2 is not considered

Given:-

$P = 6$

$f = 50\,Hz$

$I_{fl} = 60\,A$

$N_{fl} = 940\,rpm$ [(or) N]

$T_{fl} = 150\,Nm$

$I_{sc} = 300\,A$

To find :- (i) T_{st} = without any starter
(ii) T_{fl} = with star delta starter
(iii) I_{st} = starting current with starter

Soln :-

(i) Without starter

$$\frac{T_{st}}{T_{fl}} = x^2 \left(\frac{I_{st}}{I_{fl}}\right)^2 S_f$$

$$N_{fl} = N_s (1 - S_f)$$

$$\rightarrow N_s = \frac{120 f}{P}$$

$$= \frac{120 \times 50}{6}$$

$$N_s = 1000 rpm$$

$$\rightarrow 940 = 1000 (1 - S_f)$$

$$S_f = 0.06$$

$$\rightarrow \frac{T_{st}}{150} = \left(\frac{300}{60}\right)^2 \times 0.06$$

$$T_{st} = 225 \text{ Nm}$$

(ii) With star delta starter

$$x^2 = 1/3$$

$$\rightarrow \frac{T_{st}}{150} = \frac{1}{3}\left(\frac{300}{60}\right)^2 0.06$$

$$\rightarrow T_{st} = 75 \text{ N-m}$$

→ (iii) starting current with starter

$$\frac{T_{st}}{T_{fl}} = x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

$$\sqrt{\frac{T_{st}}{T_{fl}}} = x\left(\frac{I_{sc}}{I_{fl}}\right)\sqrt{s_f}$$

$$I_{sc} = \frac{\sqrt{\frac{T_{st}}{T_{fl}}} * I_{fl}}{x\sqrt{s_f}}$$

$$= \frac{\sqrt{\frac{75}{150}} * 60}{1/\sqrt{3} * \sqrt{0.06}}$$

verify

$$= 300\text{A}$$

⟹ ... wi... bu... Fu... th... co... th... un... Sa... ba... If Pa... th...

→ Speed control of three phase Induction motors:-

WKT

$$\boxed{N = N_s(1-S)}$$

(or)

$$\boxed{S = \frac{N_s - N}{N_s}}$$

From the above expression, it is seen that speed of the induction motor can be changed. either by changing the synchronous speed N_s or by changing the slip (S).

Similarly, torque produced is given by -

$$\cancel{T \propto \frac{S E_2^2 R_2}{\sqrt{R_2^2 + (S X}}}$$

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

If Parameters E_2 and R_2 are changed, then to keep the torque constant for constant load condition, the motor reacts by changing its slip and in turn the speed changes

[Ns and slip]

→ Types of speed ~~co~~

Speed control of 3 ϕ IM can be achieved from two methods

↳ 1) From stator side

↳ 2) From motor side

1) From the stator side :-

- ↳ (i) supply frequency control ~~by varying~~ to control Ns called $\left(\frac{V}{f}\right)$ method
- ↳ (ii) supply voltage control
- ↳ (iii) Adding ~~rheo~~ rheostat in the stator circuit
- ↳ (iv) controlling the no: of stator poles to control Ns

2) ↳ From the motor side :-

- ↳ (i) Adding external resistance in the motor circuit

- ↳ (ii) Cascade control
- ↳ (iii) Injecting slip frequency voltage in the motor circuit.

→ 1) From the stator side:-

- ↳ → (i) Supply frequency control or (V/f) method:-

w.r.t
$$N_s = \frac{120 f}{P}$$

Thus by controlling the supply frequency 'f' smoothly synchronous speed can be controlled over a wide range.

- The expression for air gap flux is given by-

→ supply freq in unit (or) V/F

$$\boxed{\phi_g = \frac{1}{4.44 K_1 T_{ph}} \left(\frac{V}{f}\right)}$$

Due to transformer action

[For motor or generator = T = No. of turns
↳ For transformer = N = No. of turns

$$\phi_g = \frac{1}{4.44 K_1 T_{ph}} \left(\frac{V}{f}\right)$$

where

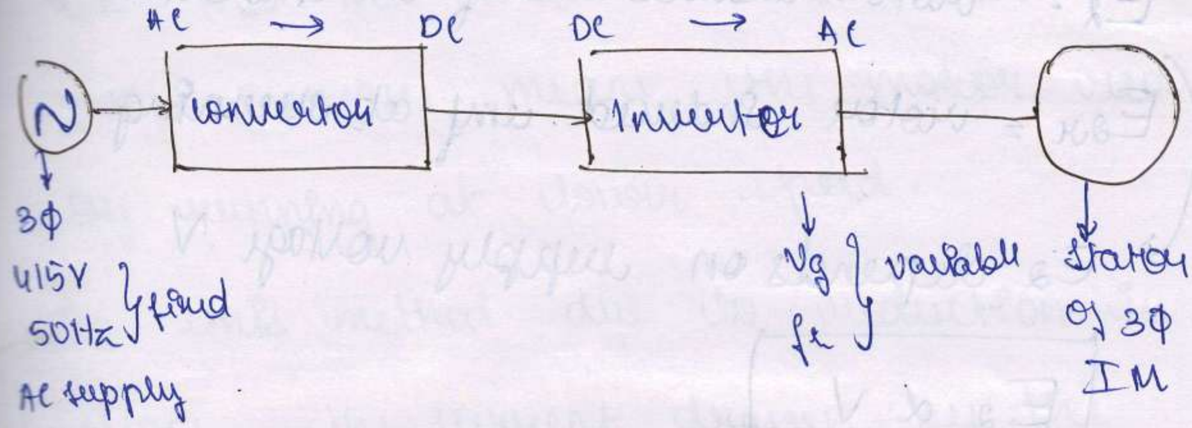
K_1 = Stator winding constant

T_{ph} = Stator turns per phase

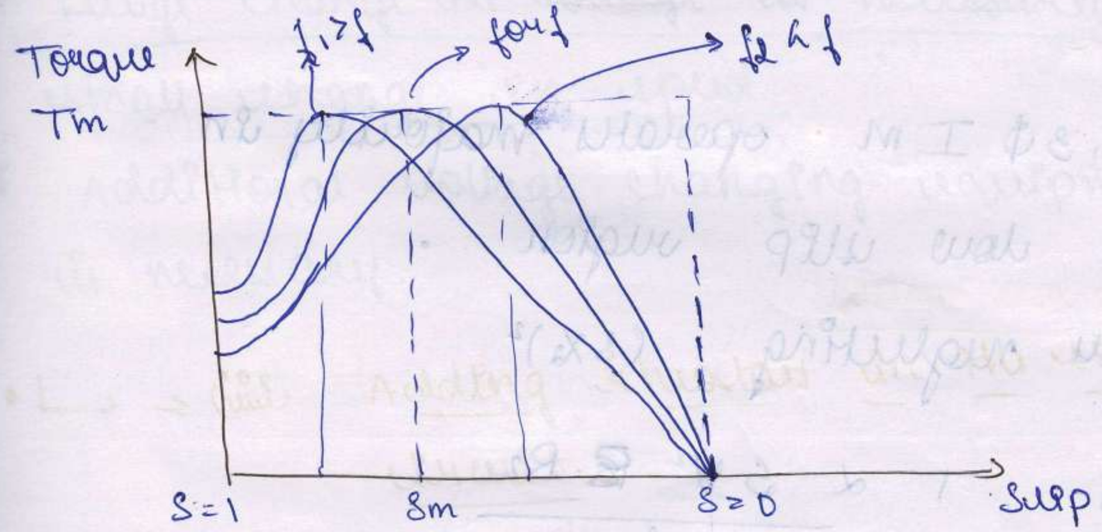
V = Supply voltage

f = Supply frequency

- It can be seen than if the supply frequency f is changed, the value of air gap flux also gets affected.
- This results saturation of stator and rotor ~~poles~~ cores and hence it is necessary to maintain air gap flux constant.
- To achieve this, along with frequency f, ~~V~~ supply voltage V also must be changed and ratio of V/f should be maintained constant.
- Hence this method is called V/f control.



→ **Torque slip characteristics:-**



f = supply frequency

f_1 = f_2 = variable frequency

f_1 = frequency greater than supply frequency

f_2 = frequency less than supply frequency

→ → (iii) **Supply voltage control:-**

W.K.T

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

E_2 = rotor induced emf at standstill

E_{2r} = rotor induced emf at running

E_2 depends on supply voltage V

$$\boxed{E_2 \propto V}$$

- For low slip region $(S X_2) << R_2$

Note :-

A 3Φ IM operates majority in the low slip region .

Thus neglecting $(S X_2)^2$

$$\therefore T \propto \frac{S V^2 \cdot R_2}{R_2^2}$$

assume R_2 ~~remaing~~ remains constant (squirrel cage rotor)

$$\therefore \boxed{T \propto S V^2}$$

- If the supply voltage V is reduced then, torque also decreases

* - But to surrain the same load it is necessary to develop the same torque , Hence slip increases

so that the torque remains same.

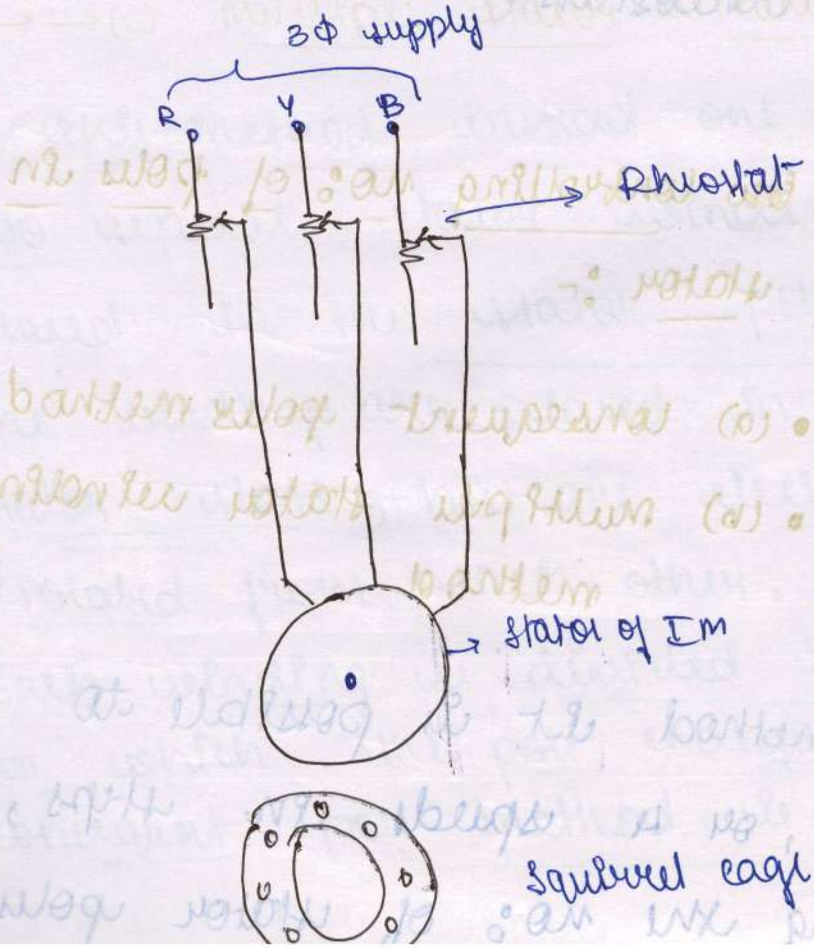
Slip increases means the motor reacts by running at lower speed.

→ In this method due to reduction in voltage, the current drawn by the motor increases

* Large change in voltage is necessary for small change in speed

* Additional voltage changing equipment is necessary.

• ⟶ → (iii) Adding rheostat in the stator circuit :-



- Reduced voltage can be applied to the stator by adding rheostat in the stator circuit.
- A part of the supply voltage gets dropped across the rheostat and in turn reduces the voltage applied to the stator.
- This causes a reduction in speed.

Disadvantage

- There are large power loss due to the rheostats.

-

↳ → (iv) ~~sta~~ controlling no: of poles in the stator :-

↳ → → (a) consequent poles method
↳ → → (b) multiple stator winding method

- In this method it is possible to have 1, 2, or 4 speeds in steps, by changing the no: of stator poles.

- A continous smooth speed control is not possible by this method.

↳ →→(a) consequent poles method:-

- In this method, connections of the stator winding are changed with the help of simple switching technique.
- Due to this, the no. of stator poles gets changed in the ratio 2:1
- Hence, either of the two synchronous speeds can be selected.

↳ →→(c) multiple stator winding method:-

- In this method instead one winding, two seperate stator windings are placed in the stator poles.
- The windings are placed in the same stator slots, but are electrically isolated from each other.
- Each winding is divided into coils to which the pole changing with consequent pole method is provided

consequent poles meth

multiple stator winding m

consequent poles method

consequent poles / multiple stator winding method

Limitations

1) can be applied to squirrel cage motors only

2) Smooth speed control is not possible, only steps changes in speed is possible

3) Two different stator windings are required to be wound, which increases the cost.

4) complicated design

~~L>(2) Rotor~~

2) Speed control from rotor side :-

(i) Adding external resistance to rotor circuit -

WKT

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

for low slip region

$$(S X_2) << R_2$$

$$T \propto \frac{S E_2^2 R_2}{R_2^2}$$

if E_2 is assumed to be constant for constant supply V_g

$$\boxed{T \propto \frac{S}{R_2}}$$

So As $R_2 \downarrow \rightarrow T \uparrow$

as $S \downarrow \rightarrow$ speed $\downarrow$

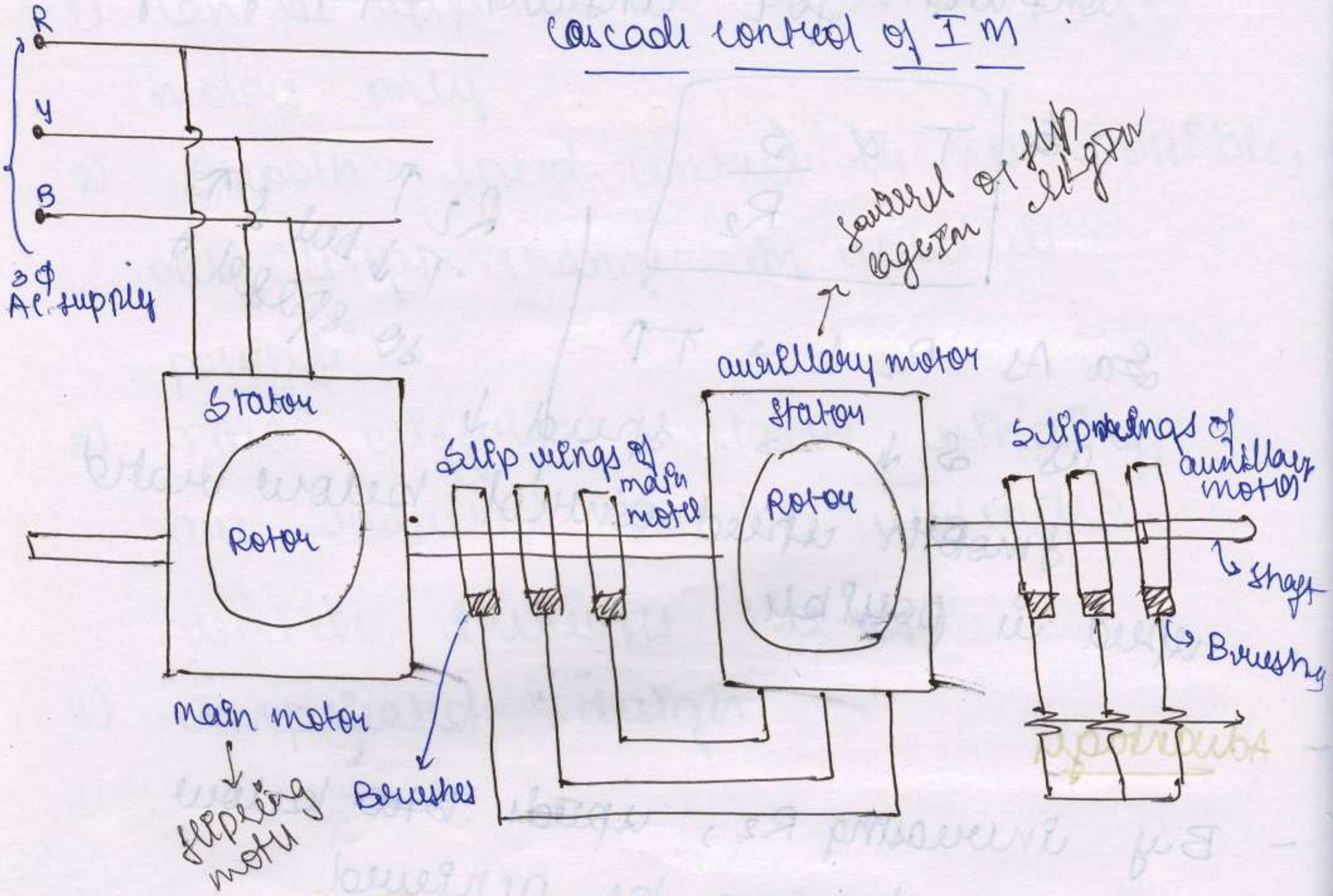
$R_2 \uparrow$
$T \downarrow$ but $S \uparrow$
so speed $\downarrow$

smooth speed control below rated speed is possible.

- Advantages
- By increasing R_2, speeds ~~bcho~~ below normal speed can be achieved
- The starting torque of the motor increases proportional to the increase in rotor resistance.

- Disadvantages
- Large speed changes are not possible
- cannot be used for squirrel cage ~~motor~~ IM
- Speed above normal speed cannot be achieved
- Large power loss due to I^2R losses
- Efficiency is low.

↳ → • (iii) Cascade control :-



- In this methods, 2 IM are mounted on the same shaft, first motor called the main motor is a slip ring IM.
- Second motor called Auxillary motor can be slip ring or squirrel cage IM

operation

- The supply to the main motor is from 3Φ line
- The supply to the auxillary motor is derived at a slip frequency from the slip rings of main motors.

- This is called cascading of motors
- If the torque produced by the motors act in the same direction, then the rotor resistance decreases and is called ~~the~~ cumulative ~~cascaded~~ cascading
- If the torque produced by the motors are in opposite direction then the rotor resistance increases called differential cascading

Let
P_A = no. of poles of the main motor
P_B = no. of poles of the auxillary motor
f = frequency of supply
f_A = frequency of ~~main~~ rotor induced emf of main motor
f_B = [frequency of rotor induced emf of auxillary motor] ×
|| (or) input frequency to the auxillary motor

i.e., $f_A = f_B$

N = speed of the ~~set~~ motor set

→ Synchronous speed of main motor

$$N_{SA} = \frac{120\,f_A}{}$$

$$N_{SA} = \frac{120 f}{P_A} \rightarrow (m)$$

Slip of main motor

$$\% S_A = \frac{N_{SA} - N}{N_{SA}} * 100$$

$N_{SA} = \frac{120 f}{P_A}$

$S_A = \frac{N_{SA} - N}{N_{SA}}$

$$S_A = \frac{N_{SA} - N}{N_{SA}} \rightarrow (1)$$

$f_A = S_A f$

$$f_A = S_A' f$$

$N_{B} = \frac{120 f_A}{P_B}$

w.KT

$= \frac{120 S_A f}{P_B}$

$$f_B = f_A = S_A f$$

$= \frac{120 f}{P}\left(\frac{N_{SA}}{}\right)$

→ Synchronous speed of auxillary motor:-

$= \frac{120 f}{P_A +}$

$$N_{SB} = \frac{120\,f_A}{P_B}$$

$$= \frac{120\,f_B}{P_B}$$

$$N_{SB} = \frac{120\,S_A f}{P_B} \rightarrow (2)$$

sub ① in ②

$$N_{sB} = \frac{120}{P_B}\left[\frac{N_{sA} - N}{N_{sA}}\right] f$$

under no load condition

$$N \simeq N_{sB}$$

$$N = \frac{120}{P_B} f \left[\frac{N_{sA} - N}{N_{sA}}\right]$$

$$= \frac{120 f}{P_B}\left[1 - \frac{N}{N_{sA}}\right]$$

ref. from (m)

$$N = \frac{120 f}{P_B}\left[1 - \frac{N}{\frac{120 f}{P_A}}\right]$$

simplifying

$$\boxed{N = \frac{120 f}{P_A + P_B}}$$

for cumulative cascading

$$\boxed{N = \frac{120 f}{P_A - P_B}}$$

for differential cascading

Thus the speed of 'N' is divided by total no: of poles equal to

$P_A + P_B$ for ~~com~~ cumulative cascading

$P_A - P_B$ for differential cascading

↳ → • (iii) <u>Injecting slip frequency voltage in the rotor circuit</u> :-

In this method voltage / emf having the slip frequency is injected into the rotor circuit.

- It is possible that the injected slip frequency voltage may oppose the rotor induced emf thus the effective rotor resistance increases

- If the injected slip frequency voltage assists or helps the rotor induced emf (in phase) then effective rotor resistance decreases

emf → Rotor induced emf
emf → external injected emf

control
↳ emf → control frequency injected emf → control resistance

→ varying resistance → varying / controlling speed

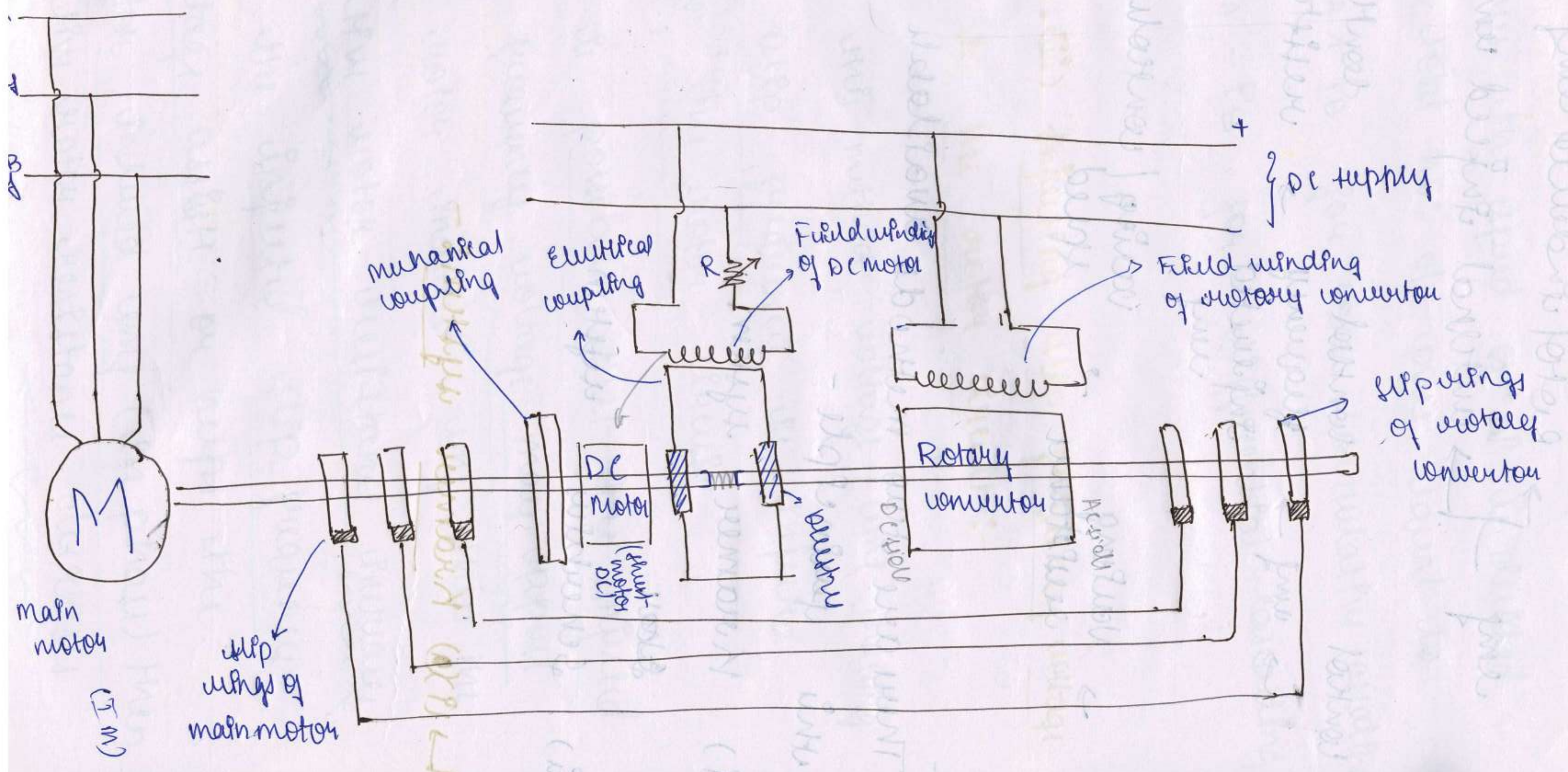
There are two methods available for this principle -

(i) Kramer system

(ii) ~~Scher~~ Scherbius system

↳ (i)(a) <u>Kramer</u> <u>system</u>:-

Kramer system



slip frequency emf is needed to be injured

slip rings of MM is connected to slip rings of RC

convertor → converts DC and AC

DC motor and RC are connected electrically

MM and DC motor are connected mechanically (coupling)

→ RMF is produced → rotor starts rotating

2 additional motors / equipment → cost is more

→ vary → R → rheostat → current changes (DC)

flux change → induced emf is produced

then given to RC through RC brushes

RC convert ~~AC~~ DC to AC

- Speed remains same throughout as in main motor

→ From RC → to slip ring goes to main motor so injecting frequency emf into the main motor

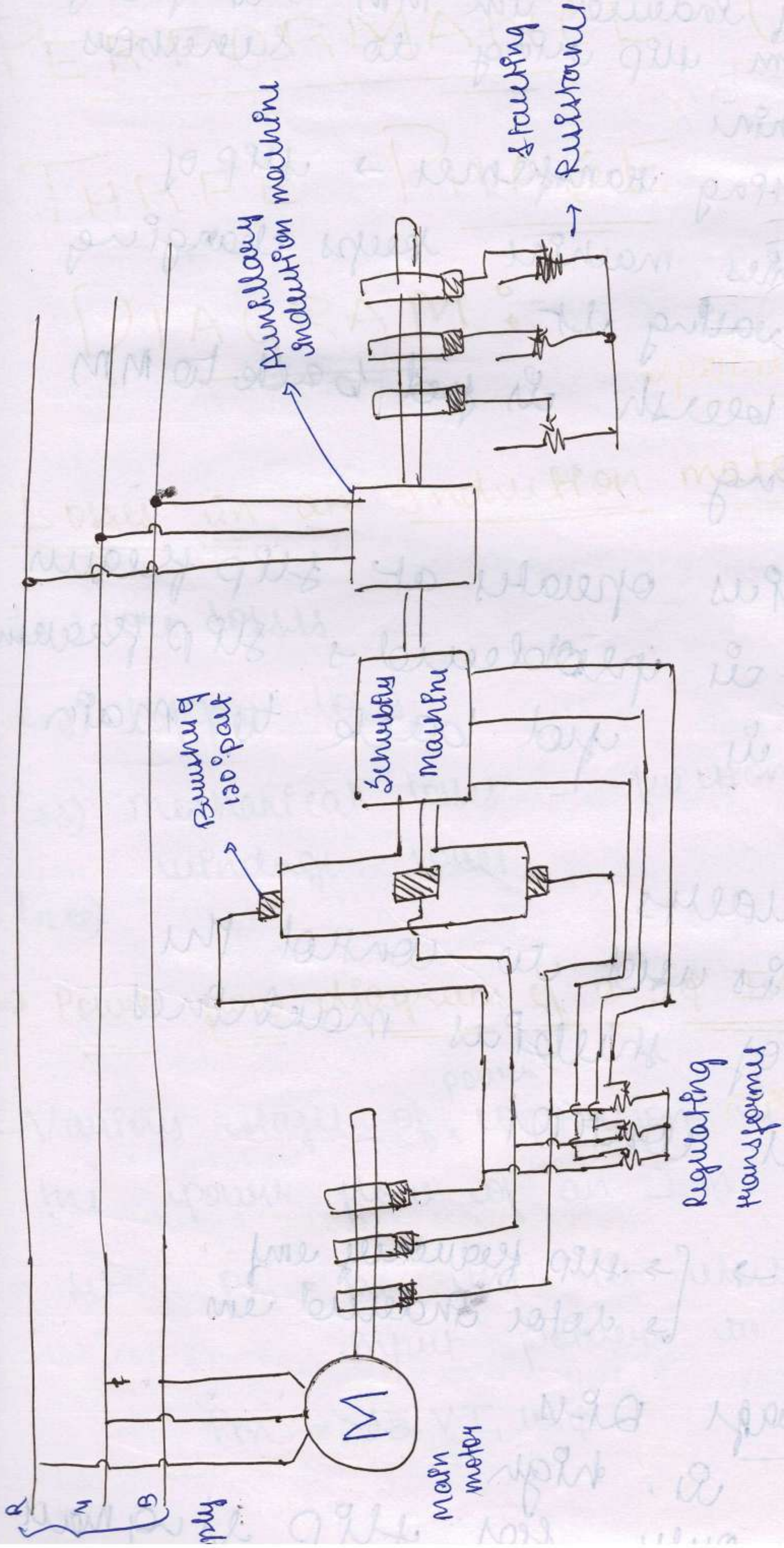
then → rotor induced emf } If these two → slip ring frequency } changes slip changes,

- Advantages
- Smooth speed control is possible
- Wide range of speed control is possible
- Design of rotary converter is independent of speed control.

- Disadvantages
1)- It can be used only ~~slip~~ for speed control slip ring IM
- To control the speed of 1 motor two additional equipments i.e., a DC shunt motor and a rotary converter is required which increases the overall cost.

- Application
- used for speed control of motors of 4000 KW in steel rolling ~~mot~~ mills

↳ (iii) • Scherbius system :-



→ 3ϕ AC supply → Main motor → (iii)

speed to be controlled

emf induced in MM → is fed

→ From slip ring to Scherbius machine

Regulating transformer → slip of Scherbius machine keeps changing by varying it

from brush is fed back to MM slip ring

Scherbius operates at slip frequency

→ emf is produced → slip frequency emf is fed back to main motor

→ Auxiliary

↳ is used to control the slip of Scherbius machines under control

at MM → [→ slip frequency emf
→ rotor induced emf

Disadvantages DPM

cost is high

used only for slip ring mach

→ MODULE - 3

PERFORMANCE OF THREE PHASE DIAGRAM :-

Losses in an Induction motor :-

↳ 1) core losses

↳ 2) copper loses

↳ 3) mechanical losses - friction and windage losses

↳ ~~4)~~

⇒ Power flow diagram of a 3Φ IM :-

- Various stages of power conversion is called the power flow of an IM.

- Let P_{in} = be the net electrical input power to the motor

$$P_{in} = \sqrt{3}\, V_L I_L \cos\phi$$

$P_{in} = \sqrt{3}\, V_L I_L \cos\phi$

where V_L = line voltage

I_L = line current

$\cos\phi$ = Power factor of the motor

This is nothing but stator input

- Part of this i/p power is utilised to supply the stator core loss as well as copper loss
- The remaining power is delivered to the rotor magnetically through the air gap with the help of RMF
- This is called rotor input power denoted by = P_2

$P_{in} \longrightarrow$ Stator cu/core loss $\xrightarrow{\text{remaining}}$ P_2 rotor)

P_{in} → loss (stator)
→ P_2 (rotor) remain

$P_2 = P_{in}$ − (stator core + stator copper loss)

$P_{in} = P_2$ + stator & Rotor cu losses

- The rotor is not able to convert its entire input (P_2) to mechanical power as has to supply rotor losses

- The rotor iron losses are very small because of rotor frequency (f_r) is very less

$f_r = s f$ → (very small) → { 'f' is in infraction value

- Thus effectively the rotor i/p (P_2) has to supply majorly the rotor copper losses only

- Thus rotor copper losses are given by

$P_c = 3 I_{2r}^2 R_2$ → (for slip ring only) ↳ due to R_2)

I_{2r} = rotor current under running

R_2 = Rotor resistance

$P_{in} = P_2 + \text{stator lo}$

$P_c = 3 I_{2r}^2 R_2$

$P_2 = P_m + P_c$

After supplying the rotor copper losses the remaining part of P_2 is converted into mechanical power called gross mechanical power developed by the motor denoted by P_m $\boxed{P_2 = P_c + P_c}$

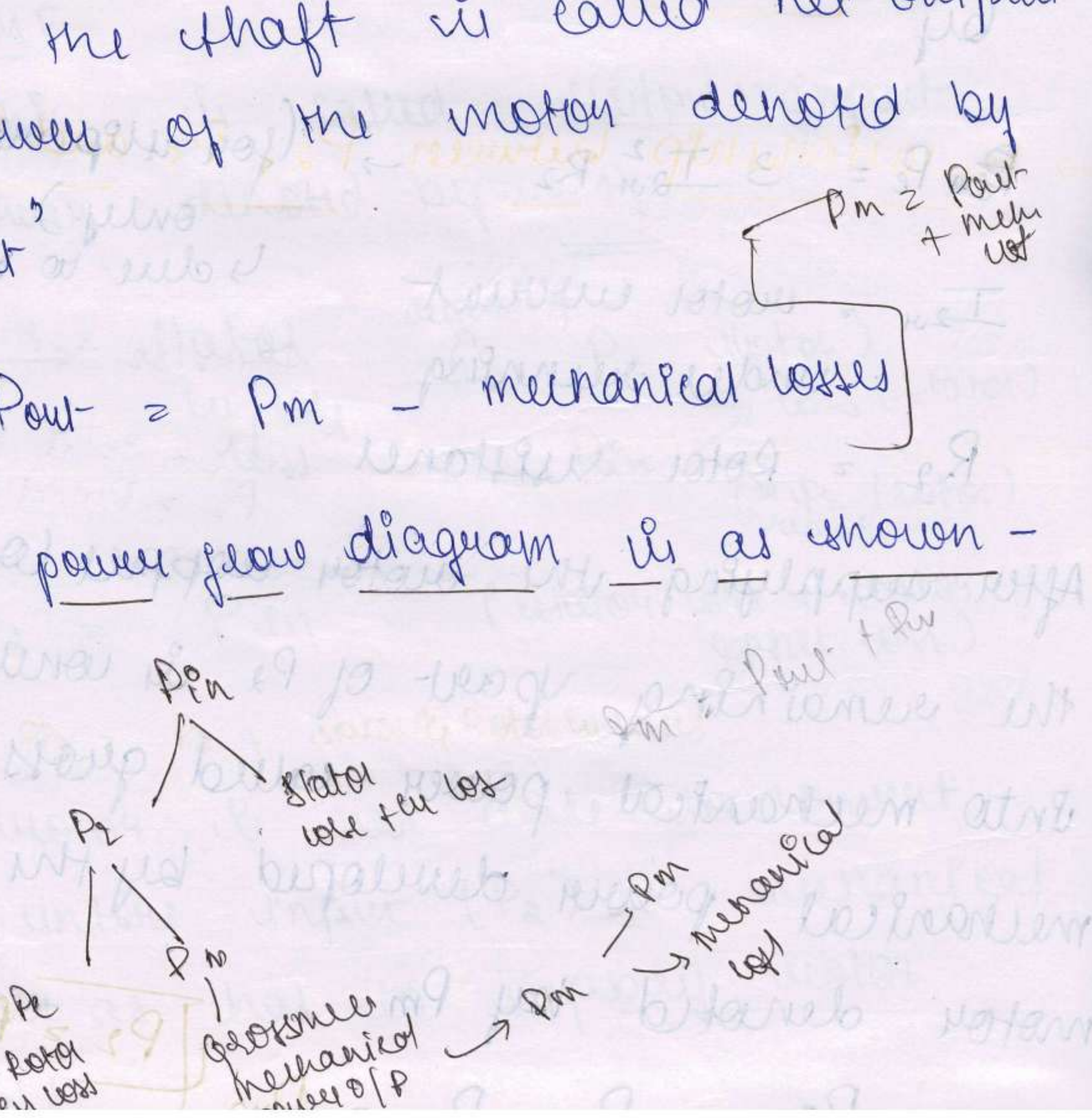
$= P_m$

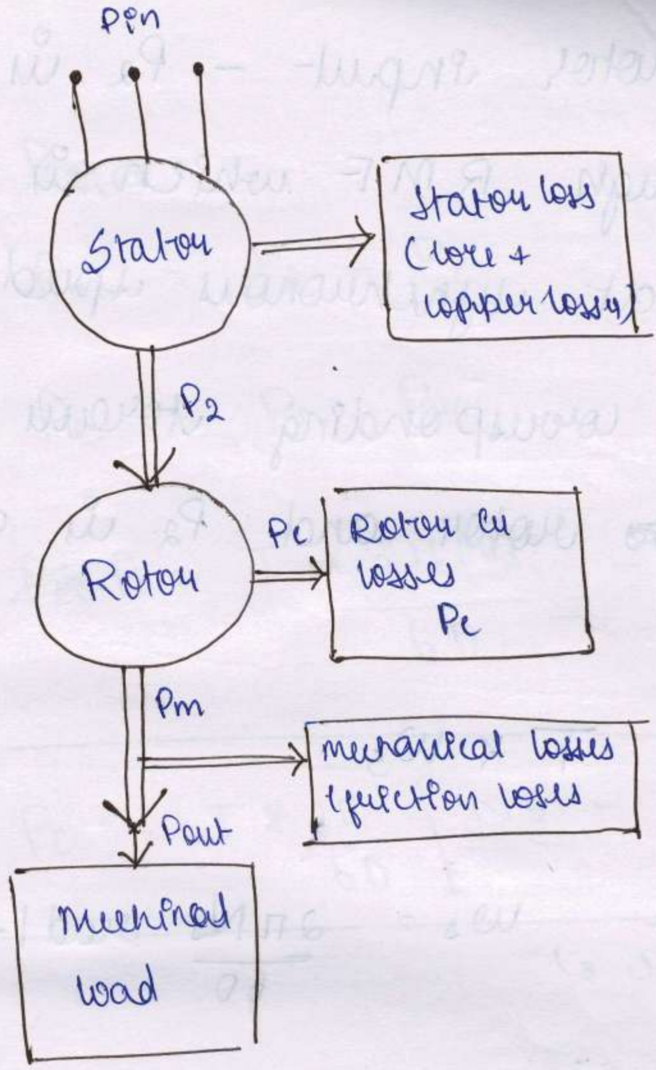
- This power Pm, the motor tries to deliver to the load connected via the shaft.
- But during this mechanical transmission, part of Pm is utilised to overcome the mechanical losses (Friction + windage).
- Finally the power available to the load at the ~~shaft~~ end of the shaft is called net output power of the motor denoted by 'Pout'.

Pm = Pout + mech lost

Pout = Pm − mechanical losses

* The power flow diagram is as shown -





P_{in}
$\downarrow$
P_2
$\downarrow$
P_c
$\downarrow$
P_m
$\downarrow$
P_{out}

→ Relationship between P_2, P_c and P_m :-

~~Rotor o/p~~

Let T = gross torque developed by the motor in N-m

W.K.T

$$P = T * \omega$$

where $\omega = \frac{2\pi N}{60}$ rad/sec

where N is in rpm

Now the rotor input - P_2 is

P_2 through RMF which is

rotating at synchronous speed N_s.

Thus the corresponding torque developed

by the ~~xx~~ rotor and P_2 is given

by

$$P_2 = T * \omega_s$$

where $\omega_s = \frac{2\pi N_s}{60}$ rad/sec

N_s = Ns in rpm

$$\therefore \boxed{P_2 = T * \frac{2\pi N_s}{60}} \rightarrow (1)$$

The motor tries to deliver this

torque to the load

Thus the rotor output Pm and

torque T is related by

$$Pm = T * \omega$$

$$\boxed{Pm = T * \frac{2\pi N}{60}} \rightarrow (2)$$

Now

~~Pme~~

$$P_m = P_2 - P_c$$

$$P_c = P_2 - P_m$$

$$\Rightarrow P_c = T * \frac{2\pi N_s}{60} - T * \frac{2\pi N}{60}$$

$$\boxed{P_c = T * \frac{2\pi}{60}\left[N_s - N\right]} \rightarrow ③$$

↳ rotor cu losses

Dividing eqn ③ by ①

$$\frac{P_c}{P_2} = \frac{\frac{T * 2\pi}{60}[N_s - N]}{\frac{T * 2\pi}{60} * N_s}$$

$$\frac{P_c}{P_2} = \frac{N_s - N}{N_s}$$

$$\frac{P_c}{P_2} = S \qquad \frac{P_c}{P_2} = S$$

$$\therefore \boxed{P_c = S P_2}$$

$P_2 =$

$P_2 = \frac{T \times 2\pi N_s}{60}$ $P_m = \frac{T \times 2\pi N}{60}$

$\Rightarrow N_s - N = P_c$

$P_m =$

$$P_m = P_2 - P_c$$

$$= P_2 - sP_2$$

$$\boxed{P_m = P_2(1-s)}$$

$$\boxed{\frac{P_m}{P_2} = (1-s)}$$

$$\therefore \quad \boxed{P_2 : P_c : P_m = 1 : s : (1-s)}$$

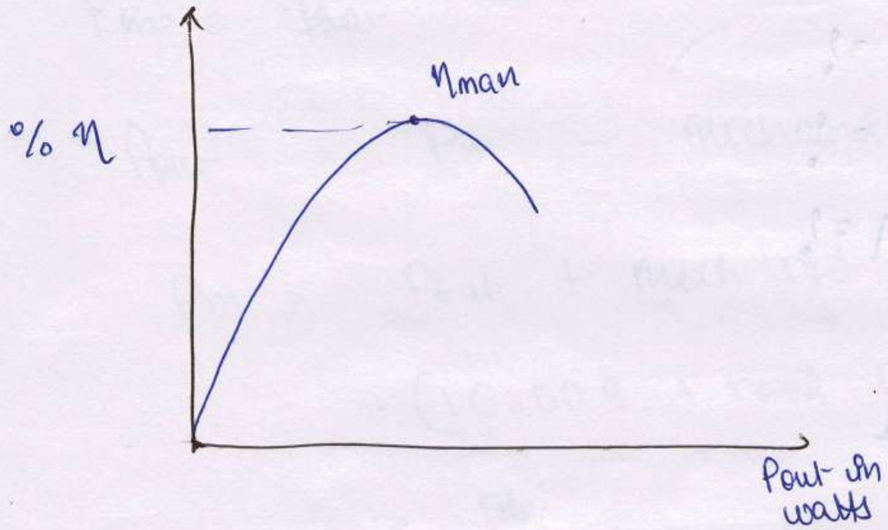
<u>Note:-</u>

The load torque is the net output torque or usefull torque given by

$$\boxed{T_{sh} = \frac{P_{out}}{\omega}} \quad N\text{-}m$$

⇒ <u>Efficiency</u> <u>of an</u> <u>induction</u> <u>motor</u>:-

$$\% \eta = \frac{P_{out}}{P_{in}} * 100$$



Q1) A six pole, 50Hz, 3φ IM, running on full load with 4% slip develops a torque of 149.3 N-m at its pulley rim ~~(****)~~. The friction and windage losses are 200 W, the stator copper and iron ~~***~~ losses are 1620 watt, calculate.

(i) O/P power

(ii) Rotor Cu losses

(iii) Efficiency at full load

Given

$P = 6$

$f = 50Hz$

$S = 4\% = 0.04$

T_{sh} = ~~****~~ pulley rim torque = 149.3 Nm

P_{fw} = 200 W = friction and windage losses

P_s = 1620 W = stator iron and Cu losses

To find :-

(i) $P_{out} = ?$

(ii) $P_c = ?$

(iii) $\%\eta = ?$

→ $N_s = \frac{120f}{P}$

$= \frac{120 * 50}{6}$

$= 1000$ rpm

→ $s = \frac{N_s - N}{N_s}$

$N = N_s - s N_s$

$= 1000 - 0.04 * 1000$

$= 960$ rpm

→ $P_{out} = T_{sh} * \omega$

$= 149.3 * \frac{2\pi * 960}{60}$

$= \underline{\underline{15.009 \text{ KW}}}$

$P_c = \frac{s}{1-s}$

$= 0.$

~~Rne~~ = ~~Pout~~

from powerflow diagram

$P_{out} = P_m$ − mechanical loss

$P_m = P_{out}$ + mech loss

$= (15.009 + \cancel{1} \; 0.2)$ KW

$= \cancel{15}.$

$P_m = \underline{15.209 \text{ KW}}$

→ $\dfrac{P_c}{P_m} = \dfrac{s}{1-s}$

$P_c = 15.209 \times \dfrac{0.04}{1 - 0.004}$

$= 0.6337$ KW

$P_c = 633.7$ watts

→ $\% \eta = \dfrac{P_{out}}{P_{in}} \times 100$

$P_2 = P_{in}$ − stator iron / cu loss

$P_{in} = P_2 +$ cu loss

$\dfrac{P_2}{P_c} = \dfrac{1}{s}$

$$P_2 = \frac{P_c}{s}$$

$$= \frac{633.7}{0.04}$$

$$= \underline{15.84 \text{ KW}}$$

$$P_{in} = (15.84 + 1.62) \text{ KW}$$

$$= \underline{\underline{17.46 \text{ KW}}}$$

$$\% \eta = \frac{15.009}{17.46} * 100$$

$$= \underline{\underline{85.96\%}}$$

Q2) A 6 pole 3ϕ IM develops 30 HP including mechanical losses of 2 HP at a speed of 950 rpm on 550 V, 50 Hz supply. Power factor is 0.58. Calculate for this load

(i) Slip

(ii) Rotor copper loss

(iii) Total i/p if stator losses are 2000 W

(iv) The efficiency

(v) The line current

Soln

$P = 6$

$P_{out} = 30$ HP

$= 30 \times 735.5$

$= 22065$ watts

$f = 50$ HZ

$N = 950$ rpm

mechanical losses $= 2$ HP

$= 2 \times 735.5$

$= 1471$ watts

$V_L = 550$ V

$\cos\phi = 0.58$

stator loss $= 2$ KW

To find :-

(i) $s = ?$

(ii) $P_c = ?$

(iii) $P_{in} = ?$

(iv) $\% \eta$

(v) I_L

(vi) f_r

$\rightarrow$ $N_s = \frac{120 f}{P}$

$= \frac{120 \times 50}{6}$

$= 1000$

$\rightarrow$ ~~$S = N_s(1-s)$~~

$= 1000(1-$

$\rightarrow \quad s = \dfrac{N_s - N}{N_s}$

$= \dfrac{1000 - 950}{1000}$

$s \rightarrow \underline{0.05}$

$\rightarrow$ Pe

P_m = Pout + Mech loss

$= 22065 + 1471$

$\rightarrow \underline{23.536 \text{ KW}}$

$\rightarrow \dfrac{P_e}{P_m} = \dfrac{s}{1-s}$

$P_e = \dfrac{(0.05)(23.536)}{(1 - 0.05)}$

$= \underline{1.238 \text{ KW}}$

$\rightarrow$ Pin = P_2 + cu loss

$P_2 = \dfrac{P_e}{s}$

$= 24.076$

$P_{in} = 24.076 + 2$

$= \underline{26.076 \text{ KW}}$

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$

$$= \frac{22.065}{26.76} \times 100$$

$$\% \eta = \underline{\underline{82.45 \%}}$$

$\rightarrow$ $P_{in} = \sqrt{3}\, V_L\, I_L \cos\phi$

$$I_L = \frac{P_{in}}{\sqrt{3}\, V_L \cos\phi}$$

$$= \frac{26774.6}{\sqrt{3} \times 550 \times 0.58}$$

$$= \underline{\underline{48.45\ A}}$$

$\rightarrow$ $f_r = s f$

$$= 0.05 \times 50$$

$$= \underline{\underline{2.5\ Hz}} = \underline{\underline{2.5\ cycles/sec}}$$

$$= 2.5 \times 60\ cycles/min$$

$$f_r = \underline{\underline{150\ cycles/min}}$$

Q3) A 25 KW, 4 pole, 3 phase 50 Hz IM is running at 1410 rpm supply full load. The mechanical losses are 850 W and stator losses are 1.7 times rotor cu loss on full load.

Calculate

(i) Gross mechanical power developed

(ii) rotor copper loss

(iii) Value of rotor resistance / phase if the rotor current on full load / phase is 65 A

(iv) Full load efficiency

Soln Given

~~Pgen~~ = 25 KW = Pout

P = 4

f = 50 Hz

N = 1410 rpm

Mech loss = 850 W

stator loss = 1.7 * cu loss

To find

- Pm
- P.c
- R
- η

$$N_s = \frac{120f}{P}$$

$$= \frac{120 \times 50}{4}$$

$$= 1500 \text{ rpm}$$

$$S = \frac{1500 - 1410}{1500}$$

$$= 0.06$$

P_m = Pout + mech loss

$= (25 + \cancel{\quad} 0.85)$ KW

$= \cancel{25}$.

$= 25.85$ KW

$\Rightarrow \frac{P_c}{P_m} = \frac{S}{1-S}$ $\quad [P_2 : P_c : P_m = 1 : S : 1-S$

$$P_c = \frac{25.85 \times 0.06}{1-0.06}$$

$$= 1.65 \text{ KW}$$

$$\Rightarrow P_c = 3 I_{2r}^2 R$$

$\rightarrow \quad R_2 = \dfrac{P_c}{3 I_{2r}^2}$

$= \dfrac{1650}{3 \times (65)^2}$

$= \cancel{0.195\,\Omega} \quad \underline{\underline{0.130\,\Omega}}$

$\rightarrow \quad \eta = \dfrac{P_{out}}{P_{in}} \times 100$

$P_{in} = P_2 + Cu\ loss$

$P_2 = \dfrac{P_c}{s}$

$= \cancel{26.75}$

$= 27.5\ KW$

stator loss $= 1.7 \times Cu\ loss$

$= 1.7 \times P_c$

$= 1.7 \times 1650$

$= 2805$

$= 2.805\ KW$

$P_{in} = 27.5 + 2.805$

$= 30.30$

$$\% \eta = \frac{P_{out}}{P_{in}} \times 100$$

$$= \frac{25}{30.3} \times 100$$

$$= 82.49 \%$$

→ Equivalent circuit of a 3Φ IM:-

- 3Φ IM can be treated as a ~~generated~~ generalised transformer

- If E_1 = emf induced in stator per phase

E_2 = Rotor induced emf ~~on~~ per phase on standstill

transformation ratio $K = \cancel{\frac{\text{stator turns}}{\text{rotor turns}}}$

$$K = \frac{\text{rotor turns}}{\text{stator turns}}$$

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

If V_1 is the supply voltage per phase given to the stator, it produces the flux (RMF) which links with both stator and rotor

In running condition E_2 becomes E_{2r}

$$E_{2r} = sE_2$$

Now E_{2r} = rotor induced emf ~~per~~ in running condition per phase

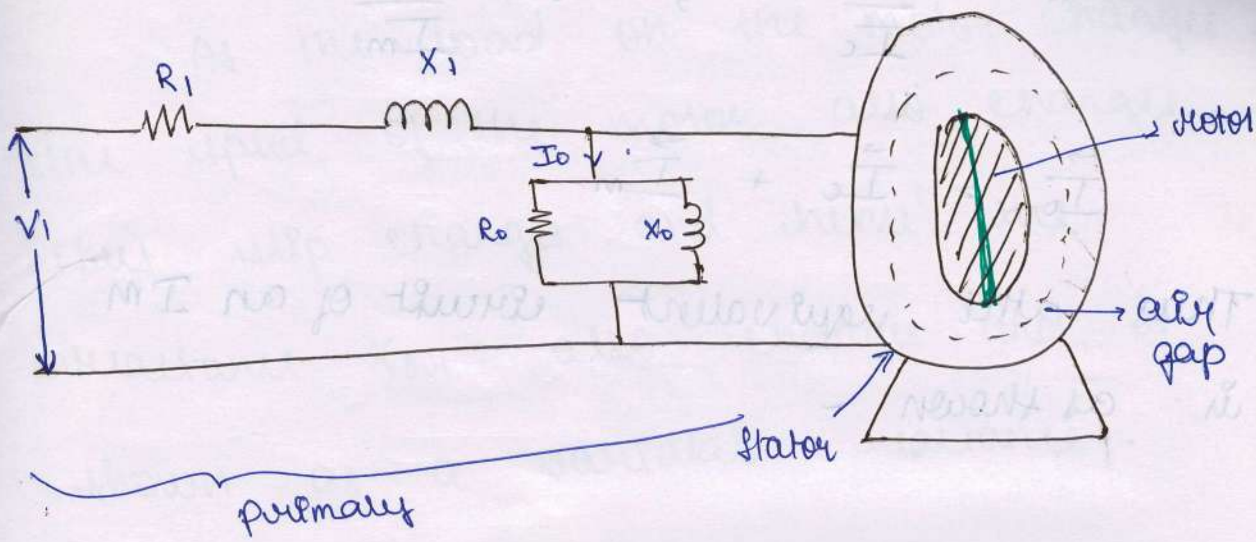
R_2 = rotor resistance per phase

X_{2r} = rotor reactance per phase in running condition.

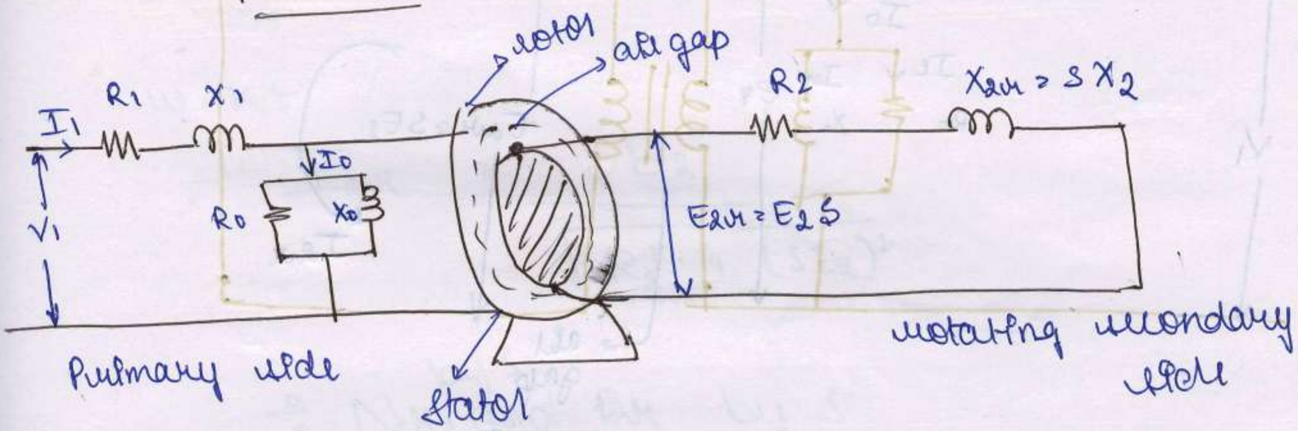
R_1 = stator resistance per phase

X_1 = stator reactance per phase

Thus the induction motor can be represented as a transformer, as shown.



Induction motor as transformer



→ Note :-

- When IM is on no load, it draws current from the supply to produce the flux in air gap and to supply iron losses.
- This current I_0 has two ~~mag~~ components I_m and I_c

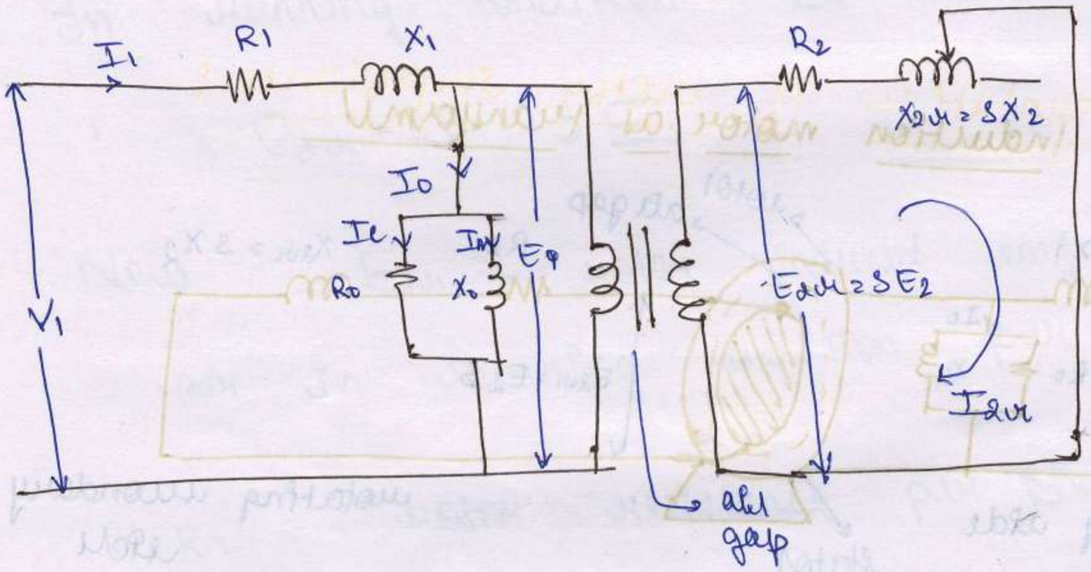
  I_m = magnetising component which ~~supplies~~ ~~sets~~ sets up the flux in the core and air gap

  I_c = active component which supplies

$$R_0 = \frac{V_1}{I_c} \; ; \; X_0 = \frac{V_1}{I_m}$$

$$\vec{I_0} = \vec{I_c} + \vec{I_m}$$

Thus the equivalent circuit of an IM is as shown -



<u>Basic</u> <u>equivalent</u> <u>circuit</u>

Rotor current in running condition is given by -

$$I_{2r} = \frac{E_{2r}}{Z_{2r}}$$

$$= \frac{E_{2r}}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$= \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \text{ Amp}$$

Note :-

As the load on the motor changes, the speed of the motor also changes, Thus slip changes and hence the reactance X_{2r} also changes and is shown as a variable reactance.

—

Representation of rotor impedance :-

w.r.t

$$I_{2r} = \frac{sE_2}{\sqrt{R_2^2 + (sE_2)^2}}$$

$I_{2r} = \frac{sE_2}{\sqrt{(R_2)^2 + (sE_2)^2}}$

∴ Nr by s and Dr by s^2

I_2

$$I_{2r} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2 + \left(\frac{sE_2}{s}\right)^2}}$$

$$\boxed{I_{2r} = \frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2 + (X_2)^2}}}$$

Thus it is assumed that the equivalent rotor ~~____~~ has a fixed reactance X_2, fixed voltage E_2 but a variable resistance $\frac{R_2}{s}$

Now $\frac{R_2}{s}$ can be written as

$$\frac{R_2}{s} = R_2 + \frac{R_2}{s} - R_2$$

$$= R_2 + R_2\left[\frac{1}{s} - 1\right]$$

$$\boxed{\frac{R_2}{s} = R_2 + R_2\left[\frac{1-s}{s}\right]}$$

The variable rotor resistance $\frac{R_2}{s}$ has two parts

(i) Rotor resistance R_2 itself which represents copper loss

(ii) $R_2\left(\frac{1-s}{s}\right) = R_L$ which represents the load resistance R_L which is called electrical equivalent of mechanical load on the motor.

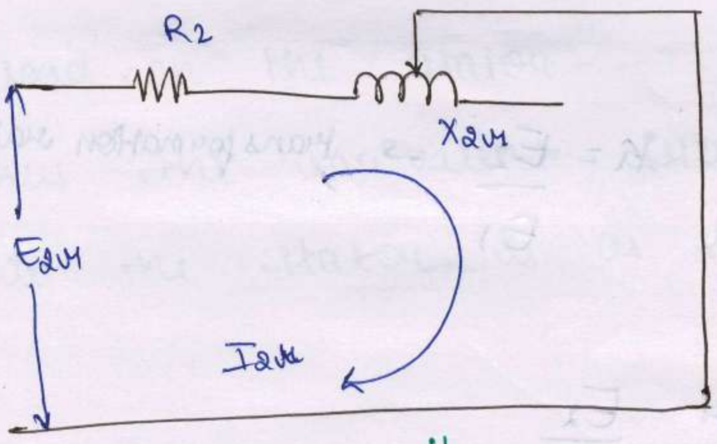
[X_{ar} = armature reaction reactance]

Note :- $R_L = R_2\left(\frac{1-s}{s}\right)$

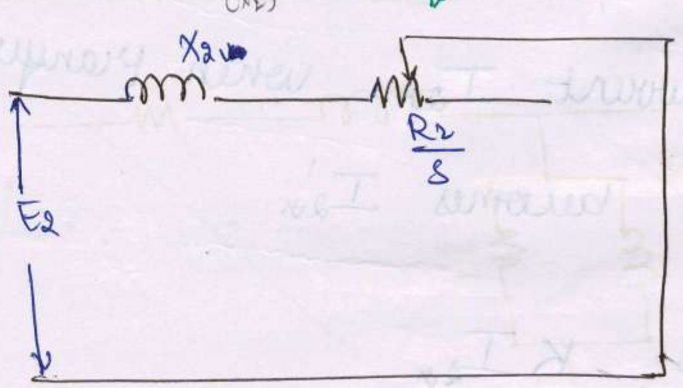
The mechanical load on the motor is represented by the fictitious resistance R_L

$$R_L = R_2\left(\frac{1-s}{s}\right)$$

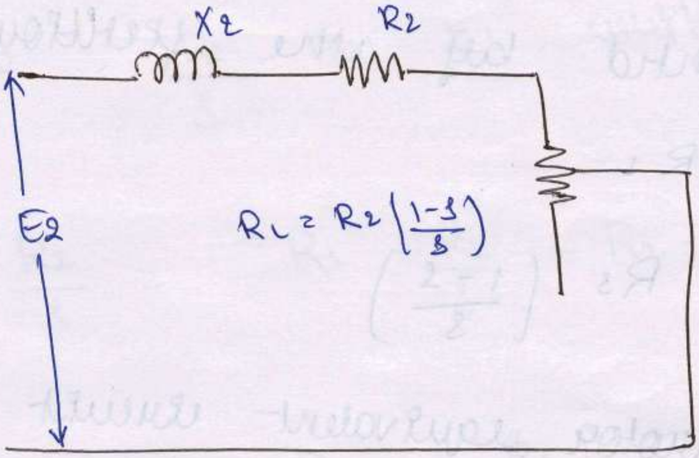
$\Rightarrow$ Thus the motor equivalent circuit can be shown as



$\Downarrow$



$\Downarrow$



⟹ Equivalent circuit reffered to stator :-

Transfer all the rotor parameters to the stator w.r.t

$K = \frac{E_2}{E_1}$ → transformation ratio

$\therefore \quad E_2' = \frac{E_2}{K}$

The rotor current I_{2r} when transferred to the stator becomes I_{2r}'

$$I_{2r}' = K I_{2r}$$

$$= \frac{K \, s \, E_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$R_2' = \frac{R_2}{K^2}$$

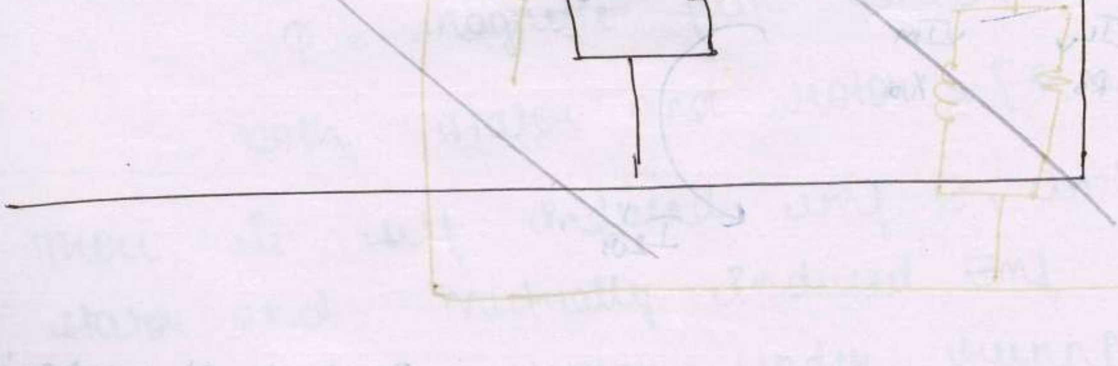
$$X_2' = \frac{X_2}{K^2}$$

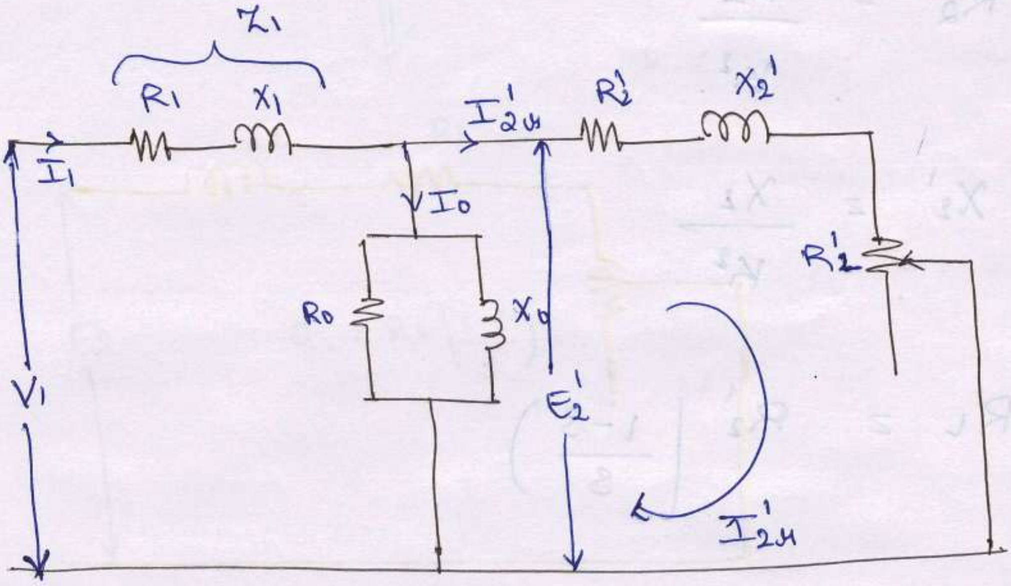
$$R_L = R_2'\left(\frac{1-S}{S}\right)$$

$$R_L = \frac{R_2}{K^2}\left(\frac{1-S}{S}\right)$$

Thus R_L' is the referred mechanical load on the stator

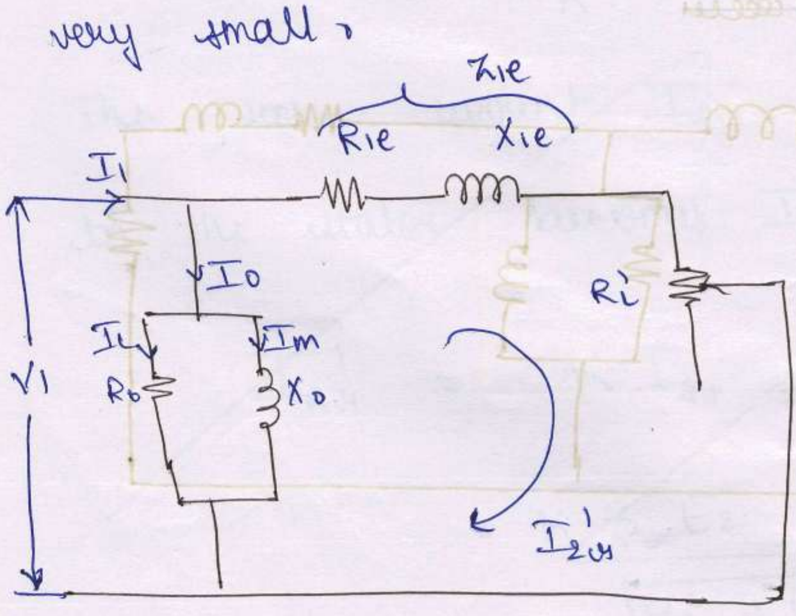
Thus the equivalent circuit referred to the stator is as shown -





Approximate equivalent circuit :-

By shifting the exciting ~~ckt~~ circuit [R_0 and X_0] to the left of R_1 and X_1 we get the approximate equivalent circuit. Due to this, we are neglecting the drop across R_1 and X_1 due to I_0 which is very small.



R_L = electrical equivalent of mechanical ... fictitious resistance

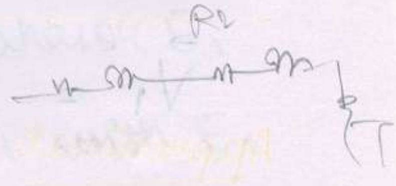
R_{1e} = equivalent resistance refferred to stator

$$R_{1e} = R_1 + R_2'$$

X_{1e} = equivalent reactance refferd to stator

$$X_{1e} = X_1 + X_2'$$

$$\boxed{\vec{I}_1 = \vec{I}_0 + \vec{I}_{2r}'}$$



where

$$\boxed{\vec{I}_0 = \vec{I}_c + \vec{I}_m}$$

$$\boxed{Z_{1e} = R_{1e} + j X_{1e}}$$

→ Phasor diagram of induction motor :-

- Phasor diagram of loaded IM is similar to a loaded transformer.

- Let

ϕ = magnetic flux which links both stator and rotor = [RMF]

There is self induced emf E_1 in the stator and mutually induced Emf E_{2r} in the rotor under running

Let R_1 = stator resistance / phase

X_1 = stator reactance per phase

The supply voltage V_1 has to overcome self induced emf E_1 and also supply voltage drops $I_1 R_1$ and $I_1 X_1$

$$\vec{V_1} = -\vec{E_1} + \vec{I_1} R_1 + \vec{I_1} X_1$$

$$\vec{V_1} = -\vec{E_1} + \vec{I_1}(R_1 + jX_1)$$

$$\vec{V_1} = -\vec{E_1} + \vec{I_1} Z_1$$

rotor induced emf in running condition has to supply drop across impedance as the rotor is short circuit.

$$\therefore \vec{E}_{2r} = \vec{I}_{2r} R_2 + \vec{I}_{2r} X_{2r}$$

$$\vec{E}_{2r} = \vec{I}_{2r}(R_2 + j X_{2r})$$

$$\vec{E}_{2r} = \vec{I}_{2r} Z_{2r}$$

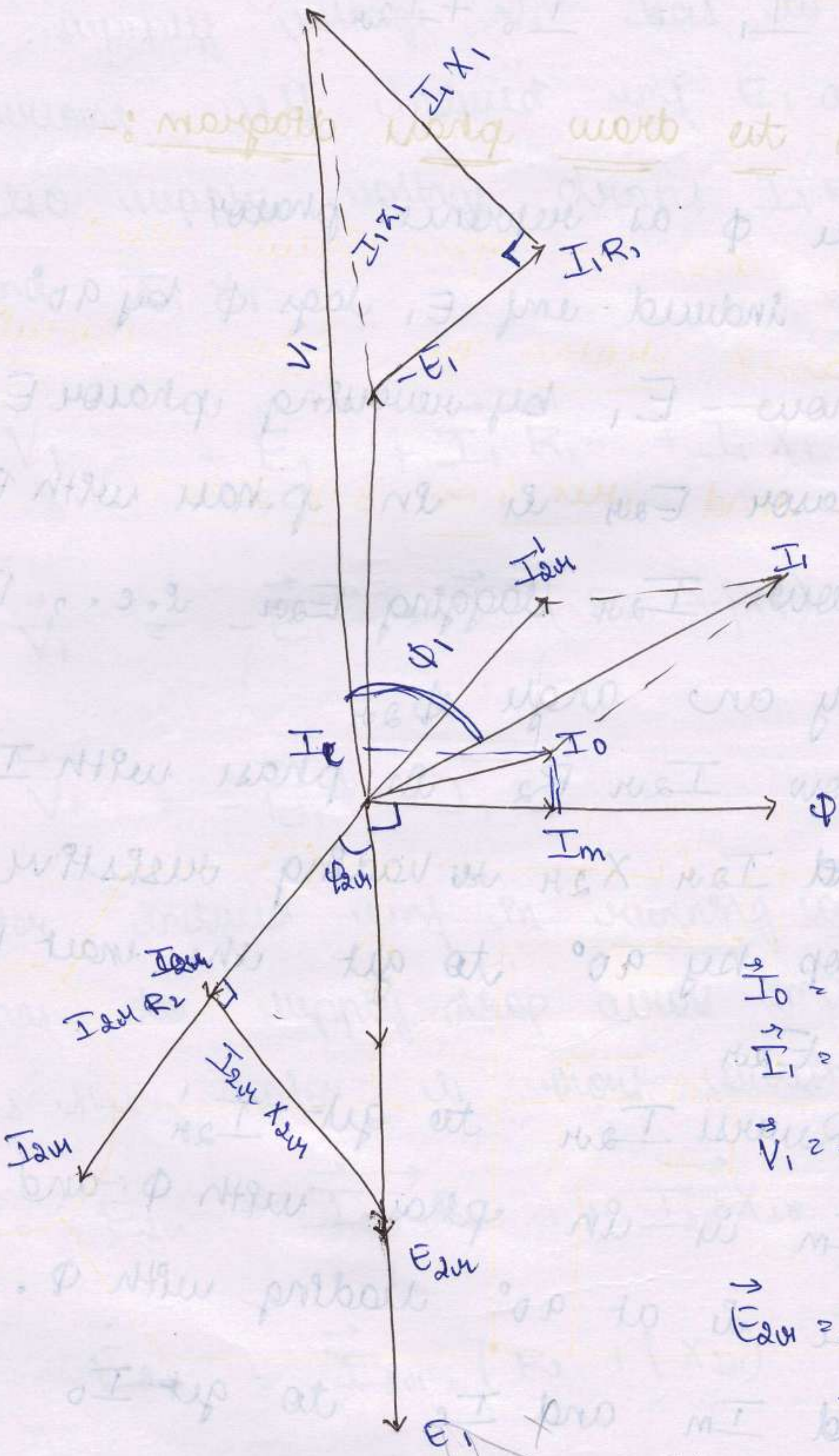
$$I'_{2r} = K I_{2r}$$

$$\vec{I}_1 = \vec{I}_0 + \vec{I}'_{2r}$$

→ **Steps to draw phasor diagram :-**

- take ϕ as reference phasor
- The induced emf E_1 lags ϕ by $90°$
- Show $-E_1$ by reversing phasor E_1
- Phasor E_{2r} is in phase with E_1
- Show I_{2r} lagging E_{2r} i.e., E_1 by an angle ϕ_{2r}
- Show $I_{2r} R_2$ in phase with I_{2r} and ~~and~~ $I_{2r} X_{2r}$ ~~to~~ leading resistive drop by $90°$ to get the exact location of E_{2r}
- Reverse I_{2r} to get I'_{2r}
- I_m is in phase with ϕ and I_c is at $90°$ leading with ϕ.
- Add I_m and I_c to get I_0
- Add I_0 and I'_{2r} to get I_1
- From the tip of -1, add $I_1 R_1$ in phase with I_1 and $I_1 X_1$ at $90°$ leading to I_1 to get

- Angle b/w V_1 and I_1 is ϕ_1

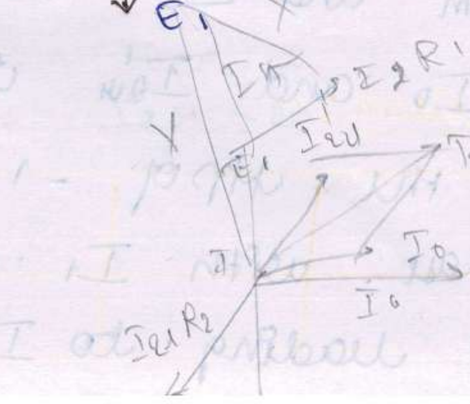


$\vec{I_0} = \vec{I_e} + \vec{I_m}$

$\vec{I_1} = \vec{I_0} + \vec{I}'_{2r}$

$\vec{V_1} = -\vec{E_1} + \vec{I_1} R_1 + \vec{I_1} X_1$

$\vec{E_{2r}} = \vec{I_{2r}} R_2 + \vec{I_{2r}} X_{2r}$



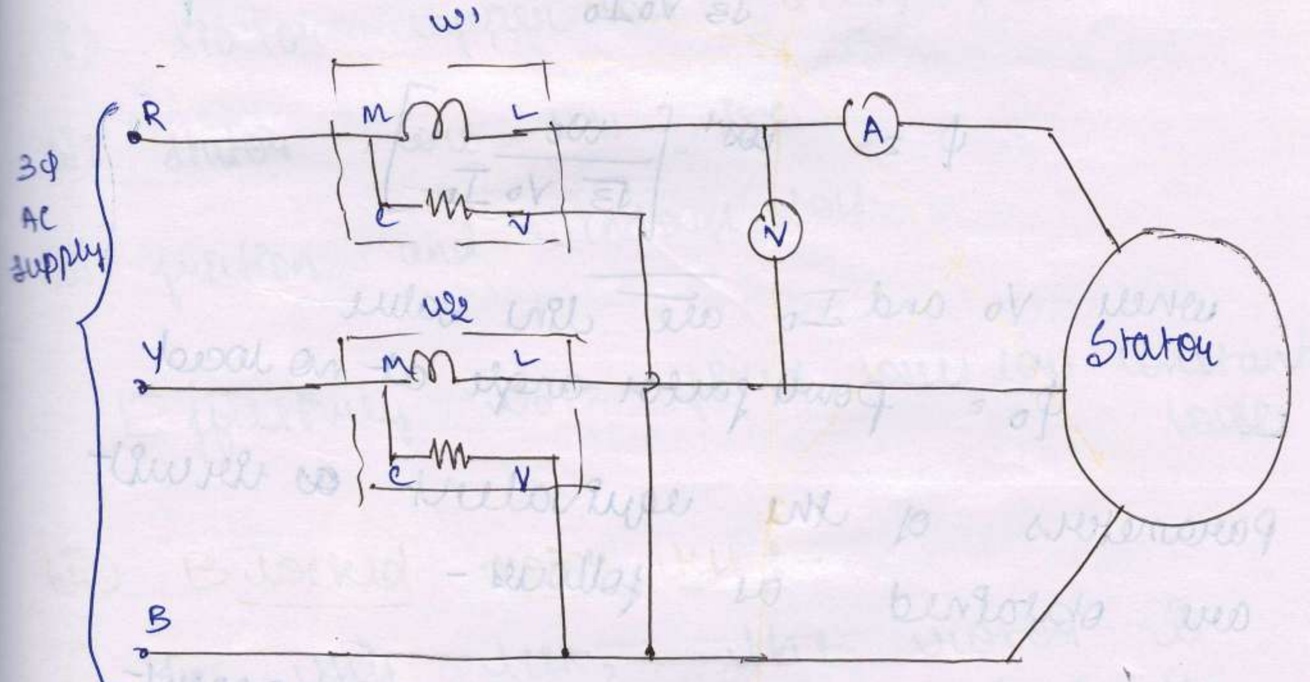
→ Circle diagram of a 3Φ IM :-

- To plot the circle diagram of 3Φ IM, two tests are conducted

(i) No load (or) open circuit test :-

(ii) Block rotor (or) Short circuit test :-

(i) No load test on 3Φ IM :-



Tabular colum :-

S.No.	V_0 (Volt)	I_0 (Amps)	W_1 (watts)	W_2 (watts)	$W_0 = W_1 + W_2$ (watts)
1)	400				

If pf is low → reactive power is more

draws ↓

on no load is very low

↳ Im draws reactive pow

↳ wattmeter measures only active power

∴ wattmeter kickback

∴ interchange I and V

↳ so LPF wattm is used

↳ on no load pf is low

→ Calculations are :-

1) No load power

$$W_0 = \sqrt{3}\, V_0 I_0 \cos\phi_0 \text{ watts}$$

$$\cos\phi_0 = \frac{W_0}{\sqrt{3}\, V_0 I_0}$$

$$\phi = \cos^{-1}\left[\frac{W_0}{\sqrt{3}\, V_0 I_0}\right]$$

where V_0 and I_0 are line value

ϕ_0 = power factor angle at no load

Parameters of the equivalent circuit are obtained as follows -

$I_c = I_0 \cos\phi_0$ → active component of the no load current

$I_m = I_0 \sin\phi_0$ → reactive component of the (or) magnetising component of no load current.

$$R_0 = \frac{V_0}{I_c}$$

$$= \frac{V_0}{I_0 \cos\phi_0}$$

$$X_0 = \frac{V_0}{I_m}$$

$$= \frac{V_0}{I_0 \sin\phi_0}$$

The no load input W_0 consists of

i) stator copper loss i.e., $3 I_0^2 R_1$

ii) stator core loss ire

iii) friction and windage loss

Effectively W_0 = fixed losses (or) constant losses

(ii) Blocked rotor test :-

In this test, the rotor is blocked manually and is not allowed to rotate

Then $S = 1$ (maximum)

$$\therefore \quad R_L' = R_2' \left(\frac{1-S}{S}\right)$$

$\therefore R_1' = R_2' \left(\frac{1}{\cancel{s}} - 1\right)^0$ at $s = 1$

$R_1' = R = 0$

~~If~~ This test is similar to short-circuit test on a transformer when supply is switch on and rated current is passed ~~it~~ through the IM at a reduced voltage.

Let V_{sc} = ~~volts~~ short circuit reduced voltage (line value)

I_{sc} = short circuit current (or) rated current (line value)

W_{sc} = short circuit i/p power

$W_s = \sqrt{3}\, V_{sc} I_{sc} \cos\phi_{sc}$ watts

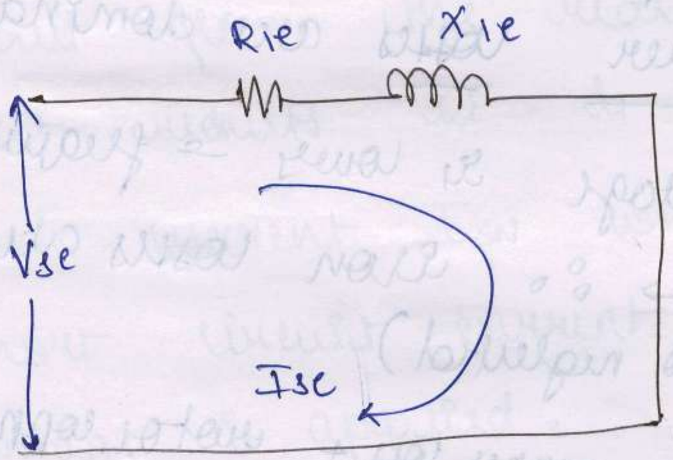
$$\cos\phi_{sc} = \frac{W_{sc}}{\sqrt{3}\, V_{sc} I_{sc}}$$

$$\therefore \phi_{sc} = \cos^{-1}\left[\frac{W_{sc}}{\sqrt{3}\, V_{sc} I_{sc}}\right]$$

~~V_{sc}~~ ϕ_{sc} is short circuit power factor angle

Sl. No.	Vsc (volt)	Isc (Amps)	W1 (watts)	W2 (watts)	Wsc = W1 + W2
		Rated			

equivalent circuit is as shown -



$W_{sc} = 3 I_{sc}^2 R_{1e}$ [R_{1e} consuming power]

$$\boxed{R_{1e} = \frac{W_{sc}}{3 I_{sc}^2} \ \Omega/\text{ph}}$$

R_{1e} = equivalent resistance referred to stator

$$Z_{1e} = \sqrt{R_{1e}^2 + X_{1e}^2}$$

$$X_{1e} = \sqrt{Z_{1e}^2 - R_{1e}^2}$$

Note

During this test the stator carries rated current and thus stator copper losses are dominant. Similarly rotor also carries short circuit component and thus rotor copper losses are dominant.

↳ applied voltage is low → flux is low → ∴ iron losses are low (so neglected)

W_{sc} = stator copper loss + rotor copper loss (variable losses)

I_{sc} → short circuit current at reduced voltage

I_{SN} → " " at full rated voltage

8/5/2017

It is necessary to obtain short circuit current when normal rated voltage is applied to the motor, this is practically not possible.

But from the reduced voltage test results it is possible to find current I_{SN} which is short circuit current when normal voltage is applied.

If

V_L = normal rated voltage (line value)

V_{SC} = reduced short circuit voltage

then $$\boxed{I_{SN} = I_{SC} * \left(\frac{V_L}{V_{SC}}\right)}$$

Now power input is proportional to the ~~~~ current to the square of the current

$$\boxed{W_{SN} = \left(\frac{I_{SN}}{I_{SC}}\right)^2 * W_{SN}} \quad \text{watts}$$

W_{SN} = core losses + Stator copper loss

+ Rotor copper loss

→ Construction of circle diagram :-

~~By~~ ~~to~~

By using the data obtained from no load and blocked diagram circle diagram can be constructed using following steps -

1) Take reference phasor V as reference axis

2) Select suitable current scale such that the diameter of the circle is 20 - 30cms

From no load test I_0 and ϕ_0 are obtained

3) Draw vector I_0, lagging V by an angle ϕ_0 this is line OO'

4) Draw horizontal through extremity of I_0 i.e., at DO' parallel to x axis

5) Draw the current ~~Esn~~ I_{SN} calculated from I_{sc} with the same scale lagging V by an angle ϕ_{sc} from the origin O

This is phase O A

6) Join O'A called the output line

7) Draw a $\perp$r bisector of O'A extended to meet the line drawn $\parallel$el to x axis at point C. This is the centre of the circuit

8) With C as centre radius = O'C draw the semi circle which meets the horizontal line ~~p~~ ~~drawn~~ drawn $\parallel$el ~~to~~ x axis at point B

9) Draw a $\perp$r from point A on the x axis to be O'B at point F and D the x axis at point B

10) Construction of torque line.

~~Construction~~

- Construction of torque line

- Length AD represents the power input at short circuit W_{SN}

- Now FD represents fixed losses

∴ length of (AF) ∝ (stator cu loss + Rotor cu loss)

Then point E can be located as follows

(i) <u>Slip ring IM</u>

In slip ring IM stator and rotor currents can be measured using ammeters

If I_1 = stator current

I_2 = rotor current

$K = \frac{I_1}{I_2}$ - transformation ratio

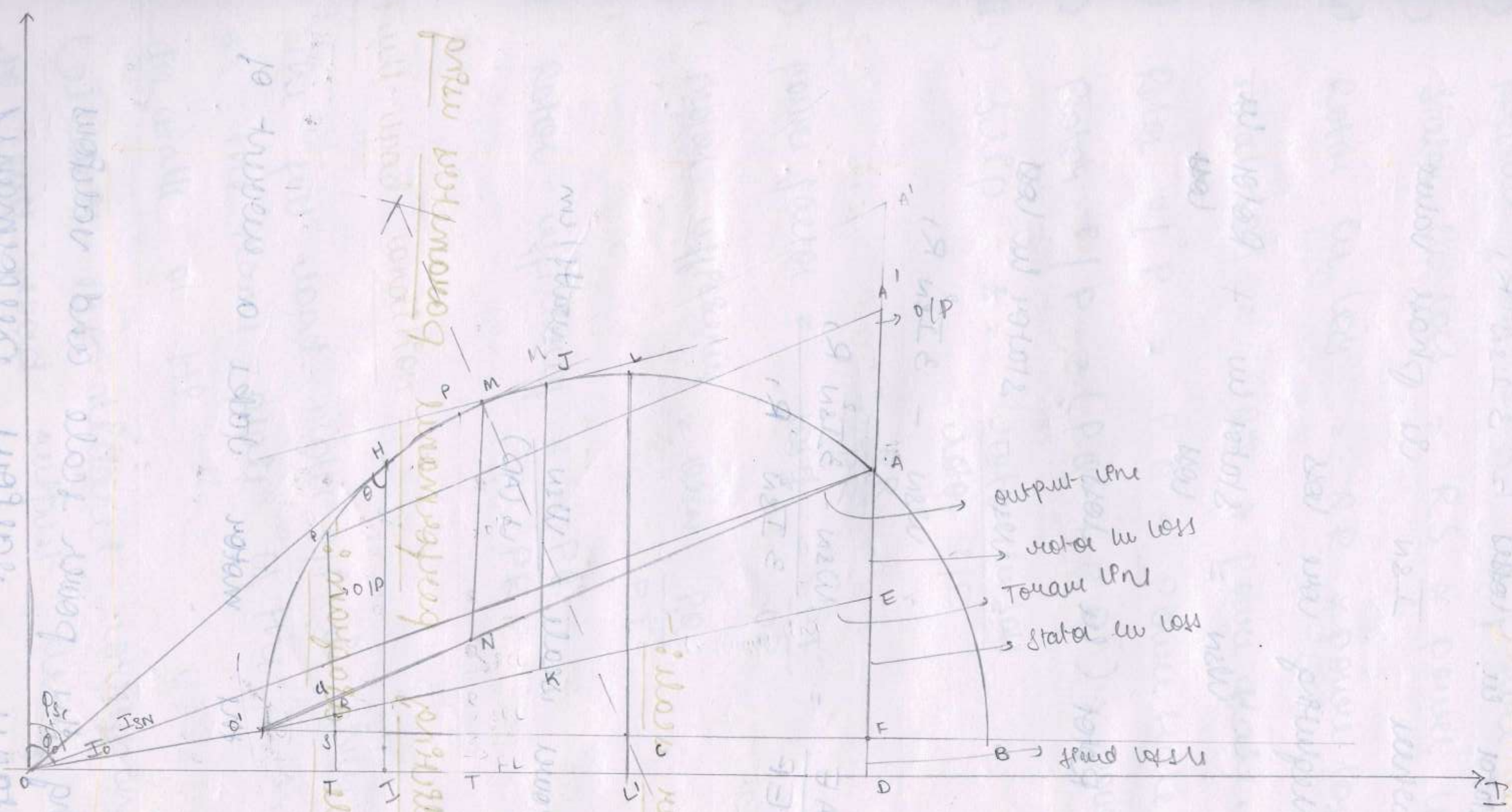
∴ Assuming O'E represents the torque line

Now $\frac{AE}{EF} = \frac{\text{rotor cu loss}}{\text{stator cu loss}} = \frac{I_2^2 R_2}{I_1^2 R_1}$

$= \frac{R_2}{R_1}\left(\frac{I_2}{I_1}\right)^2 = \frac{R_2}{R_1} \times \frac{1}{K^2}$

$= \frac{R_2'}{R_1}$ ~~at~~ w.r.t $\left[R_2' = R_2 / K^2 \right]$

Thus point E is obtained by dividing the line in the ratio R_2' / R_1



V
I
O
O'
A
A'
B
C
D
E
F
H
I
J
K
L
M
N
P
Q
R
S
T
U
ϕ_{sc}
ϕ_0
I_0
I_{SN}
O/P
output line
rotor cu loss
Torque line
stator cu loss
fixed losses
FL

(iii) Squirrel cage IM:-

stator cu losses $= 3 I_{sN}^2 R_1$

where I_{sN} is phase value

Neglecting core loss

$$W_{sN} = \text{stator cu loss} + \text{Rotor cu loss}$$

∴ Rotor cu loss

$$= W_{sN} - \text{stator cu loss}$$

$$= W_{sN} - 3 I_{sN}^2 R_1$$

$$\therefore \frac{AE}{EF} = \frac{W_{sN} - 3 I_{sN}^2 R_1}{3 I_{sN}^2 R_1}$$

Power scale:-

$$\text{Power scale} = \frac{W_{sN}}{l(AD)} \text{ watts/cm}$$

Predicting performance parameters using circle diagram:-

Let the motor take a current of OP

Using the power scale and various distance, various performance parameters can be obtained

i) Total motor i/P PT * power scale

ii) Fixed loss = ST * power scale

iii) Stator cu loss = RS * power loss

iv) Rotor cu loss = QR * power loss

v) Total loss = QT * power scale.

vi) Rotor o/P = PQ * power scale

vii) Rotor i/P = (PQ + QR) * power scale

viii) Slip $s = \frac{\text{rotor cu loss}}{\text{rotor i/P}}$

$= \frac{QR}{PR}$

(ix) power factor = $\cos\phi = \frac{PT}{OP}$

(x) motor efficiency = $\frac{PQ}{PT}$

(xi) Rotor efficiency = $\frac{PQ}{PR}$

→ Full load condition -

The full load motor o/P is given on the name plate of the IM in watts or HP

Calculate the distance corresponding to full load output using the power scale.

Extend AD ~~upto~~ upwards from A equal to the distance corresponding to full load O/P i.e., A'

Draw parallel to the O/P line O'A from ~~a~~ A' to meet the circle at point P

Q1) Draw a circle diagram for a 20HP, 50 Hz, 3 ϕ star connected IM with the following data

(i) No load test :- 400V, 9 A, 0.2 pf lag

(ii) Blocked motor test :- 200V, 50 A, 0.4 pf lag

Determine the line current, efficiency and slip for full load condition from the circle diagram.

Soln

$\cos\phi_0 = 0.2$

$\phi_0 = 78.46^\circ$, $I_0 = 9$ A, ~~V0 = 400V~~

$\cos\phi_{sc} = 0.4$

$\phi_{sc} = 66.42^\circ$, $I_{sc} = 50$A, ~~Vsc = 200V~~

$$I_{SN} = \frac{I_{SC} * V_L}{V_{SC}}$$

$$= \frac{50 * 400}{200}$$

$$\underline{I_{SN} = 100A}$$

$$W_{SC} = \sqrt{3}\, V_{SC}\, I_{SC} \cos\phi_{SC}$$

$$= \sqrt{3} * 200 * 50 * 0.4$$

$$= 6928.20\,W$$

$$W_{SN} = \cancel{\cos}\; W_{SC}\left(\frac{I_{SN}}{I_{SC}}\right)^2$$

$$= \cancel{692.80}\; 6928.20\left(\frac{100}{50}\right)^2$$

$$W_{SN} = \underline{27712.81 \text{ watts}}$$

(or)

$$W_{SN} = \sqrt{3} * \cancel{100}\, V_L\, I_{SN} \cos\phi_{SC}$$

$$= \sqrt{3} * 400 * 100 * \cancel{\cos}\, 0.4$$

$$= \underline{27712.81 \text{ watts}}$$

Power scale = $\frac{W_{SN}}{l(AD)}$

$= \frac{27712.81 \times}{8.6}$

$= 3222.41$ watts / cm

Full load o/p = 20 HP = 20×735.5

= 14710 W

$= \frac{14710}{}$

= 4.56 cm = A'

$l(OP)$ = 6.5 cm $\times 5$ = 32.5 A

= full load line current

pf = power factor = cos (angle angle by OP w.r.t y axis)

= cos (29)

= 0.8746 lag

$\eta = \frac{PQ}{PS} = \frac{4.7}{\cancel{5.105}} = \frac{4.7}{5.7} \times 100$

= 82.54

$$\text{Slip} = \frac{QR}{PR} = \frac{0.65}{5.3} * 100$$

$$= \underline{\underline{12.22\ \%}} = \underline{\underline{0.1222}}$$

~~To determine various maximum quantities from generalised circle diagram~~

<u>To</u> <u>determine</u> <u>various</u> <u>maximum</u> <u>quantities</u> <u>from</u> <u>generalised</u> <u>circle</u> <u>diagram</u>:-

(i) Max O/P :-

Draw a line ∥el O'A which is also tangent to the circle at point M

The max O/P is given by l(MN) at power scale.

(ii) Max I/P :-

It occurs on the highest point on the circle i.e., point U

Max i/p is given by

l (LL') at power scale.

(iii) Max torque :-

Draw a line parallel to the torque line which is also tangent to the circuit at point J.

l (JK) = represents the max torque in synchronous watts at the power scale.

(iv) Max power factor :-

Draw a line tangent to the circle from the origin O meeting the circle at point H.

Drop a ⊥r from H on the x axis untill point I

~~For~~ maximum pf = cos ∠OHI

(or) $\frac{HI}{OH}$

Q1) Draw the circle diagram ~~for~~ from no load and short circuit test of a 3ϕ ~~[illegible]~~ 14.92 KW, 400V, 6 pole IM with the following test data (line value).

No load :- 400V, 11A, 0.2 pf (lag)

SC test :- 100V, 25A, 0.4 pf (lag)

The rotor cu loss at standstill is half the total cu losses. From the diagram find - line current, slip, efficiency, power factor at full load, max torque.

Soln

$\cos\phi_0 = 0.2$

$\phi_0 = 78.46^\circ$

$I_0 = 11A$

$\cos\phi_{sc} = 0.4$

$\phi_{sc} = 66.42^\circ$

$I_{sc} = 25A$

$$I_{SN} = \frac{I_{sc} * V_L}{V_{SC}}$$

$$= \frac{25 * 400}{100}$$

$$= 100\,A$$

$$W_{SC} = \sqrt{3}\, V_{sc}\, I_{sc} \cos\phi_s$$

$$= \sqrt{3} * 100 * 25 * 0.4$$

$$= \underline{1732.05\,W}$$

$$W_{SN} = \sqrt{3}\, V_L\, I_{SN} \cos\phi_{sc}$$

$$= \sqrt{3}\; 400 * 100 * 0.4$$

$$= \underline{27712.81\,W}$$

$$\text{Power scale} = \frac{W_{SN}}{l(AD)} = \frac{27712.81}{8.4}$$

$$= \underline{3299.14 \text{ watt/cm}}$$

Full load O/P = 14.92 KW

~~AOC~~

$$I (AA') = \frac{\text{Full load O/P}}{\text{Power scal}}$$

$$= \frac{14.92 * 10^3}{3299.14}$$

$$= 4.52 \text{ cm}$$

$$I (OP)' = 6.445$$

$$= \underline{\underline{32A}}$$

$$pf = \cos(32')$$

$$= \underline{\underline{0.8480 \text{ lag}}}$$

$$\text{slip} = \frac{QR}{PR}$$

$$= \frac{0.25}{5.2}$$

$$= 0.048 = \underline{\underline{4.80\%}}$$

$$\eta = \frac{PQ}{PT}$$

$$= \frac{4.45}{5.4} * 100$$

$$= \underline{\underline{82.40\%}}$$

u (J K) = 8.5

= 8.5 * 3299.14

= 28.042.69

= ~~28 K~~

= 28.042 syn watts

[synchronous watts]

Q2) 50 KW, 6 poles, 50 HZ, 450 V, 3φ

Im gave the following test results

(i) No load test :- 450 V, 20 A, 0.15 pf lag

(ii) SC test :- 200 V, 150 A, 0.3 pf lag

The ratio of stator to rotor cu loss is 5 : 4. Draw a circle diagram and determine

(i) full load current and pf
(ii) max torque and max power i/p
(iii) slip at full load
(iv) Efficiency on full load

$\cos\phi_0 = 0.055$

$\phi_0 = \cancel{80}^\circ\ 81.37^\circ$

$\cos\phi_{sc} = 0.3$

$\phi_{sc} = 72.54$

$I_{SN} = \dfrac{I_{sc} * V_L}{V_{sc}}$

$= \dfrac{150 * 450}{200}$

$= 337.5 A$

$W_{sc} = \sqrt{3}\, V_{sc}\, I_{sc} \cos\phi_1$

$= \sqrt{3}\ 200 * 150 \times \cancel{\cos}\ 0.3$

$= 15,588.45\, W$

$W_{cN} = \sqrt{3}\ V_L\ I_{SN} * 0.3$

$= 78916.56\, W$

power scale $= \dfrac{W_{SN}}{l(AD)} = \dfrac{7891605.6}{4.85}$

$= 16271.45\ w/cm$

Full load O/P = 50 KW

$l(AA')$ =

$$\frac{\text{stator cu loss}}{\text{Rotor cu loss}} = \frac{\cancel{5}}{\cancel{4}} \frac{4}{\cancel{5}} \frac{5}{4} = \frac{EF}{AE}$$

~~1.25~~ =

1.25 AE = EF

AF = AE + EF

AF = AE + 1.25 AE

= 2.25 AE

(or) $AE = \frac{AF}{2.25}$

$= \frac{4.65}{2.25}$

= 2.066 cm

Power scale = $\frac{50 \times 10^3}{16271.45}$

= 3.07 cm

$I(OP) = 3.6$ cm

$= 3.6 \times 5.0$

$= 18$ A

$pf = \cos(.18)$

$l(OP) \ast$ curr scale

$LOP' = \; A$

$\cos\phi =$

Max torque $JK = 5.6$ cm

↳ in syn w

$= 103.98 \times 10^3$

Max i/p $\Rightarrow L - L'$

26.9

$l(LL') \ast$ Power scale

$=$ Max i/p 125.12 Kw

slip $\frac{QR}{PV} = 3.44\%$

P

$= 90.3$

MODULE - 5

SYNCRONOUS MOTORS

alternator → field winding / rotor winds

→ given DC supply →

single phase

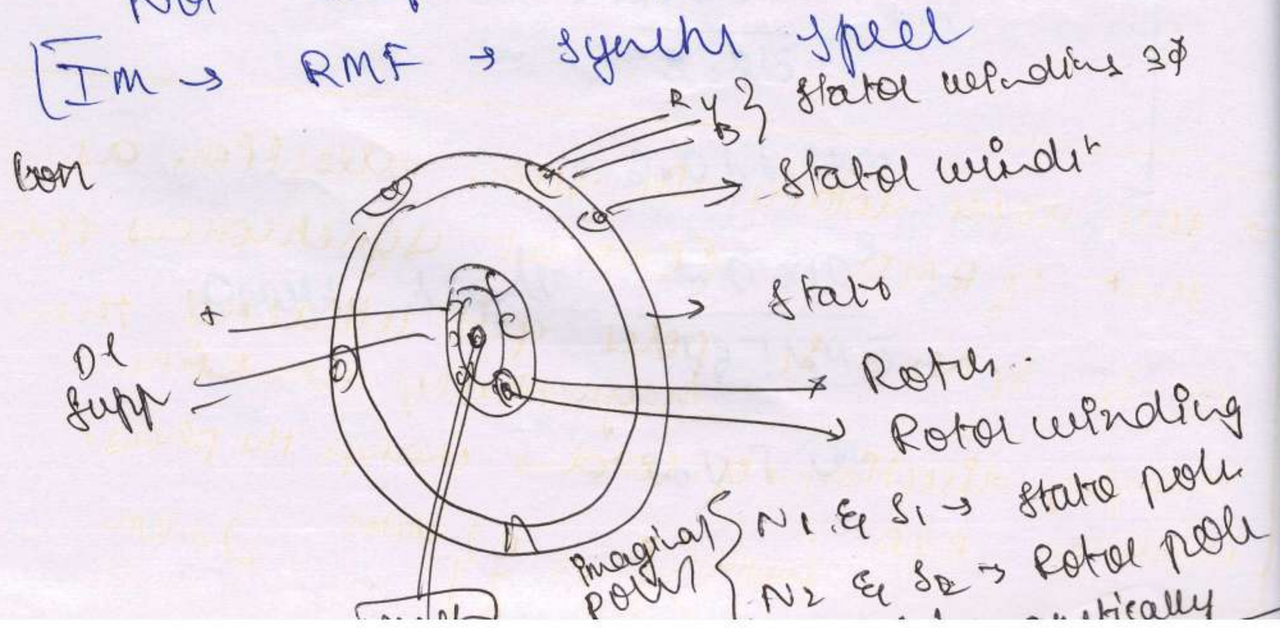
↳ mechanical to electrical energy conversion

synchronous motor (or) generator remains same

↳ working on the principle of magnetic locking

Not self starting

[IM → RMF → synchr speed



→ construction of synchronous motor - 3Φ :-

Two major parts are

stator and ~~#~~ rotor

~~rod~~

rotor -

- → Salient pole rotor
- → Non salient pole rotor

If an alternator (3Φ synchronous generator) is run as a motor, it will rototate at synchronous speed and is called synchronous motor

The speed at which RMF rotates is given by -

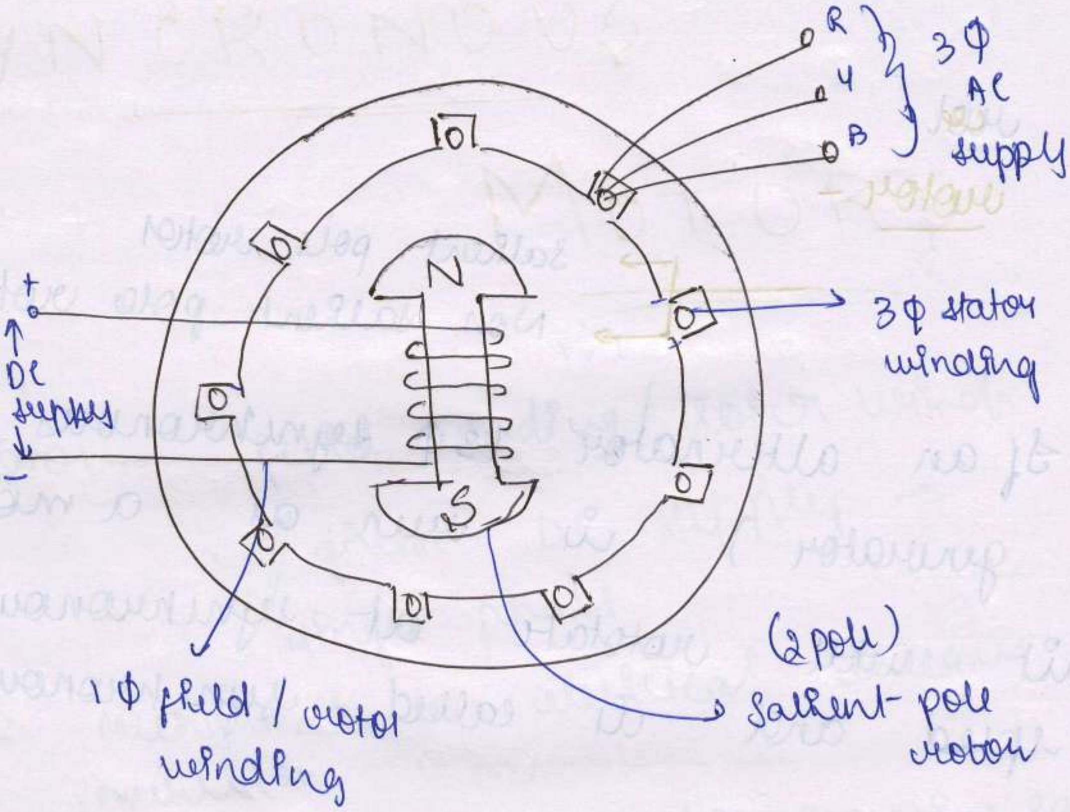
$$N_s = \frac{120 f}{P} \text{ rpm}$$

→ then rotor rotates in same direction as that of RMF (RMF at synchronous speed) $N_1 - S_2$ & $N_2 - S_1$ poles gets attracted. then magnetically locked

changing direction → of rotor → change the phase sequence RYB

supply $\left\{\begin{matrix} R \\ Y \\ B \end{matrix}\right. \Rightarrow \left.\begin{matrix} R \\ Y \\ B \end{matrix}\right\}$ stator) → RM

→ Schematic representation of 3 ϕ synchronous motors :-



90% rotor are salient pole rotor.

It contains 1 ϕ field winding + DC supply using slip rings

(DC supply → (station) → rotor (rotating) → so through slip ring)

stator → is supplied by 3 ϕ AC supply and it produces RMF

→ Working principle :-

- Works on the principle of magnetic locking

- To have magnetic locking there must exist two unlike poles and the magnetic axis of the two poles must be brought very close to each other.

- Assume the stator is wound for 2 poles (say) with 50 Hz supply.

- Let these two ~~pole~~ stator poles be N_1 and S_1 which are rotating at a speed of N_s (rpm)

- Assume the direction of rotation of RMF as clock wise

- ~~Then~~ Assume when the field / rotor winding is excited by a DC supply, it also produces two poles,

- Let these two rotor poles be N_2 and S_2

At standstill N_1 S_1 are rotating at N_s rpm

N_2 S_2 are ~~at~~ zero

If by somehow methods N_1 gets attracted to S_2 and N_2 get attracted to S_1 then magnetic locking takes place and N_2 S_2 starts rotating at synchronous speed.

At start / beginning when mechanical load is applied momentarily it get reduced and still maintains synchronous speed

Synchronous motor will never rotate in any other speed other than synchronous. (It is effect of RMF that is considered as 2 pole N_1 & S_1)

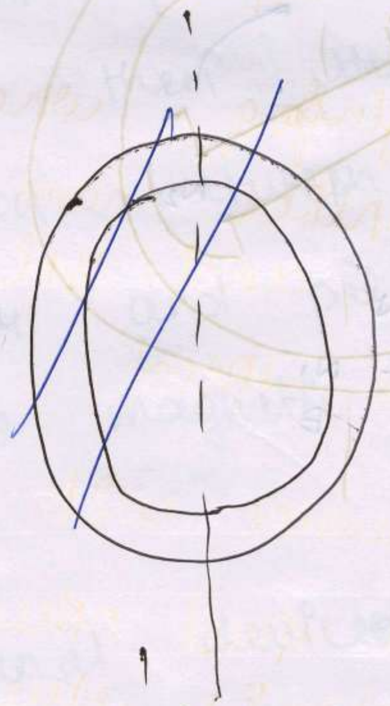
⇒ Synchronous motor is not self ~~stato~~ starting.

Consider the RMF is equal

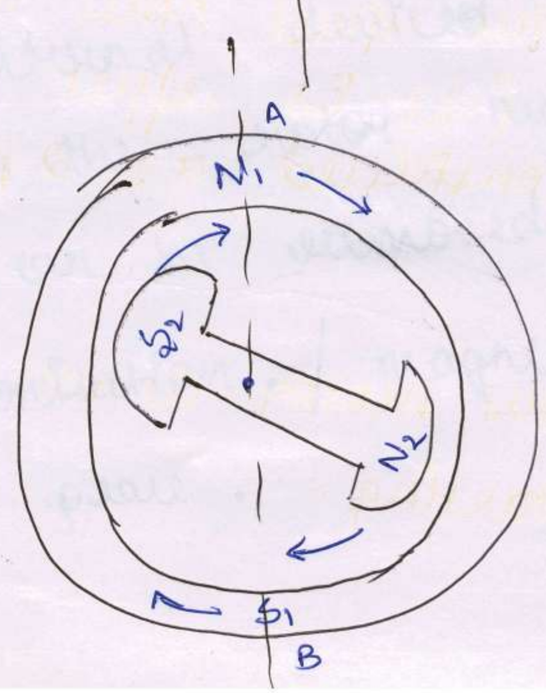
physical poles N_1 and S_1

and are at a position when stator magnetic axis is verticle i.e., along A-B

At this instant, the rotor poles are arbitrarily positioned, at this instant rotor is stationary and ~~unt~~ unlike poles will try to attract each other.

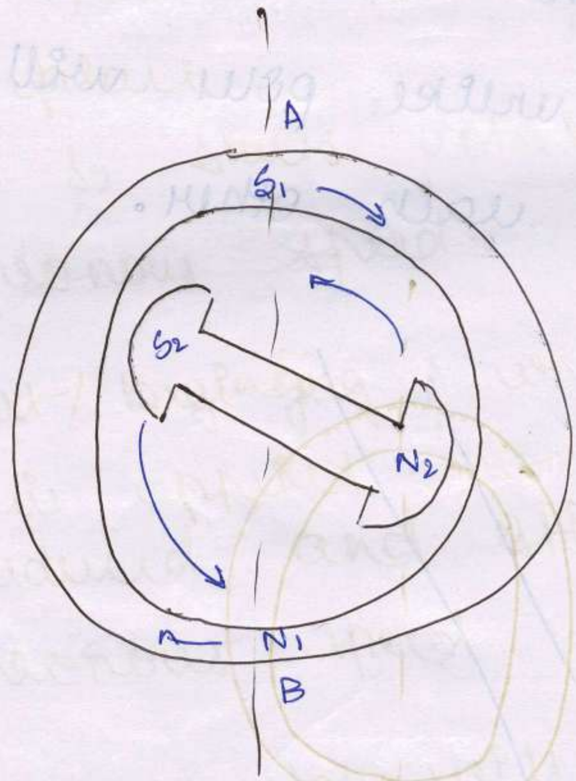


case (ii):-



Due to this the rotor gets subjected to an instantaneous torque in clock wise direction.

Case (iii) :-



→ To start a synchronous motor:-

Suppose the rotor is rotated by some external means at a speed almost equal to synchronous speed and then rotor is excited to produce the poles. At a certain instance, the stator and rotor poles will face each other and then there is a force of attraction between the stator and rotor and pulls both of them into magnetic locking condition.

The external devices used to rotate the rotor near synchronous speed can be removed once synchronisation / magnetic locking takes place.

→ Methods of starting synchronous motor :-

1) Using pony motors :-

2) Using damper winding :-

3) As a slip ring IM :-

4) Using small DC ~~motor~~ machine :-

1) Using Pony motors :-

In this method, the rotor of synchronous motor is brought to synchronous speed with the help of a small internal IM called pony motor.

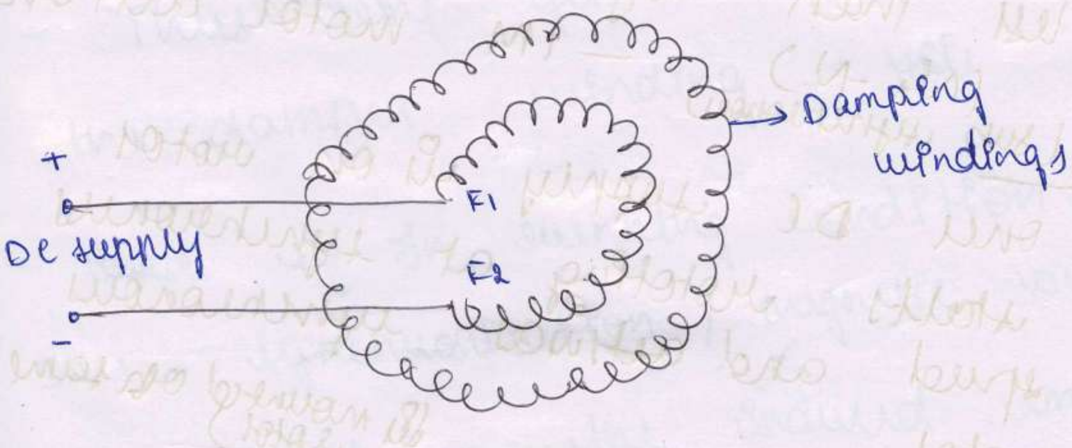
Once synchronisation is established, the pony motor is decoupled / removed

2) Using damper winding:-

In this method, in addition to the normal field winding (or rotor winding), an addition winding consisting of cu bars are placed in the slots in the pole face.

The bars are short circuited with the help of end rings.

Such an additional winding is called damper winding.



Damper → Pole phase rotor

then
synchronous motor works as

IM Initially (At start

- supply - 3ϕ → stator → ~~RMF~~ →

RMF → is produces and cuts

rotor windings (DC is not supplied)

and this RMF → current is

produced → emf is induced →

flux is produced → in damper

winding

1) flux → (i) RMF
(ii) Damper winding flux

Thus due to interaction of 2 fluxes

rotor starts rotations at speed

less than synchronous speed

(N_s N) — IM motor action

(sub synchronous

once DC supply is on rotor

starts rotating at synchronous

speed and ~~act~~ works synchronous

motor (is mounted on same rotor)

↳ for Damper winding is rotating

in same synchronous speed

so there is change in

[illegible]

At start rotor is station
Damper windings is station
RMF is rotating
↳

→ Same $N_2 - S_1$, $N_1 - S_2$ magnetic locking — synchronous speed
↳ rotor does not stop
The IM motor action stops and synchronous action continues.
→ No flux is induced --

- At start, the RMF cuts the stationary damper winding which is placed in the rotor slots.
- Thus emf gets induced in the damper winding - ~~the~~
- ~~once~~ In running condition, once synchronisation / magnetic locking takes place, the induced emf in the damper winding becomes zero because after magnetic locking the rotor will rotate at synchronous

speed N_s which is same as RMF.

[Damper windings are placed on the rotor in the winding slots]

[Damper winding operation remains same initially as that of squirrel ~~cag~~ cage IM] (or) short circuited rotor]

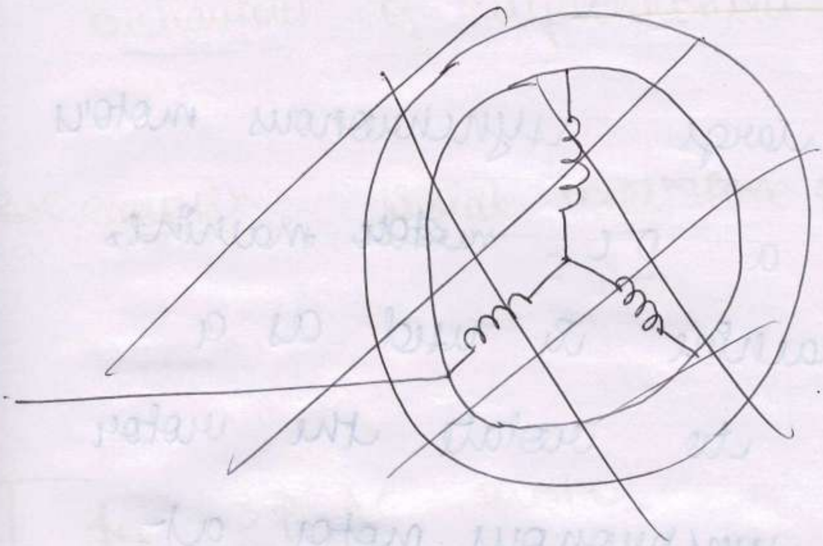
- starters has to be required to start

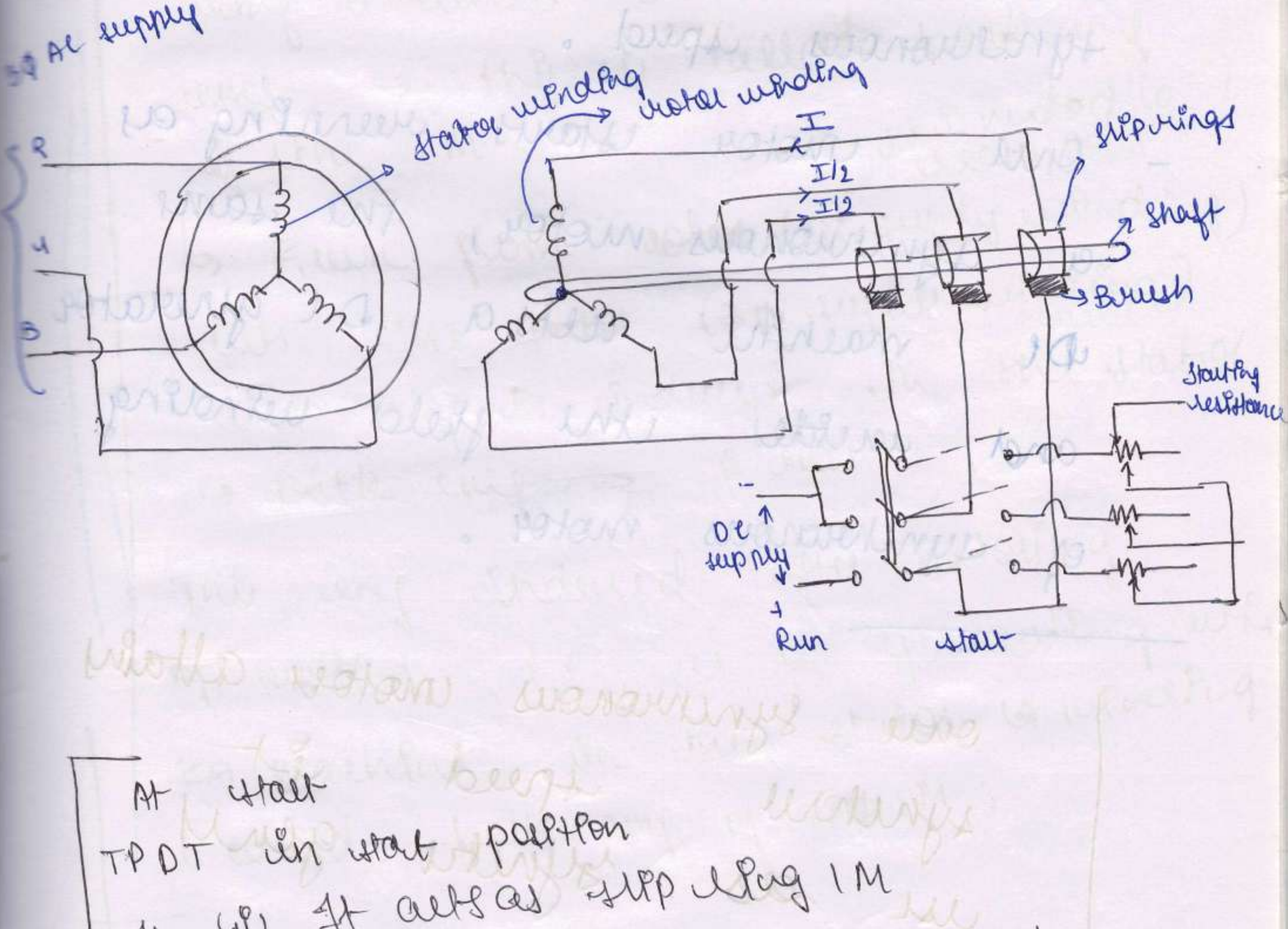
3) As a slip ring IM:-

- In the damper winding method it is difficult to achieve high starting torque.

- To achieve high torque instead of shorting the damper winding, it is designed to form a 3ϕ ~~ϕ~~ star or delta connected winding

- The 3 ends of this winding are brought out through slip rings ~~and~~





At start
TPDT in start position
It (i) It acts as slip ring IM
Here starting torque can be varied by
by varying starting resistance

(ii)
Same steps as previous one ||
but slip ring connected to variable
resistance to get high starting

4) Using small DC machine:-

- Usually large synchronous motors we use a DC ~~motor~~ machine.
- This machine is used as a DC motor to rotate the rotor of the synchronous motor at synchronous speed.
- Once motor starts running as a synchronous motor, the same DC machine acts a DC generator and excites the field winding of synchronous motor.

once synchronous motor attains synchro speed it act as synchro genr

→ Behaviour of synchronous motor on loading:

~~Characteristics~~ :- ~~ideal conditions on noload~~ :-

In 3φ AC motor

emf induced in stator → back emf → this is called back emf of the IM -

↳ Flux from rotor (DC supply winding) → it is needed to create poles cuts the stator (3φ supply winding) and emf is induced in the stator

→ Back emf → ~~φ~~ this

This emf induced after motoring of motor i.e, as a generating (at time) ~~mo~~ machine in the stator ~~&~~ winding is called back emf of 3φ IM;

consider a DC shunt motor whose voltage eqn is given by

$$V = E_b + I_a R_a$$

$$E_b = V - I_a R_a$$

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

E_b = back emf i.e., induced emf in a DC motor due to generating action

Similarly in synchronous motor, there is an induced emf in the 3ϕ stator winding due to alternator action (synchronous ~~altio~~ generator) after magnetic locking takes place

This induced emf is known as back emf of a synchronous motor whose magnitude is given

$$E_{b_{ph}} = 4.44 \, f \phi \, T_{ph} K_c K_d \text{ volts}$$

where $K_c = \cos(\alpha/2)$

$$K_d = \frac{\sin(m\beta/2)}{m \sin(\beta/2)}$$

$\therefore$ $\boxed{E_{bph} \propto \phi}$

As the speed ~~to~~ is always synchronous (N_s) frequency is ~~a~~ constant and Hence magnitude of back emf can be controlled by flux ϕ produced by the motor.

Let R_a = stator winding resistance

and X_s = synchronous reactance of the stator

then synchronous impedance of the motor is given by -

$$Z_s = R_a + jX_s \quad \Omega/ph$$

Thus similar to a DC motor, voltage equation for a synchronous motor can be written as

$$\vec{V}_{ph} = \vec{E}_{bph} + \vec{I}_{aph}\vec{Z}_s$$

$$\boxed{\vec{I}_{aph} = \frac{\vec{V}_{ph} - \vec{E}_{bph}}{Z_s}} \text{ Amps}$$

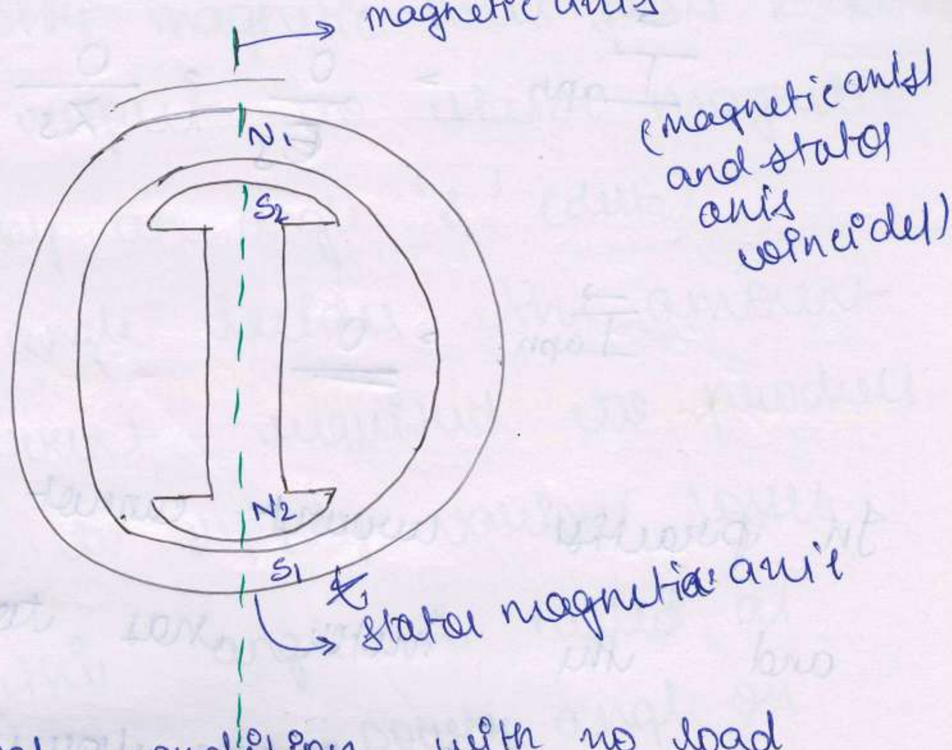
- ↳ → (ii) Ideal condition on no load:-

magnitude of E_{bph} is made almost equal to V_{ph} by controlling the flux produced by field winding

Thus for ideal condition on no load, neglecting various losses

$$\boxed{V_{ph} = E_{bph}}$$

Under this condition the magnetic locking b/w stator & rotor is in such a way that the magnetic axis of both coincide with each other



(a) ideal condition with no load

The magnitudes of ~~Ebph~~ E_{bph} and V_{ph} are equal but they are in opposite direction Lenz's law.

$$|E_{bph}| = |V_{ph}|$$

~~W.K~~

W.K.T

$$\vec{I}_{ap} = \frac{\vec{V}_{ph} - \vec{E}_{bph}}{Z_s}$$

$$\vec{I}_{aph} = \frac{0}{E_s} = \frac{0}{Z_s}$$

$$\vec{I}_{aph} = \underline{\underline{0}}$$

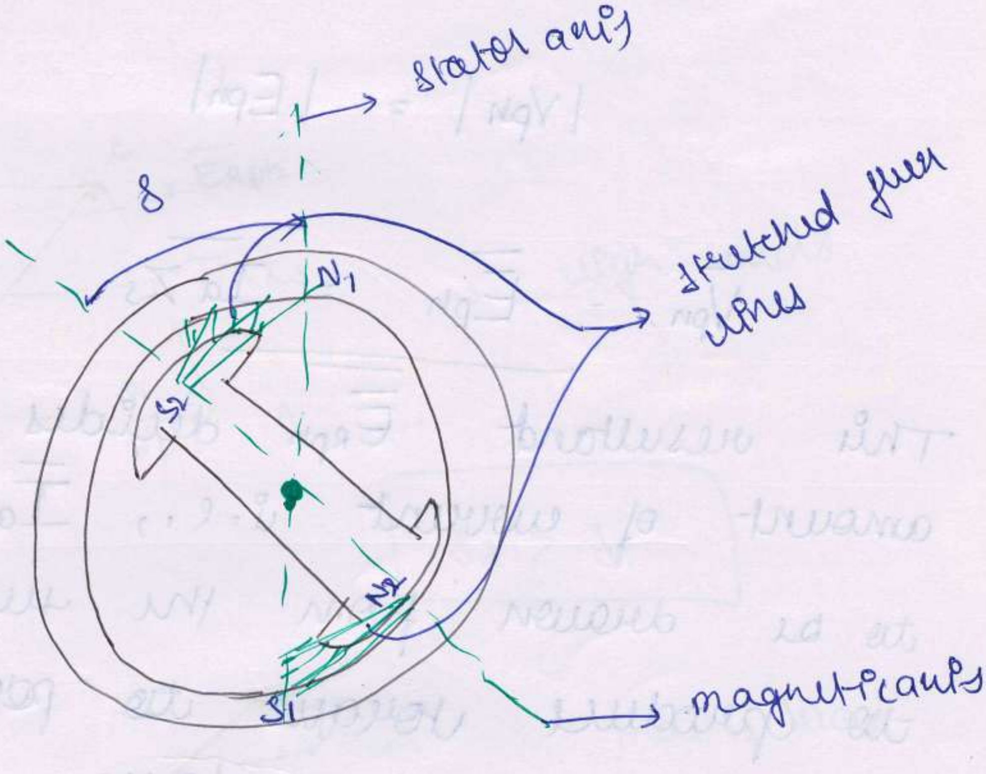
In practice current cannot be zero and the motor has to supply mechanical and iron losses under no load condition

To produce the torque required to overcome these losses - the motor draws current from the supply.

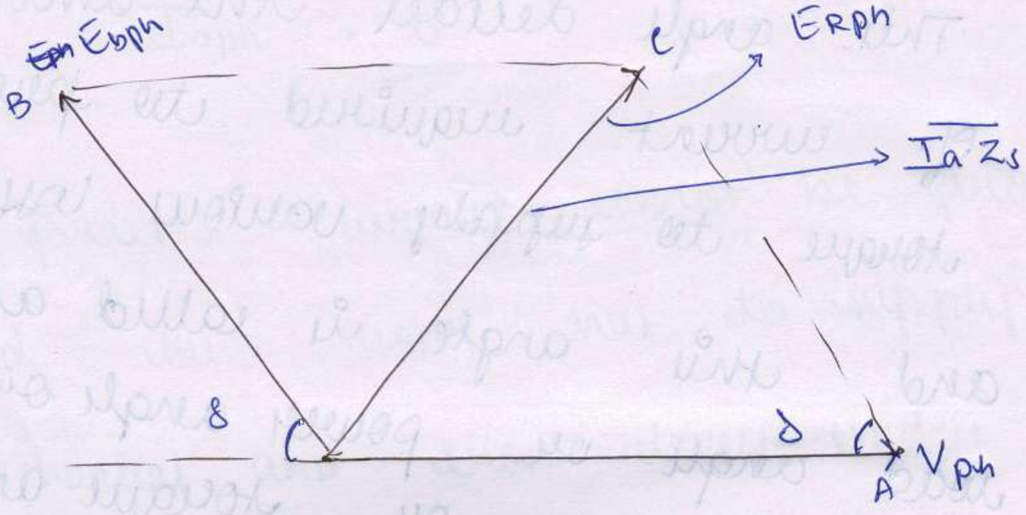
- ↳ → (iii) On no load (with losses) :-

Due to various losses present practically in a motor on no load, the magnetic locking exists between the stator and rotor but in such a way that they exists a small angular difference b/w the ~~ax~~ axis of 2 magnetic fields.

- The rotor magnetic axis falls back with respect to stator magnetic axis by an angle 'δ' (delta)
- This angle decides the amount of current required to produce torque to supply various losses and this angle is called as load angle or power angle or coupling angle or torque angle or angle of retardation.



greater angle (δ) (above δ ≥ 90°) magnetic locking is less and synchronous speed is stopped



phasor diagram for no load with losses

$$|V_{ph}| = |E_{ph}|$$

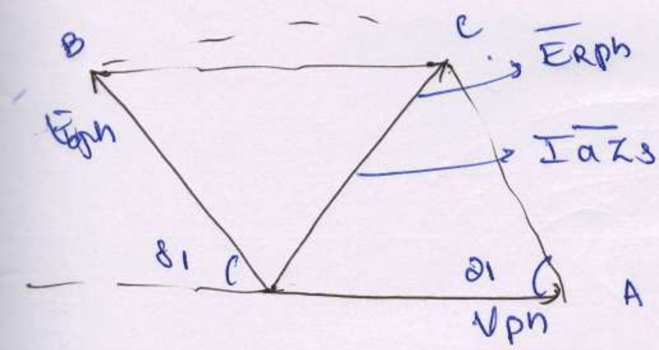
$$\overline{V_{ph}} - \overline{E_{ph}} = \overline{I_a Z_s} = \overline{E_{Rph}}$$

This resultant $\overline{E_{Rph}}$ decides the amount of current i.e., $\overline{I_{aph}}$ to be drawn from the supply to produce torque ~~to~~ ~~pass~~ which meets the various losses under no load condition δ is very small and hence $\overline{E_{Rph}}$ is also very small.

(iii) Synchronous motor on load

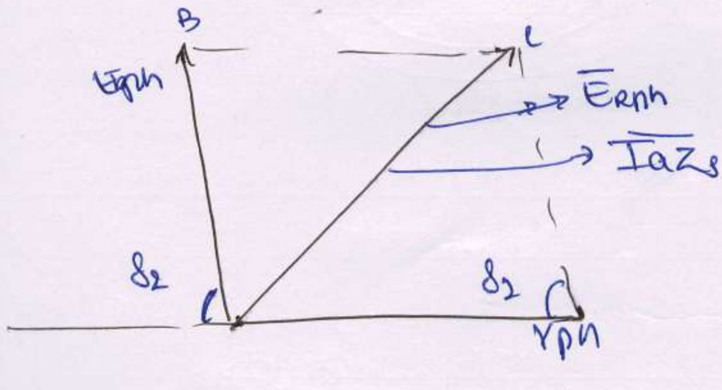
As the load on the synchronous motor increases there is no change in its speed but load angle δ gets affected

Hence if the load increases, δ increases but speed remains synchronous



→ High loads

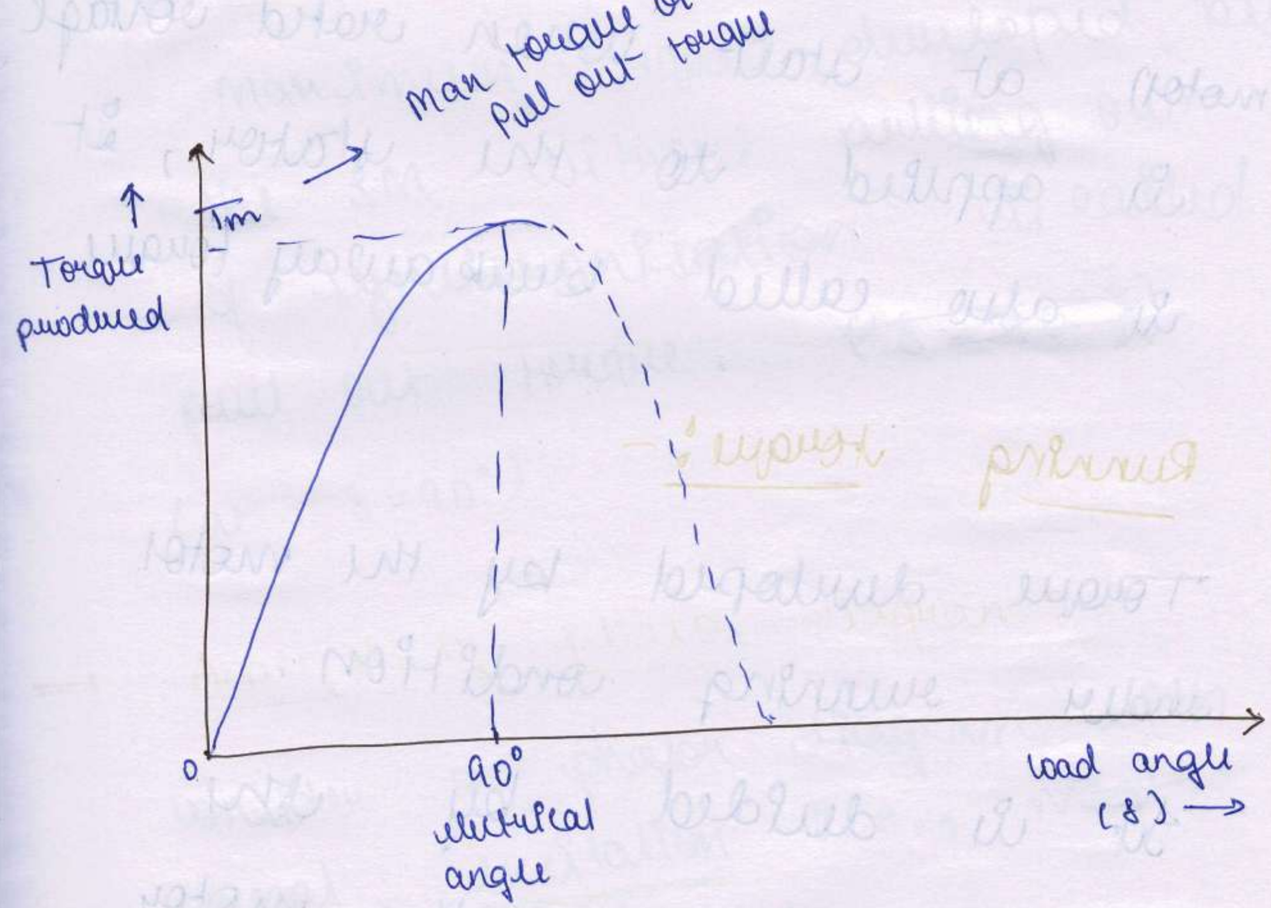
$$\boxed{\delta_2 > \delta_1}$$



Heavy load

⟹ MODULE - 5 [continuation]

Torque angle characteristics :-



as load on synch motor increases
δ also increases
beyond 90° magnetic locking is
lost and torque is reduced. and
motor ~~is~~ comes out of synchronisation
and ~~no~~ torque is not produced

→ Types of torques in a synchronous motor :-

1) Starting torque :-

Torque developed by SM (Synchronous motor) at start when rated voltage is applied to the stator, it is also called break away torque

2) Running torque :-

Torque developed by the motor under running condition.

It is decided by the output rating of the motor and speed

3) Pulling torque :-

~~when~~ the speed of the rotor is near synchronous speed

The amount of torque developed by the motor at the ~~p~~ time of pulling into synchronisation is called ~~synchro~~ pulling torque.

4) Pull out torque (maximum torque):-

maximum torque developed by the SM without pulling out of synchronisation is called pull out torque. ~~(at $\delta = 90°$)~~

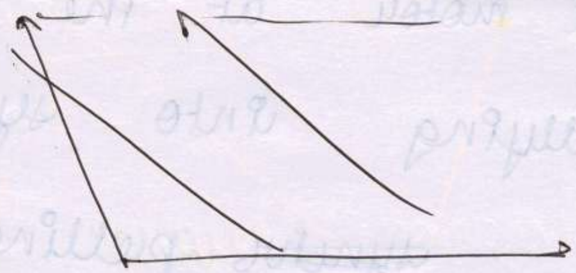
(at $\delta = 90°$)

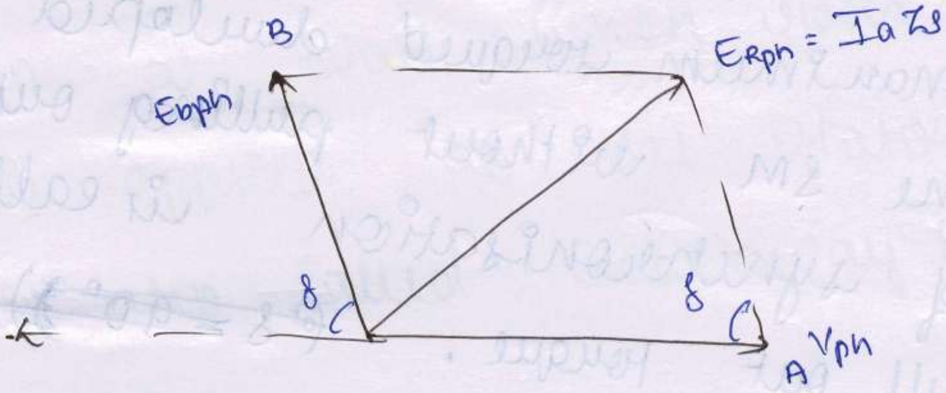
⟹ Analysis of phasor diagram:-

consider a phasor diagram with normal excitation i.e., ~~mag~~ ~~$|E_{bph}|$~~ is ~~sam~~

~~$|E_{bph}| = |V_{ph}|$~~

$$|E_{bph}| = |V_{ph}|$$





$$\rightarrow \bar{V}_{ph} - \bar{E}_{bph} = \bar{E}_{Rph}$$

$$\Rightarrow \bar{V}_{p} - \bar{E}_{ph} = \bar{I}_a Z_s$$

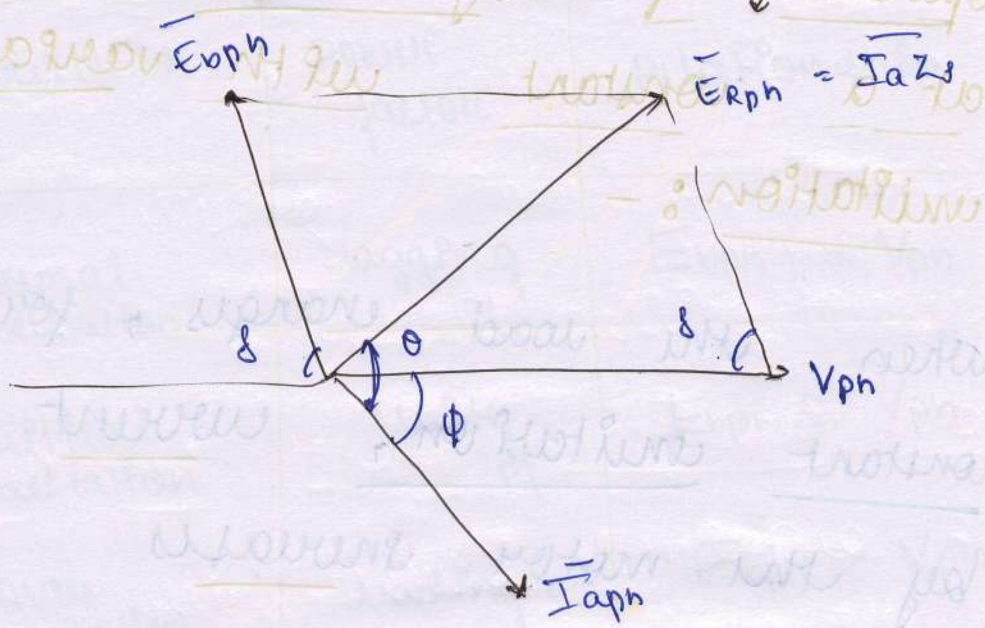
$$Z_s = R_a + j X_s \quad \Omega / ph$$

$R_a \rightarrow$ stator resistance per ~~Eph~~ phase

$X_s \rightarrow$ synchronous reactance of stator per phase

$$|Z_s| = \sqrt{R_a^2 + X_s^2}$$

~~phasor~~ phasor diagram under normal working condition]



$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$$

The angle θ = is called impedance angle or internal machine angle.

Practically R_a is very small compared to X_a

X_a = reactance of stator (Not sync...]

Hence θ tends to 90°

→ operation of synchronous motor at a constant with variable excitation :-

when the load changes, for a constant excitation, current drawn by the motor increases

But if the excitation (field current I_f) is changed keeping the load constant, SM reacts by changing its power factor of operation.

Types of excitation :-

1) Normal excitation

2) under excitation

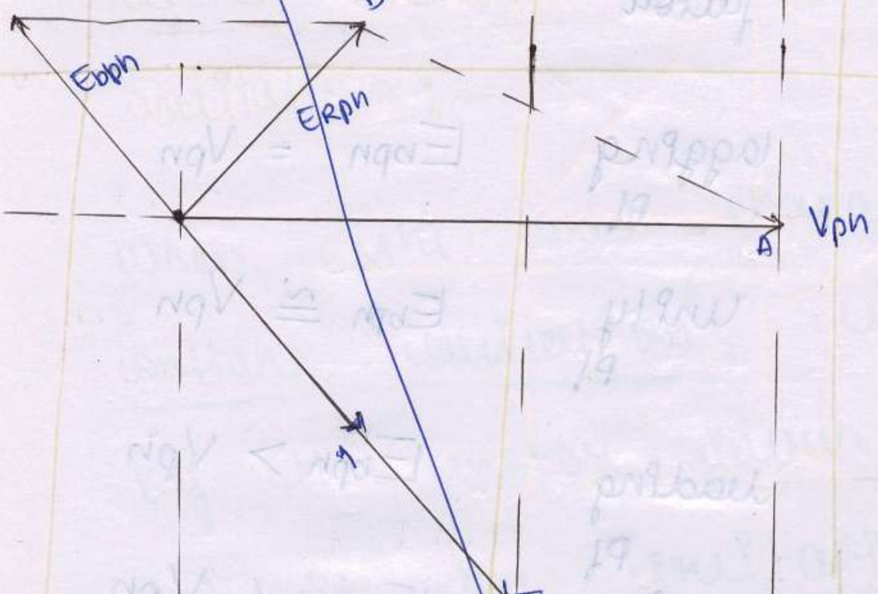
3) over excitation

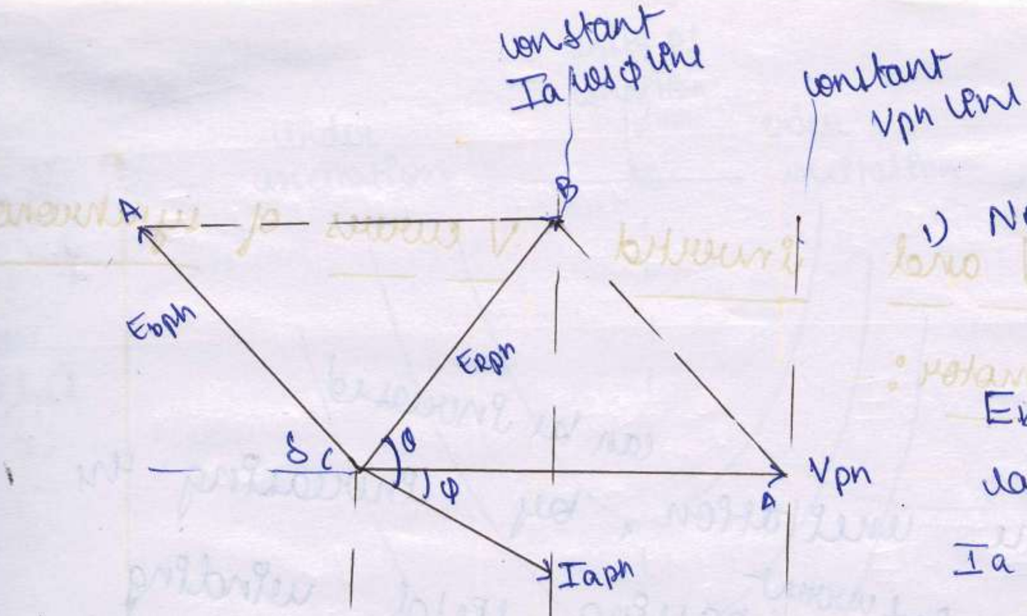
4) critical excitation

Sl. No.	Exitation	power factor	Relationship
1)	Normal excitation	lagging pf	$E_{bph} = V_{ph}$
2)	Critical excitation	Unity pf	$E_{bph} \cong V_{ph}$
3)	Over excitation	leading pf	$E_{bph} > V_{ph}$
4)	Under excitation	lagging pf	$E_{bph} < V_{ph}$

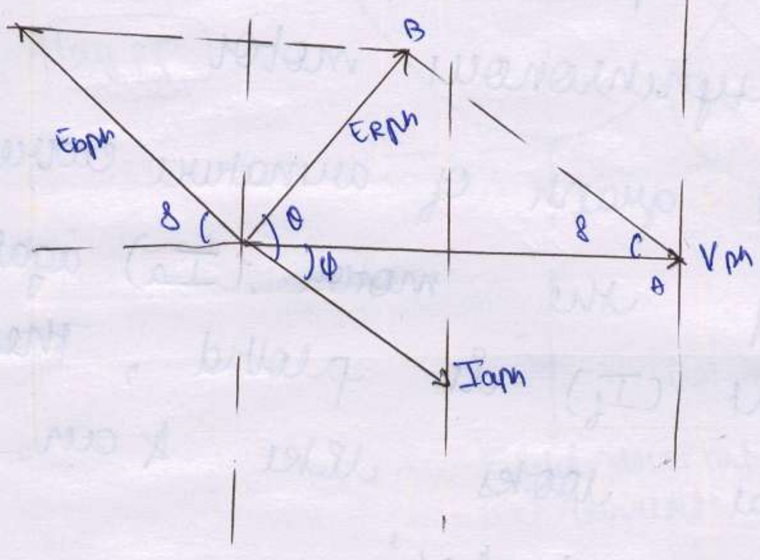
23/2

1) Normal excitation

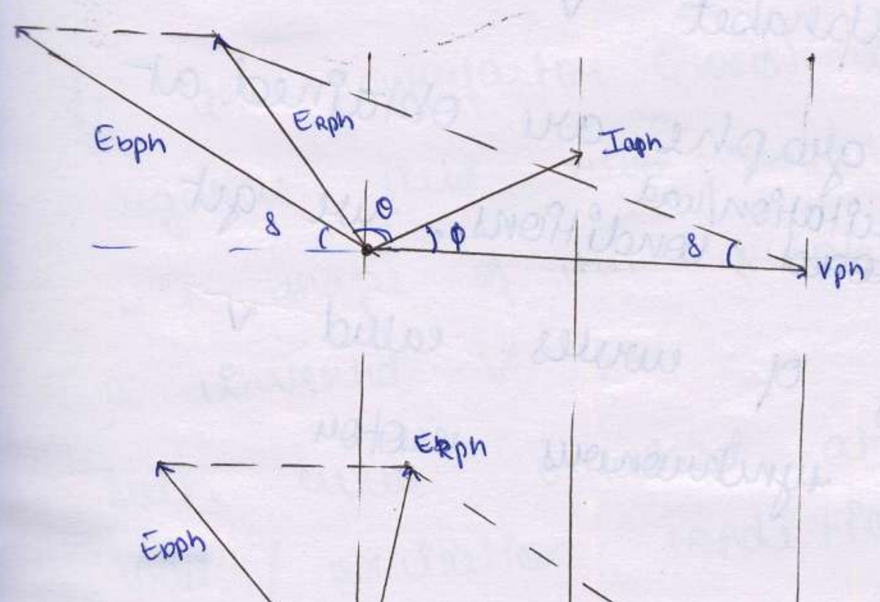




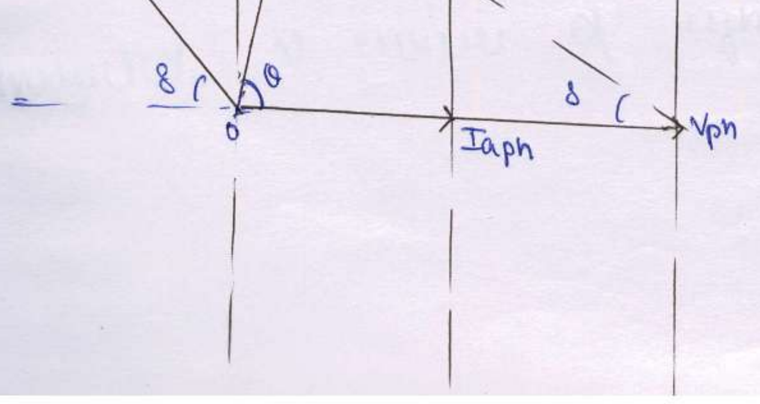
1) Normal
excitation
line
$E_{bph} = V_{ph}$
lagging pf
Ia increases



2) under
excitation
line
$|E_{bph}| < |V_{ph}|$
(φ is greater
here)
Ia ~~increases~~
decreases



3) over
excitation
$|E_{bph}| > |V_{ph}|$
(φ is less here)
Ia



$\left[\begin{array}{l} \phi = 0 \\ \cos\phi = 1 \end{array}\right]$

4) critical
excitation

$E_{bph} \cong V_{ph}$

unity power
factor

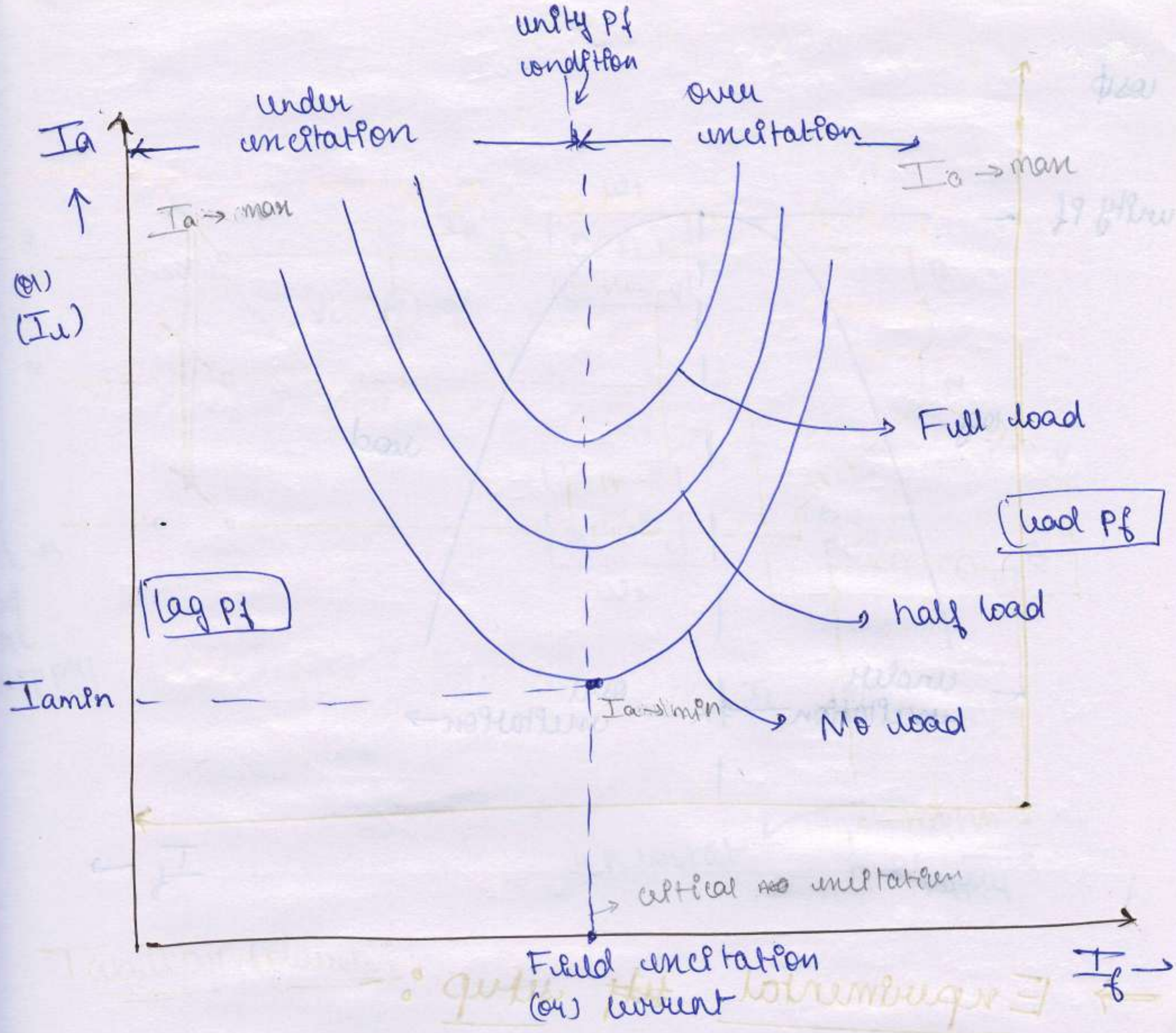
Iaph is less/decreases

→ V and inverted V curves of synchronous motor:-

- The excitation can be increased by increasing the field ~~cu~~ current passing field winding of the synchronous motor

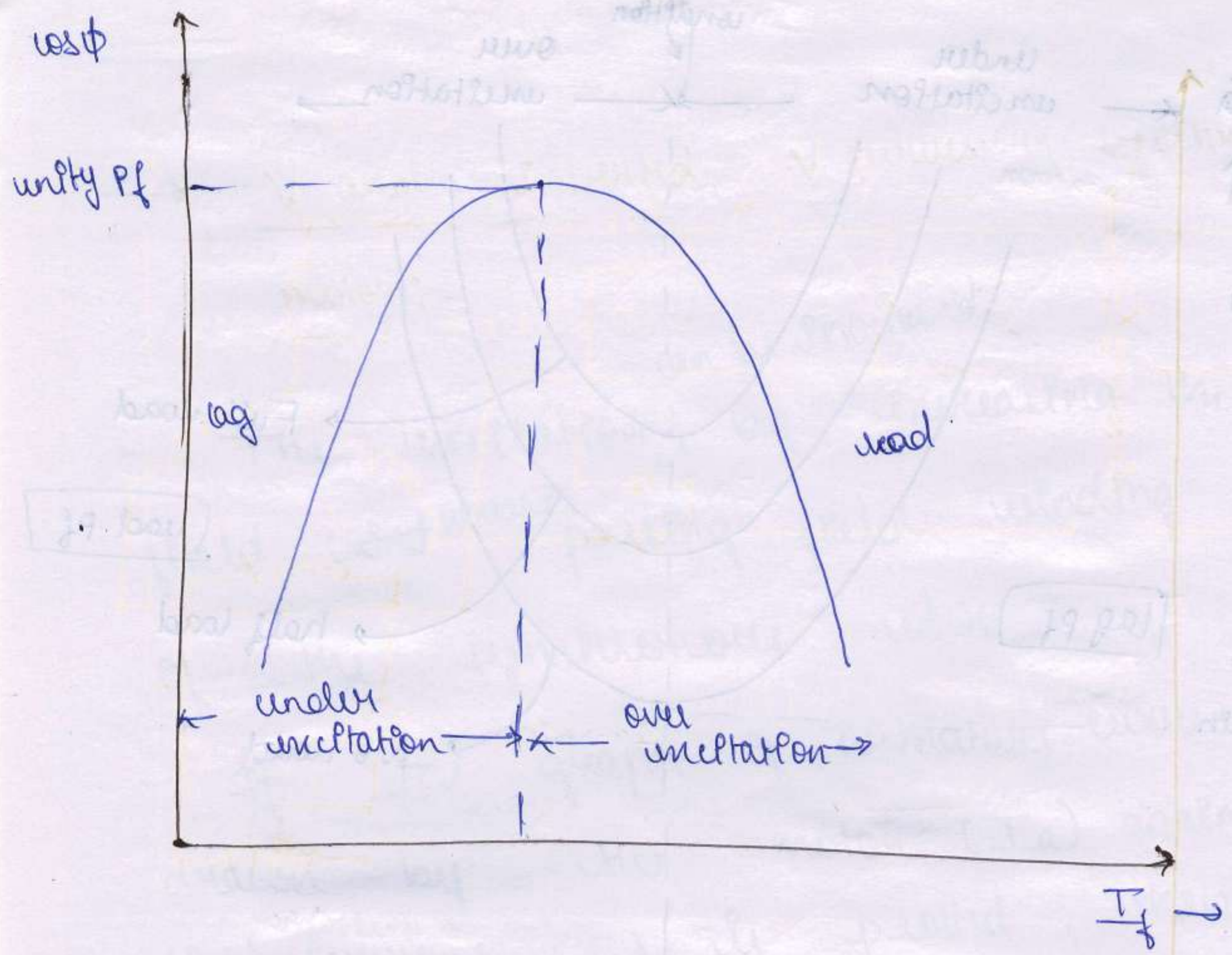
- If the graph of armature current drawn by the motor (I_a) against field current (I_f) is plotted, then its shape looks like ~~&~~ an english alphabet 'V'

- If such graphs are obtained at various ~~load~~ excitation/load conditions, we get a family of curves. called V curves of synchronous motor

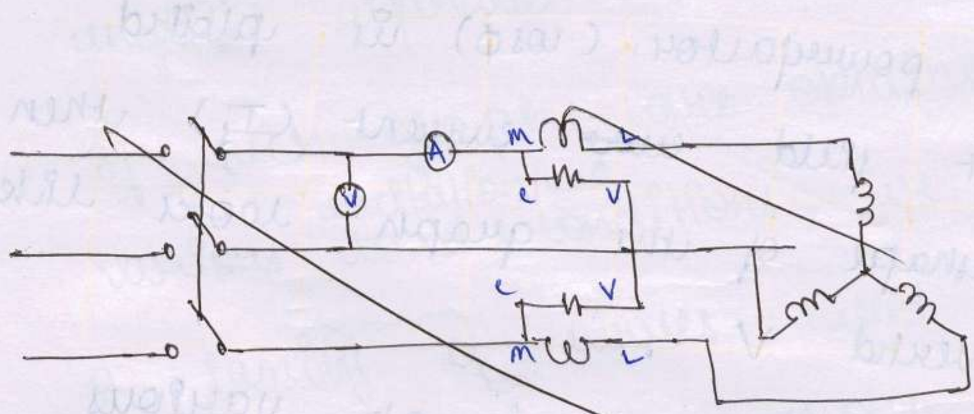


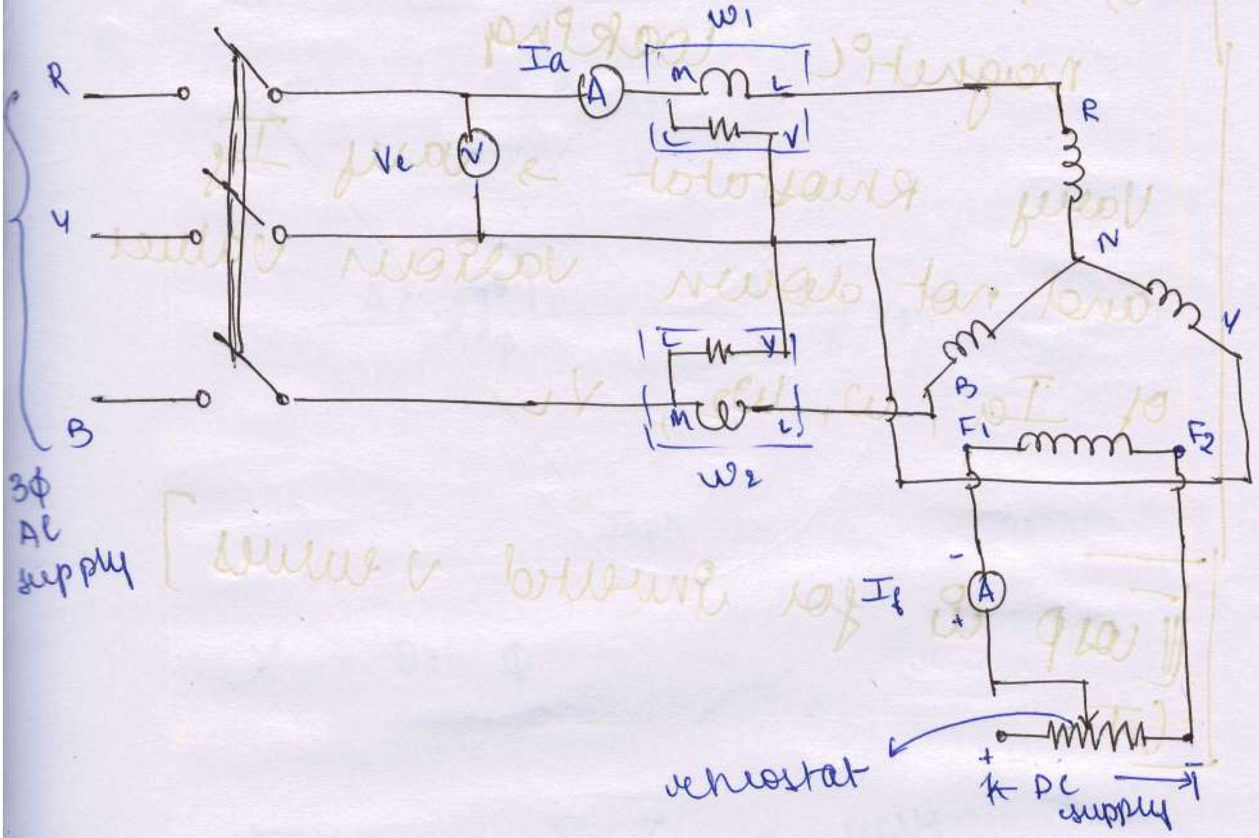
If the powerfactor ($\cos\phi$) is plotted against field ~~curr~~ current (I_f) then the shape of the graph looks like a inverted V.

Such curve obtained at various load / excitation conditions are called inverted v curves of synchronous motor



→ Experimental ~~###~~ setup :-





Tabular column:-

Sl. No:	V_L (volts)	I_a (Amps)	I_f (Amps)	W_1 (watts)	W_2 (watts)	$\cos\phi$ $\cos\tan^{-1}\left[\sqrt{3}\frac{W_1-W_2}{W_1+W_2}\right]$

$\cos\phi = \cos\left[\tan^{-1}\frac{\sqrt{3}(W_1-W_2)}{W_1+W_2}\right]$ $\left[\phi = \tan^{-1}\left[\sqrt{3}\frac{W_1-W_2}{W_1+W_2}\right]\right]$

→ Switch ~~of~~ on AC supply & then used (pony, damper, DC motor, 1ϕ IM, slip ring.., DC machine) ~~rot~~ motor

once motor starts rotation supply DC field

poles are creates
↳ pole N_1 S_1, N_2 S_2
magnetic locking

Vary Rheostat → vary I_f
and not down various values
of I_a, W_1, W_2, V_L

[$\cos\phi$ is for inverted V curves]

⟹ Expression for back emf (E_{bph}) :-

↳ 1) For under excitation

$$E_{bph} < V_{ph}$$

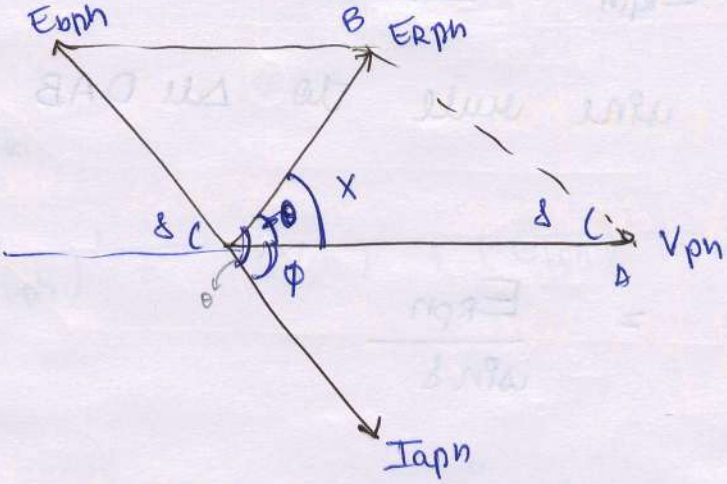
$$Z_s = R_a + jX_s \quad \Omega/ph$$

(or)

$$Z_s = |Z_s| \angle\theta \quad \Omega/ph$$

where

$$\theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$$



$$X = \theta - \phi$$

E_{Rph} $\quad E_{Rph} = \overline{I_a} \, \overline{Z_s}$ volts

E_R

angle b/w E_{Rph} and $V_{ph} = \theta$

angle b/w V_{ph} and $I_{aph} = \phi$

applying cosine rule to triangle OAB

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - \cancel{2}$$

$$- 2 V_{ph} E_{Rph} \times \cos[\text{angle b/w } V_{ph} \,\&\, E_{Rph}]$$

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \cos(X)$$

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \cos(\theta - \phi)$$

where $\bar{E}_{Rph} = \bar{I_a Z_s}$

Applying sine rule to Δle OAB

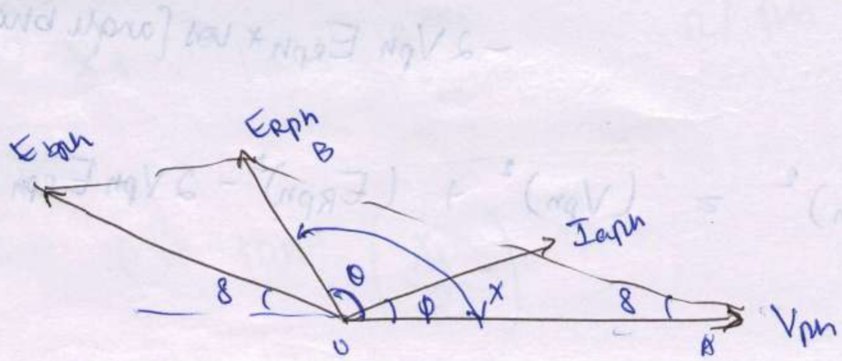
$$\frac{E_{bph}}{\sin x} = \frac{E_{Rph}}{\sin \delta}$$

i.e.,
$$\frac{E_{bph}}{\sin(\theta - \phi)} = \frac{E_{Rph}}{\sin \delta}$$

$$\boxed{\sin \delta = \frac{E_{Rph} * \sin(\theta - \phi)}{E_{bph}}}$$

• ↳ 2) over excitation :-

$E_{bph} > V_{ph}$



$$X = \theta + \phi$$

→ Applying cosine rule for Δle ~~OAB~~ OAB

$\cancel{E_{R_1}}$

$$\cancel{(E_{bph})^2 = (V_{ph})^2 + (E_{bph})^2 - 2 V_{ph} E_{Rph} \cos(} \cancel{\text{angle b/w}}$$
V.

$$(E_{bph})^2 = (V_{ph})^2 + (E_{bph})^2$$
$$- 2 V_{ph} E_{Rph} \cos(\text{angle b/w } V_{ph} \text{ \& } E_{Rph})$$

$$(E_{bph})^2 = (V_{ph})^2 + (E_{bph})^2 - 2 V_{ph} E_{Rph} \cos(X)$$

$$(E_{ph})^2 = (V_{ph})^2 + (E_{Bph})^2 - 2 V_{ph} E_{Rph} \cos(\theta + \phi)$$

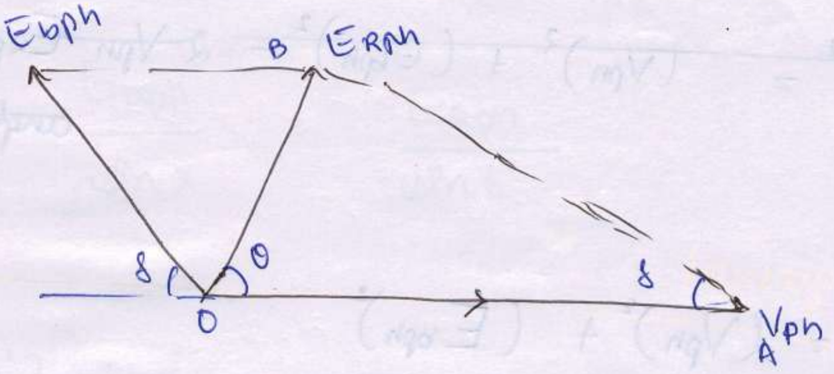
→ Applying sine rule to ΔOAB

$$\frac{E_{bph}}{\sin X} = \frac{E_{Rph}}{\sin \delta}$$

$$\boxed{\sin \delta = \frac{E_{Rph} * \sin(\theta + \phi)}{E_{ph}}}$$

↳ 3) Critical excitation :-

$$E_{bph} \simeq V_{ph}$$



$X = \theta$ [∵ $\phi = 0$]

→ Apply cosine rule

$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2V_{ph}E_{Rph}\cos$ (angle b/w E_{Rph} and V_{ph})

Eq.

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2V_{ph}E_{Rph}\cos(X)$$

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2V_{ph}E_{Rph}\cos\theta$$

→ Apply sine rule

$$\frac{E_{bph}}{\sin\theta} = \frac{E_{Rph}}{\sin\delta}$$

$$\boxed{\sin\delta = \frac{E_{Rph} \times \sin\theta}{E_{bph}}}$$

→ In general

$$\boxed{(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2\, V_{ph} E_{Rph} \cos(\theta \pm \phi)}$$

+ → over excitation → leading pf

− → under excitation → lagging pf

Q1) A 2300 V, 3ϕ, star connected SM has a resistance of 0.2 Ω/ph and a synchronous reactance of 2.2 Ω/ph. The motor is operating at 0.5 pf lead with a line current of 200 A. Determine the value of generated emf per phase

Soln

$V_L = 2300\ V$

$R_a = 0.2\ \Omega/ph$

$X_s = 2.2\ \Omega/ph$

$Z_s = R_a + jX_s$

$= 0.2 + j2.2$

$\cos\phi = 0.5$ lead

$I_L = 200\ A = I_a$

$E_{bph} = ?$

$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{2300}{\sqrt{3}}$

$= 1327.90\ V$

$I_{ph} = I_L$

$Z_s = 0.2 + j2.2$

$= 2.2 \angle 84.8\ \Omega/ph$

$|Z_s| \angle\theta$

$\theta = 84.8$

→ $\cos\phi = 0.5$

$\phi = \cos^{-1}(0.5)$

$\phi = 60^\circ$

$I \angle \pm\phi$

$I[\cos\phi \pm i\sin\phi]$

[star connect
∴ $I_{aph} = I_{L}$

Delta connected
$I_{ph} = \frac{I_L}{\sqrt{3}}$

→ $E_{Rph} = \overline{I_a Z_s}$

$= 200 * 2.2$

$= 440$ volts

→ $(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \cos(\theta + \phi)$

$= (1327.9)^2 + (440)^2 - 2(1327.9)(440) \times \cos(84.8 + 60)$

$E_{ph} = \sqrt{~~2791387.77~~ \; 2911794.71}$

$V_{ph} = V_L$

$E_{ph} = ~~1670.74 \text{ volts}~~$

$Z_s = R_a + jX_s$

$= Z_s \angle\theta$

$E_{ph} = 1706.39$ volts

$E_{Rph} = \overline{I_a Z_s}$

$E_{bph} = E_{Rph} + V_{ph} - 2V_{ph}E_b \cos(\theta + \phi)$

Q2) A 400 V, 3ϕ, star connected SM has an armature resistance of 0.2Ω/ph and synchronous reactance of 2Ω/ph, while driving a certain load, it takes 25A from supply. Calculate the back emf induced if the motor is working at

(i) 0.8 lag → 200.5 V

(ii) 0.9 lead → 252.5 V

(iii) UPF → 231.38 V

Soln

$$Z_s = 0.2 + j2$$

$$\cancel{R_a} =$$

$$Z_s = 2\angle 84.28$$

$$= |Z_s| \angle \theta$$

$$\theta = 84.28$$

→ $\cos\phi_1 = 0.8$

$$\phi_1 = 36.86$$

→ $\cos\phi_2 = 0.9$

$$\phi_2 = 25.84$$

→ $\phi_3 = 0$

$E_{Rph} = I_a Z_s$

$= 25 \times 2$

$= 50V$

(ii) $\rightarrow (E_{Bph})^2 = \left(\frac{400}{\sqrt{3}}\right)^2 + (50)^2 - 2 \times \frac{400}{\sqrt{3}} \times 50 \times \cos(84.28 - 36.86)$

$\frac{400}{\sqrt{3}} \Rightarrow 230.94$

$E_{bph_1} = 200.5V$

(iii) $(E_{bph})^2 = (230.94)^2 + (50)^2 - 2 \times 230.94 \times 50 \times \cos(84.28 + 25.84)$

$E_{bph_2} = 252.54V$

(iii) ~~$(E_{ph})^2$~~

$(E_{Bph})^2 = (230.94)^2 + (50)^2 - 2 \times 230 \times 50 \times \cos(84.28)$

$E_{bph_3} = 231.38V$

24/5/2017

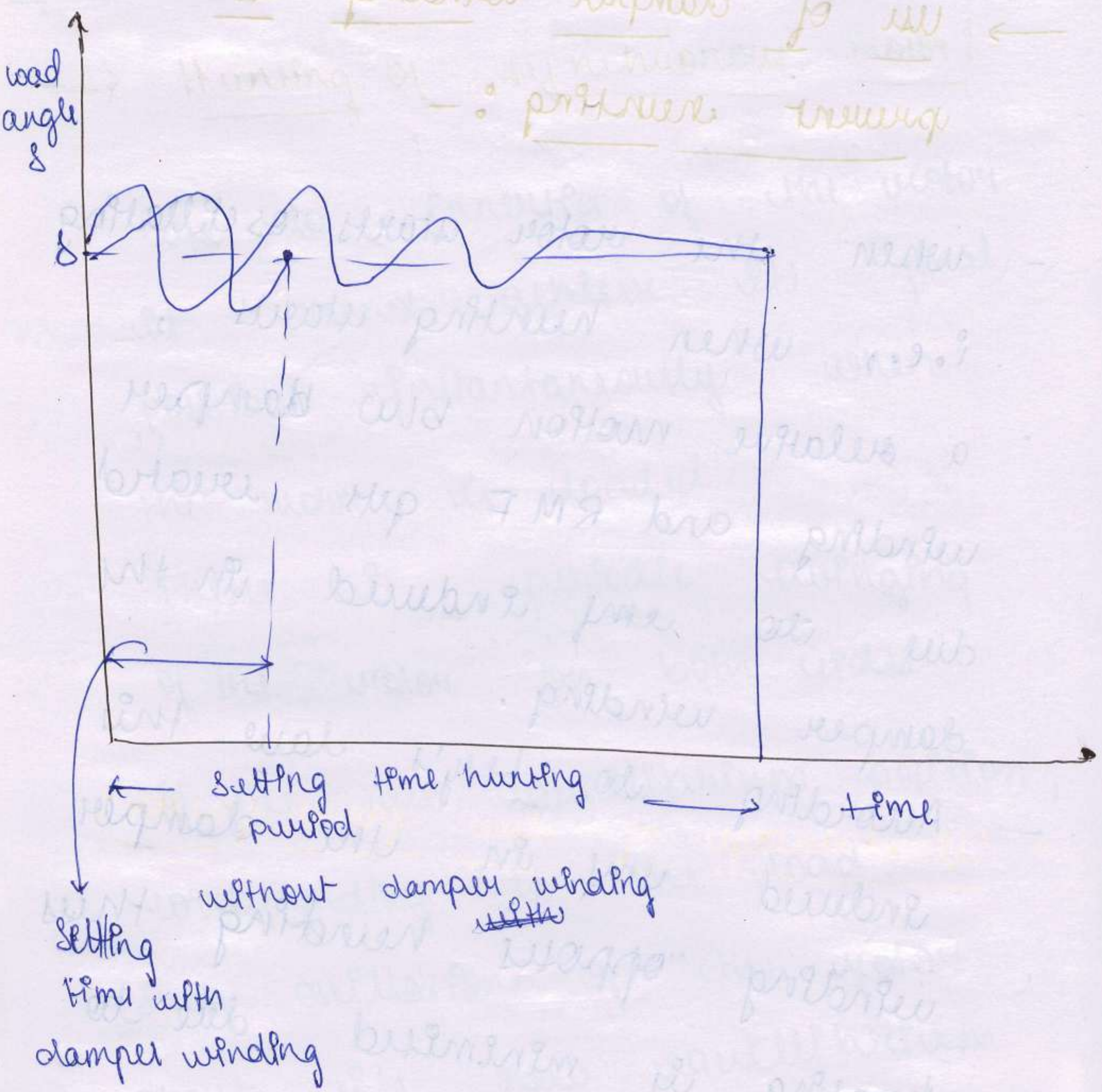
$\rightarrow$ Hunting in synchronous motor :-

→ Hunting of synchronous motor:-

- Due to inertia of the rotor it cannot achieve its final position instantaneously when the motor is loaded.
- There is periodic swinging of the rotor on both sides of the new equilibrium position, corresponding to the load such oscillations of the rotor about its new equilibrium position, due to sudden application or removal of load is called swinging or hunting in synchronous motor.

→ use of damper winding to prevent hunting :-

- when the rotor starts oscillating i.e., when hunting starts, a relative motion b/w damper winding and RMF gets created due to emf induced in the damper winding.
- According to Lenz's law the induced emf in the damper winding opposes hunding thus hunting is minimized due to damper winding.



→ **Synchronous condensers :-**

- A synchronous motor running on no load when over excited ($E_{bph} > V_{ph}$) is called a **synchronous condenser** or **synchronous capacitor**

- Under such condition, the current I_A will lead the voltage (V_{ph}) ~~...~~ by an angle almost equal to $90°$.

- This is the property due to which synchronous motor are used as powerfactor improvement device (or) phase advansor.

-

→ **Disadvantages of low power factor:-**

* Single phase power

$$P = VI\cos\phi$$

$$I = \frac{P}{V\cos\phi}$$

- Let $P = 5\ KW$ and $V = 230V$

consider

~~cos φ~~ =

<u>case (i)</u> :-

$pf = 0.8$

case <u>(iii)</u> :-

$pf = 0.6$

voltage regulation $\propto \frac{1}{pcos}$ efficiency

(i) $\underline{I} = \frac{5 \times 10^3}{230 \times 0.8}$

$= \underline{\underline{27.17\,A}}$

(iii) $\underline{I} = \frac{5 \times 10^3}{230 \times 0.6}$

$= \cancel{8}$

$= \underline{\underline{36.23\,A}}$

for any machine pf should be high so current drawn by the motor should be less

* High current due to low pf has the following disadvantage -

* The conductor size ~~should be more~~ increase which increases the cost

* More copper losses and less efficiency

* large current causes large voltage drop in transmission lines and this results in poor regulation

*

$$VI \cos\phi = \text{Active power}$$

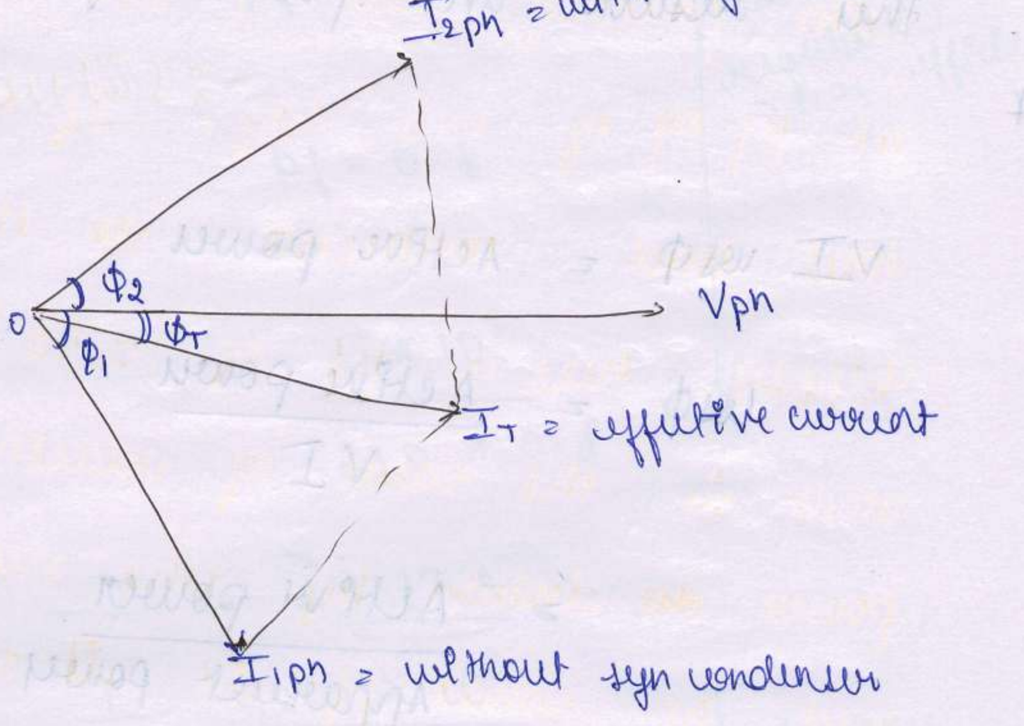
$$\cos\phi = \frac{\text{Active power}}{VI}$$

$$= \frac{\text{Active power}}{\text{Apparent power}}$$

$$pf \cos\phi = \frac{KW}{KVA}$$

If the pf is low then KVA rating of the equipment is high which increases the cost.

→ use of synchronous condenser in power factor improvement -



as $\phi_T \downarrow \rightarrow \cos\phi_T \uparrow \rightarrow$ Pf $\uparrow$

explanation
(own)

Note :-
Such Pf correction equipment ~~must~~ (syn condensers) is connected across the supply

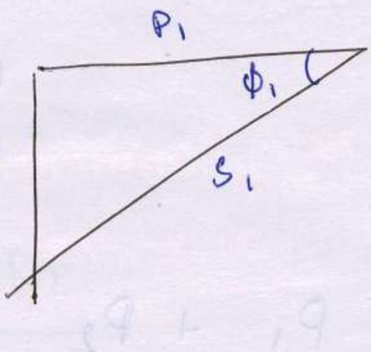
Q1) A synchronous motor developing 20 KW is connected in ||el with factory load of 200 KW at pf ~~of~~ of 0.8 lag. If the total load connected to the supply has a pf of 0.92 lag what is the value of reactive power ~~do~~ drawn by the motor and at what pf is it operating?

<u>soln</u>

<u>Given</u> :-

load 1 = factory load 200 KW

$\cos\phi_1 = 0.8$ lag



<u>soln</u>

$\cos\phi_1 = 0.8$

$\phi_1 = 36.86^\circ$

$\tan\phi_1 = \frac{Q_1}{P_1}$

$Q_1 = P_1 \tan\phi_1$

$= 200 * 10^3 * \tan 36.80$

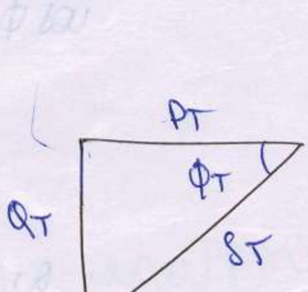
$Q_1 = \underline{150 \text{ KVAR}}$ (Reactive power drawn by factory load)

for sync motor

$P_2 = 20 \text{ KW}$

$\cos\phi_T = 0.92$

$\phi_T = 23.07^\circ$



& $P_T = P_1 + P_2$

$= 200 + 20$

$= \underline{220 \text{ KW}}$

$$Q_T = P_T \tan \phi_T$$

$$= 220 \times 10^3 \times \tan 23.07$$

$$Q_T = 93.70 \text{ KVAR}$$

Factor ~~symmotr~~ → ~~Ro~~ synmotr

$$\therefore Q_1 + Q_2 = Q_T$$

$$Q_2 = Q_T - Q_1$$

$$= 93.7 - 150$$

$$Q_2 = -56.3 \text{ KVAR}$$

∴ -ve sign indicated leading power

The reactive power drawn by the motor is - ~~56~~ -56.3 KVAR and -ve sign indicates its leading nature

$$\tan \phi_2 = \frac{Q_2}{P_2}$$

$$\phi_2 = \tan^{-1}\left(\frac{Q_2}{P_2}\right)$$

$$= \tan^{-1}\left(\frac{-56.3\ \cancel{KV}}{20\ \cancel{K}}\right)$$

$$\phi_2 = -70.44^\circ$$

$$\therefore \cos\phi_2 = \cos(-70.44^\circ)$$

$$= 0.33^\circ \text{ leading}$$

Blondel diagram

BD ~~ick~~ of a SM is an extension of simple phasor of sm ~~synchronous motor simple~~ ~~phasy~~ for synchronous motor

$P_{in} = V_{ph} I_{ph} \cos\phi$

Copper loss $= (I_{aph})^2 R_a$

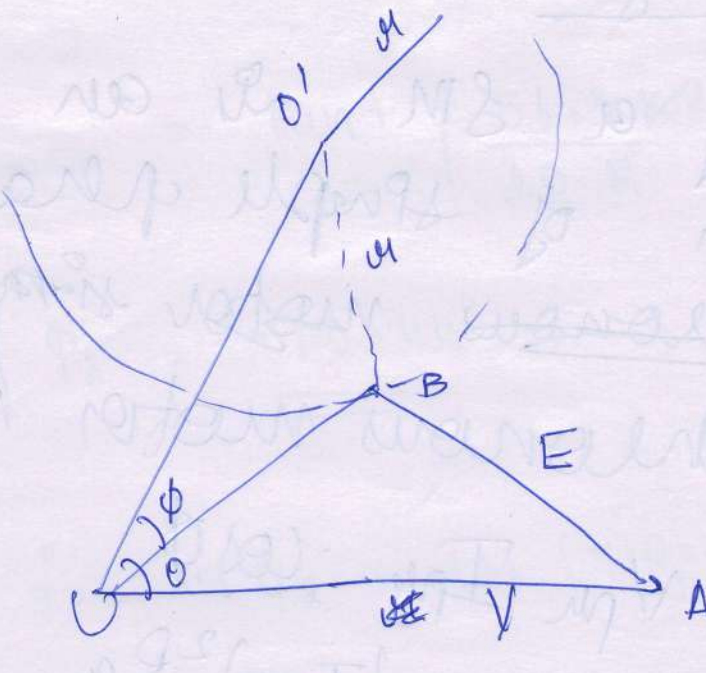
$P_m = P_{in} - P_{cu}$

$P_m = VI\cos\phi - I_a^2 R_a$

$I^2 R_a - VI\cos\phi + P_m = 0$

$I^2 - \frac{VI\cos\phi}{R_a} + \frac{P_m}{R_a} = 0$ —(1)

ean (1) represents polar ean of a circle to this, and draw a line or at angle θ
Pin



The circle drawn with centre at O' and radius at $O'B$ represents circle of constant power

This is called constant power.
This is called Blondel diagram

- if excitation is varied while the power is kept constant then ~~workdomt~~ working point B while moving along the circle of constant power

$$P_{m(max)} = \frac{V^2}{4R_a}$$