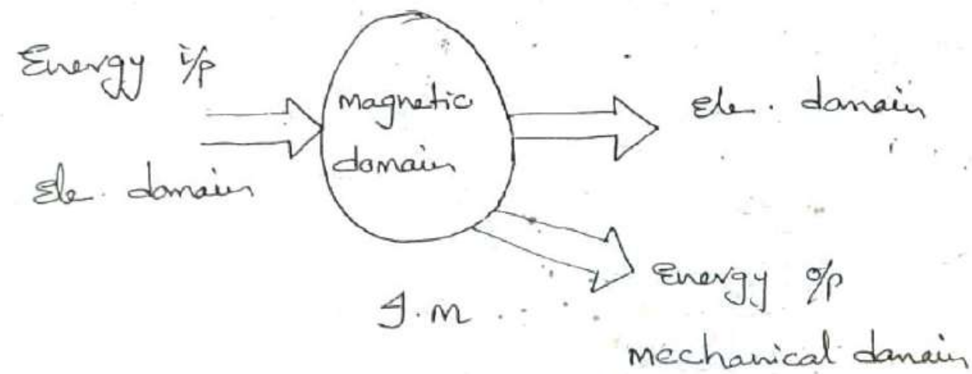
Polyphase Induction Motors

The polyphase induction motor is the most widely used ac motor almost 80% of the mechanical power used in industry because of its low cost, simple and rugged construction, absence of commutator, good operating characteristic and good speed regulation.

Induction motor also called as Asynchronous motor as they run at a speed other than the synchronous speed (N_s) of the rotating field developed by the stator currents. An asynchronous machine may be considered to be a transformer in the sense that the power is transferred from the stator (primary) to the rotor (secondary) winding only by mutual induction. due to this reason such a machine is often called the "induction machine" and also called as "generalized transformer".



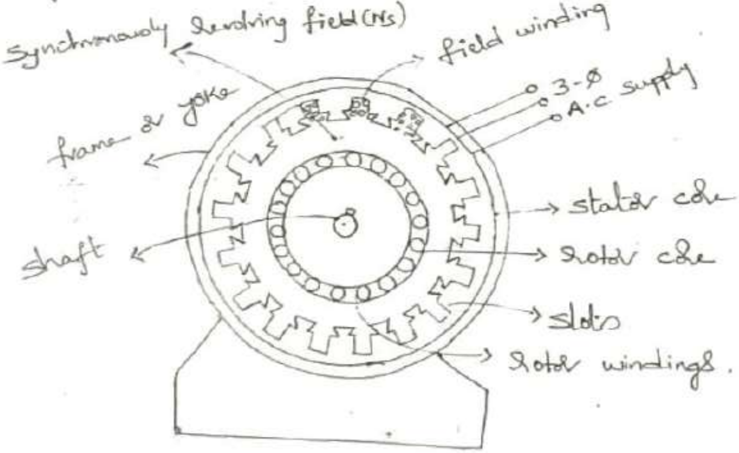
In case of Induction motor (slip ring) both electrical & mechanical domains possible in case of squirrel cage I.M only mechanical domain is possible because both ends are shorted.

→ Constructional details :~

the 3-ø I.m is vely simple in construction comp red to dc motor & a synchronous motor. the main palts consist of

1) frame & yoke
2) laminated stator cole
3) laminated Rotor cole
4) Squirrel cage & slip Ring Rotor
5) shaft and Bearings.

the below figure will shows constructional over view of an Induction motor.



1) frame :~ It is the outer body of the motor.

functions :

→ Support the stator cole and winding to protect the inner palts i.e mechanical strength and serve as a ventilating house

– Machines upto 50KW Rating may have frame die-cast in a strong silicon - aluminium alloy.

→ for large motor 250KW to 10,000KW the frames are generally fabricated in the form of box-type almost Exclusively fabricated.

→ the process of die-casting has the advantage. it facilitates the use of "thicker cross-section of frame" where greater mechanical strength is required.

2) Stator cole :

→ In order to Reduce eddy currents & hysteresis loss in the stator cole it is assembled of high grade, low electrical loss, silicon steel punchings.

→ the thickness of punchings varies from 0.35mm to 0.5mm

→ the stampings are assembled under hydraulic pressure and are keyed to the frame.

→ the air gap b/w the stator is made as small as practicable. for small machines 0.3 to 0.35mm and for high power machine 1 to 1.5mm.

→ field winding

→ motors upto 250KW operate usually at voltages in the Range of 380 – 440V. 250 to 300KW motors are in the Range of 3.3KV and > 750KW are in the Range 11KV.

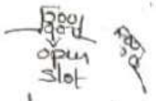
→ the 3-ø of the winding can be connected in either Y/Δ depending upon the methods of starting used.

→ generally concentric & distributed winding are going to be Employed based on the Requirements.

Slots :

→ open type slot :

→ this type of slots also facilitates in removal and replacement of defective coils.



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

→ In open type slots reactance is less. $\downarrow X_L = 2\pi f L \downarrow$

→ In alternator, dc machines use open type slot.

*→ dis advantage of distributing the air gap flux into branches which tends to produce ripples in the Emf wave.

→ Semi open type slot :

→ In these type of slot reactance is more as compare to open type.

→ harmonics are reduces.

→ generally semi open type slots are Employed in Induction motor.

→ In large, high speed motors pole pitch is large, so the desired flux density in the air gap can be attained with out an Excessive magnetising current. Even if open type slots are Employed.

→ **closed type slot** :

→ In these type of slot reactance is more as compared to open & semi open type slot.

*→ the main draw back of this slots are in closed type manner if any faults are take place internally or Externally. it may have chance to damage the windings. to identify, which winding is damaged. it is difficult.

3> **Rotor core** :

→ the rotor comprises a cylindrical laminated iron core, much the same as that of a dc machine, with slots around the core, carrying the rotor conductors.

→ sheet steel laminates are Employed for rotor as well as stator.

→ due to the lower frequencies of the rotor flux, thicker laminations can be Employed with out Excessive iron loss.

4> a) **Squirrel cage rotor**

→ Almost 90% of I.M are provided with squirrel cage rotor because of its very simple, robust & almost indestructible construction.

→ upto 100 kw rotor is made of aluminium cast under pressure will be plated welded securely to the end rings.

→ In cage construction Copper, brass or aluminium bars are placed.

→ At both ends of the rotor, the rotor conductors are all short circuited by the continuous end rings of similar material. to that of the rotor conductors.

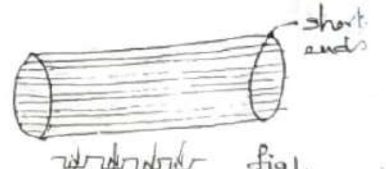


fig1.

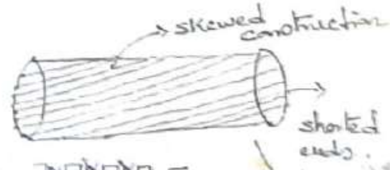


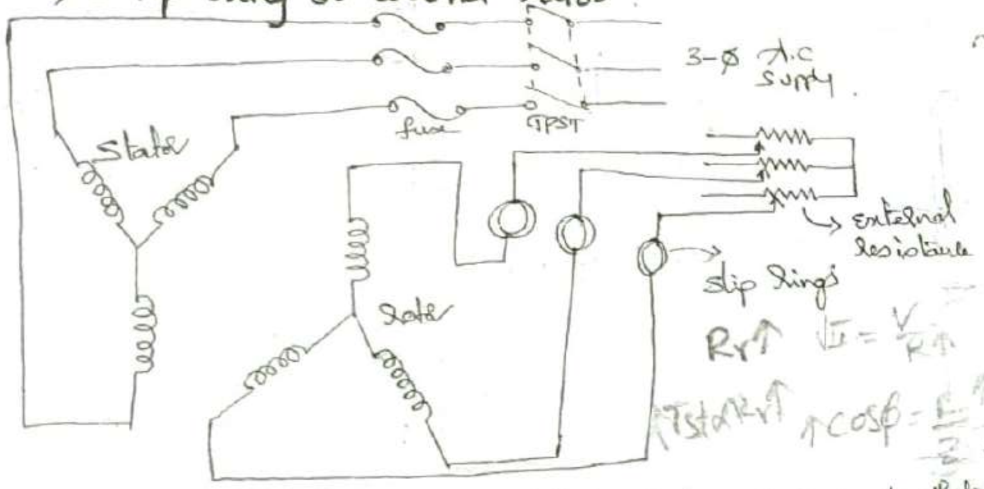
fig2

→ purpose of skewed construction.

→ to reducing the magnetic locking phenomenon (stall to re-flux).

→ it requires less magnetising current because the effective cross-sectional area of the air-gap is increased.

b) Slip ring or wound rotor:



-> Rotor is wound with an insulated winding similar to that of the stator except that the no. of slots is smaller and fewer turns per phase of a heavier conductors are used.
-> Bar, strap, or wire is used for rotor windings connection are either Y or Δ.
-> A large no. of rotor turns increases the secondary voltage and reduces the current that flows through the slip-rings.
-> The rotor can be wound for 2-ϕ, 3-ϕ even stator wound for 3-ϕ but in actual practise rotor is wound for 3-ϕ.

*-> functions of External resistance
-> it increase the starting torque $T_{st} \propto R_2$
-> it reduces the starting current drawn by the I.m
-> We can vary the speed of I.m by varying the resistance
-> Rotor P.f is increased $\uparrow \cos\phi = \frac{R_2\uparrow}{Z_2}$ of current.

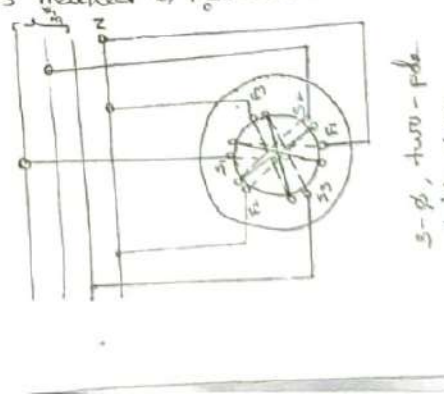
*-> Squirrel cage I.m are used where excellent running characteristics are required.
*-> slip ring I.m are used where high starting torque are required.

5) Shafts & Bearings.
-> the rotor shaft is made cast iron or cast steel.
-> the rotor shaft is supported by bearings housed in the end shield.
-> the rotor shaft must be made short & stiff so that the rotor may not have any significant deflection.
-> Ball & roller bearings are generally employed as their use makes accurate centring much simpler than with journal bearings.

Production of Rotating magnetic field

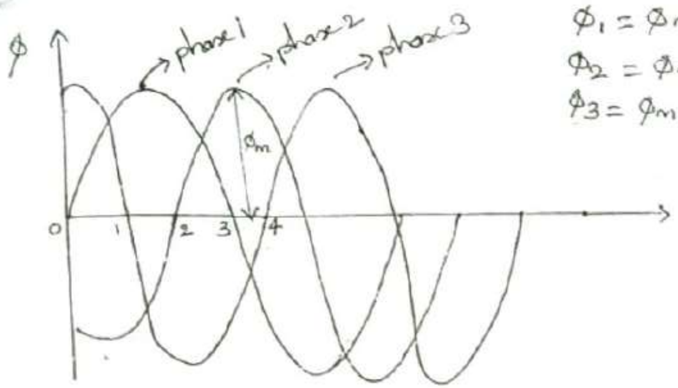
Consider three similar coils A, B and C are displaced in space by 120° as shown in fig. the flux assumed to be sinusoidal due to 3-ϕ windings as shown in fig.

Let the maximum value of flux due to any one of the three phases be ϕ_m. the resultant flux ϕ_r at any instant is given by the vector sum of the individual fluxes, ϕ_1, ϕ_2 and ϕ_3 due to three phases. we will consider values of ϕ_r at four instants 60° or 1/6th time period apart corresponding to points marked 0, 1, 2, and 3 as shown in fig.

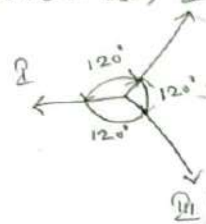


3-ϕ, two-pole stator I.m

(5)



$\phi_1 = \phi_m \sin \omega t$
$\phi_2 = \phi_m \sin(\omega t - 120°)$
$\phi_3 = \phi_m \sin(\omega t - 240)$



→ Case 1 : when $\theta = 0$

here $\phi_1 = 0$, $\phi_2 = \phi_m \sin(\omega t - 120)$, $\phi_3 = \phi_m \sin(\omega t - 240)$

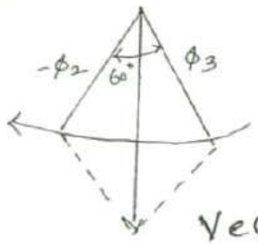
$\phi_2 = \phi_m \sin(0 - 120)$ $\quad$ $\phi_3 = \phi_m \sin(0 - 240)$

$\phi_2 = -\sqrt{3}/2\, \phi_m$ $\quad$, $\phi_3 = \sqrt{3}/2\, \phi_m$

$\therefore \phi_r = \sqrt{|\phi_2|^2 + |\phi_3|^2 + 2|\phi_2||\phi_3| \cos\alpha}$

$\therefore \phi_r = \sqrt{\left(-\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2\left(\frac{\sqrt{3}}{2}\phi_m\right)\left(-\frac{\sqrt{3}}{2}\phi_m\right)\cos 60}$

$\therefore \boxed{\phi_r = 1.5\,\phi_m}$



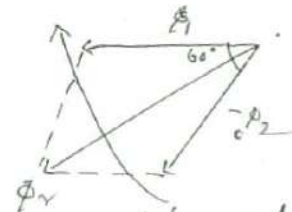
Vector diagram for $\theta = 0°$

→ Case 2 : when $\theta = 60°$

$\therefore \phi_1 = \sqrt{3}/2\, \phi_m$, $\phi_2 = -\sqrt{3}/2\, \phi_m$, $\phi_3 = 0$

$\phi_r = \sqrt{|\phi_1|^2 + |\phi_2|^2 + 2|\phi_1||\phi_2| \cos\alpha}$

$\therefore \boxed{\phi_r = 1.5\,\phi_m}$

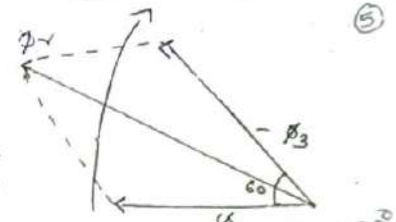


Vector diagram for 60°

→ Case 3 : when $\theta = 120°$

$\therefore \phi_1 = \frac{\sqrt{3}}{2}\phi_m$, $\phi_2 = 0$, $\phi_3 = -\frac{\sqrt{3}}{2}\phi_m$

$\therefore \boxed{\phi_r = 1.5\,\phi_m}$ $\quad$ $\phi_r = \sqrt{|\phi_1|^2 + |\phi_3|^2 + 2|\phi_1||\phi_3| \cos\alpha}$

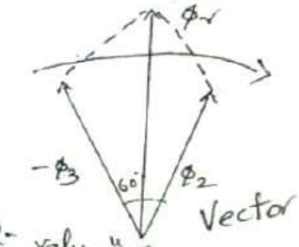


V.d – $\theta = 120°$

→ Case 4 : when $\theta = 180°$

$\therefore \phi_1 = 0$, $\phi_2 = \frac{\sqrt{3}}{2}\phi_m$, $\phi_3 = -\frac{\sqrt{3}}{2}\phi_m$

$\therefore \boxed{\phi_r = 1.5\,\phi_m}$ $\quad$ $\phi_r = \sqrt{|\phi_2|^2 + |\phi_3|^2 + 2|\phi_2||\phi_3| \cos\alpha}$

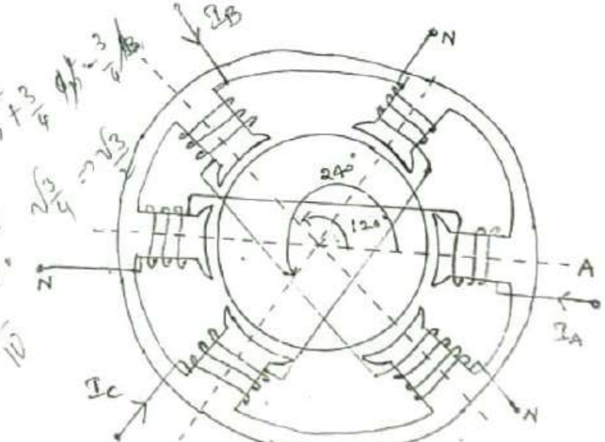


Vector

the resultant flux is of constant value "$\phi_r = 1.5\,\phi_{max}$" i.e 1.5 times the maximum value of the flux due to any phase. the resultant flux rotates around the stator at synchronous speed given by $N_s = 120f/P$.

→ **Principle of operation** :

$\frac{3}{4}\phi_m^2 + \frac{3}{4}\phi_m^2$



3-ϕ Induction motor.

$\phi_r = 1.5\,\phi_m$

when the stator or primary winding of a 3-ø Induction motor is connected to a 3-ø AC supply, a rotating magnetic field is established which rotates at synchronous speed. the direction of revolution of this field will depend upon the phase sequence of the primary currents. the direction of rotation of the field can be reversed by interchanging the connection to the supply of any two leads of a 3-ø Induction motor.

the no. of magnetic poles of the revolving field will be the same as the no. of poles for which each phase of the primary or stator winding is wound. the speed at which the field produced by the primary currents will revolve is called the synchronous speed of the motor and is given by

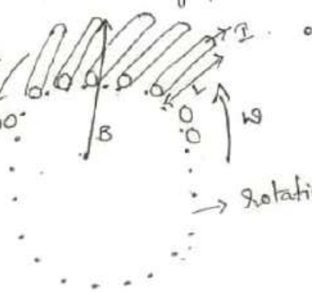
$$N_s = \frac{120f}{P}$$

$\because N_s \rightarrow$ synchronous speed

$\because f \rightarrow$ supply frequency

$\because P \rightarrow$ no. of poles on stator

As the rotating magnetic field produced by the primary currents sweeps across the rotor conductors an Emf is induced in these conductor just as an Emf is induced in the secondary winding of a transformer by the flux set up by the primary by the "induction principle".



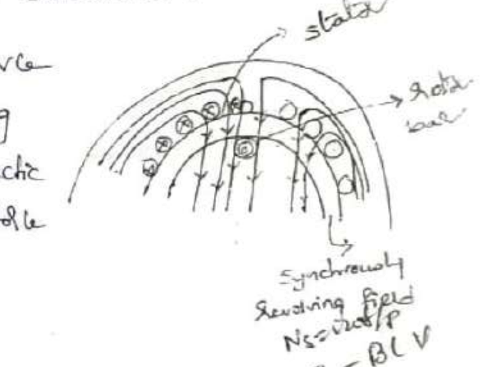
... = BlV

$\because e$ = rotating magnetic field

$\because l$ = length of the conductor

$\because v$ = relative velocity b/w field and conductors.

since the rotor winding is either directly shorted or closed through some external resistance. the Emf induced in the secondary by the revolving field causes a current to flow in the rotor conductors.



According to lorentz's force law. when a current carrying conductor placed in a magnetic field it will experience a force and it is given by

$$F = Bil$$

$\because B \rightarrow$ magnetic field

$\because i \rightarrow$ current through rotor conductors.

$\because l \rightarrow$ length of the conductor.

this force will push the rotor. then rotor starts catching the synchronously revolving field. or in other words the inter action of stator flux and rotor flux will cause the tendancy of rotation of the rotor.

when the rotor is stationary and about to start, the frequency of induced Emf in the rotor is equal to that of the supply fed to the stator. because the relative motion is at synchronous speed. As the motor picks up the speed. the relative motion b/w the rotor and the synchronously rotating magnetic field becomes less and

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Slip

The difference between the speed of a stator field known as synchronous speed (N_s) and the actual speed of the rotor (N_r) is known as slip. And it is denoted by 's', it is measured in RPM or radians per second.

$$\text{percentage slip} = \frac{N_S - N_R}{N_S} \times 100$$

At normal load the slip of Induction motor usually between 2 to 5 percent. At no load 0.5%.

- As the load increased (or) applied, the natural effect of the load torque is to cause the machine to slow down, and as it does so, slip increases.

→ ROTOR EMF AND ROTOR FREQUENCY

Rotor EMF

When the rotor is at standstill, the motor is equivalent to a 3-ϕ Transformer with secondary short circuited. So induced EMF in the rotor at standstill condition.

$$E_2 = E_1 \times \frac{N_2}{N_1}$$

when E_1 is applied to stator winding, N_2 & N_1 are the no. of turns per phase on rotor & stator respectively.

→ when the rotor starts running, the relative speed of the rotor w.r.to stator flux i.e., slip 's' will be consider of ~~the~~ secondary induced EMF.

At slip 's', the induced EMF per phase in rotor w/g $E_2 = sE_2$

Rotor Frequency (or) Frequency of rotor current (OR EMF)

the rotor of an Induction motor runs in the direction of rotating magnetic field. when the rotor is stationary, rotor conductors are being cut by the rotating flux at Synchronous speed $(N_s) = \frac{120f}{P}$.

- Therefore the frequency of rotor current (or Emf) is same as that of supply frequency.
- But rotor starts rotating (or) revolving, the rate at which the rotor conductors are being cut by the rotating flux depends upon the relative speed between the rotor and stator revolving magnetic field called the slip speed

$$\text{Rotor Emf frequency } f' = \frac{\text{Relative speed in Rpm}}{120/P} \Rightarrow \frac{N_s - N_R}{120/P} \quad \text{—} ①$$

$$\text{Slip} \cdot s = \frac{N_s - N_R}{N_s} \Rightarrow sN_s = N_s - N_R.$$

$$N_s - N_R = s \times \frac{120f}{P} \quad \text{—} ②$$

Sub ② in ①

$$\text{Rotor EMF frequency } f' = s \times \frac{120f}{P} \times \frac{P}{120}$$

$$\boxed{f' = sf}$$

Hence the frequency of rotor EMF (or) current in an I.M is given by the product of slip 's' and supply frequency 'f'. i.e, it is called "slip frequency".

→ Rotor Reactance, Rotor current and power factor at standstill and under running conditions.

→ The circuit diagram of an induction motor rotor is given by Fig1.

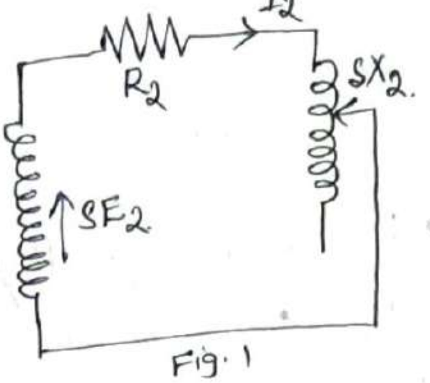


Fig. 1

- Let the resistance and inductance per phase of rotor be R_2 and L_2 resp. and induced EMF/phase in rotor at standstill be E_2

At standstill i.e., Rotor

Induced EMF/phase in rotor $= E_2$

Rotor winding Resistance/phase $= R_2$

Rotor winding Reactance/phase $X_2 = 2\pi f L_2$ $\because f =$ supply frequency

Rotor winding impedance/phase $Z_2 = \sqrt{R_2^2 + X_2^2}$

Rotor current $$I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$$

p.f of rotor current $$\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$$ $\because \frac{R}{Z} = \cos\phi$

At slip 's' : During Running condition

Induced EMF per phase in rotor winding $= sE_2$

Rotor w/g Resistance/phase $= R_2$.

Rotor w/g Reactance/phase$(X_2) = 2\pi f' L_2$ $\because f' = sf$

$$= 2\pi sf L_2 \Rightarrow s(2\pi f L_2) \Rightarrow sX_2$$

Rotor w/g impedance per phase $\sqrt{R^2 + (sX_2)^2}$

Power factor of Rotor current $$\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

(4)

Rotor current per phase $I_2 = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$

'I_2' can be rewritten as $I_2 = \frac{sE_2}{\sqrt{s^2\left[X_2^2 + \left(\frac{R_2}{s}\right)^2\right]}} \Rightarrow \frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2}}$ — (1)

The eq(1) gives convenient form of rotor equivalent circuit as shown fig2

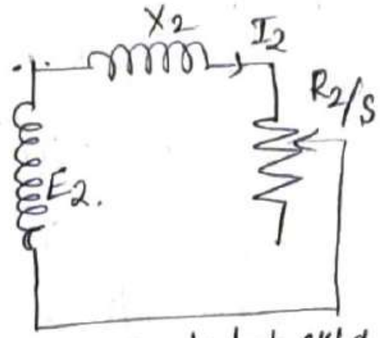


Fig2: Equivalent Ckt of Rotor

- The resistance R_2/s is a function of slip and can be splitted into two parts R_2 and $R_2\frac{(1-s)}{s}$ where R_2 is rotor resistance and $R_2\frac{(1-s)}{s}$ is the fictious resistance representing electrical load on the Rotor. The final simplified equivalent circuit of I.M. rotor is given Fig 3.
- The power consumed by fictious R is $I_2^2 R_2\frac{(1-s)}{s}$.

$$\boxed{\because \frac{R_2}{s} = R_2 + \frac{R_2(1-s)}{s}}$$ (split)

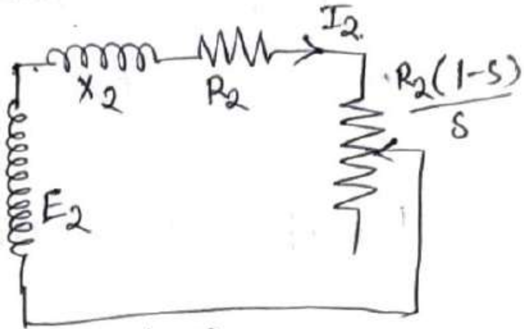


Fig. 3

STANDSTILL

- When rotor at stationary, i.e., $s=1$, the frequency of rotor EMF is same as supply frequency
- EMF induced in rotor is maximum because the relative speed between rotor and revolving stator flux is maximum

During RUNNING condition

- When rotor starts running, the relative speed b/w rotor and rotating stator flux is decreased. Hence induced rotor EMF also decreases. Similarly frequency is $f' = sf$

$\because$ EMF $E_2 = sE_2$

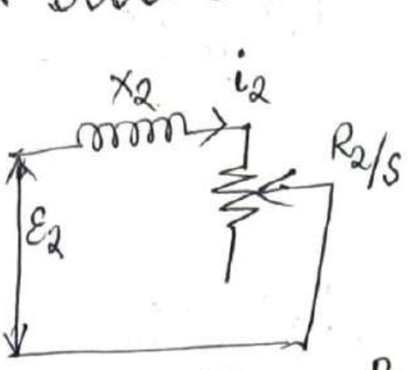
$\because$ Frequency $F_2' = sf_2$

$\because$ Reactance $X_2 = sX_2$

(5)

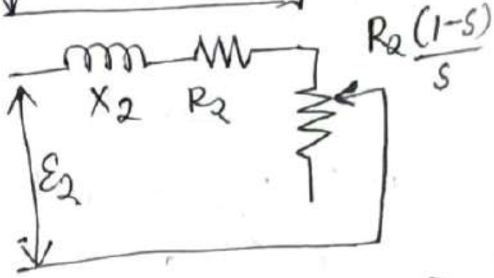
Relationship between power Input, copper losses and Mechanical power for Rotor

The rotor equivalent circuit as shown



Air gap power (or) stator output $P_g = E_2 I_2 \cos\phi_2$

$$P_g = E_2 I_2 \left[\frac{R_2}{s\sqrt{\left(\frac{R_2}{s}\right)^2 + x_2^2}}\right] \quad \because \cos\phi_2 = \left[\frac{R_2}{\sqrt{R_2^2+(sX_2)^2}}\right]$$



$$P_g = E_2 I_2 \left[\frac{R_2/s}{\sqrt{(R_2/s)^2 + x_2^2}}\right]$$

$$P_g = I_2 \frac{R_2}{s}\left[\frac{E_2}{\sqrt{(R_2/s)^2 + x_2^2}}\right] \Rightarrow I_2^2 R_2/s \qquad \because I_2 = \left[\frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2 + x_2^2}}\right]$$

$\frac{R_2(1-s)}{s}$ = Electric power to Rotor per phase

Put input to the rotor i.e., air gap power "P_g".

$$P_g = I_2^2 R_2/s \text{ - per phase;} \quad P_g = 3 I_2^2 \frac{R_2}{s} \text{ for 3-}\phi$$

P_g is the power transferred from stator to rotor across the air gap in the view of the P_g is called air gap power.

P_g can be rewritten as
$$P_g = I_2^2 \frac{R_2}{s}$$
$$= I_2^2\left[R_2 + R_2\left[\frac{1-s}{s}\right]\right]$$
$$= I_2^2 R_2 + I_2^2 R_2\left[\frac{1-s}{s}\right]$$
$$= sP_g + (1-s)P_g$$

$\because \frac{R_2}{s} = R_2 + R_2\left[\frac{1-s}{s}\right]$

$\because P_g = I_2^2 R_2/s$

$I_2^2 R_2 = s P_g$

P_g = Rotor ohmic loss + Internal mechanical power

$$P_g = P_c + P_m$$

$$P_m = I_2 \frac{R_2}{s}(1-s) \Rightarrow (1-s) P_g$$

Cu loss/phase: $P_c = I_2^2 R_2$

(6)

Rotor input : copper losses : Mechanical power

$$P_g : P_c : P_m = \cancel{I_2^2} R_2/s : \cancel{I_2^2} R_2 : \cancel{I_2^2} \cancel{R_2}\left[\frac{1-s}{s}\right]$$

$$= \frac{1}{s} : 1 : \frac{1-s}{s}$$

$$\boxed{P_g : P_c : P_m = 1 : s : 1-s}$$

Conclusion :- If some power P_g is delivered to a rotor, then a part sP_g is lost in the rotor itself as copper loss (and appears as heat) and remaining $(1-s)P_g$ appears as gross mechanical power P_m (including friction and windage loss)

Torque Equation

Torque is the twisting force that tends to cause a rotation.

It is measured in "N-m"

We know that Torque formula through Power = Torque x Angular speed

$$\text{Torque} = \frac{P}{W}$$

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

Rotor Torque Developed

$$T = \frac{P_m}{\frac{2\pi N_R}{60}} \Rightarrow \frac{60}{2\pi}\left[\frac{P_m}{N_R}\right]$$

$\because P_m = (1-s)P_g$

$$= \frac{60}{2\pi N_R}\left[P_m\right] \Rightarrow \frac{60}{2\pi}\left(\frac{(1-s)P_g}{N_R}\right)$$

$$= \frac{60}{2\pi} \times \frac{1}{N_R}\left[(1-s)P_g\right]$$

$$= \frac{60}{2\pi} \times \frac{1}{N_R}\left[\left[1-\left[\frac{N_s-N_R}{N_s}\right]\right]P_g\right]$$

$$= \frac{60}{2\pi} \times \frac{1}{N_R}\left[\left(\frac{\cancel{N_s}-\cancel{N_s}+N_R}{N_s}\right)P_g\right]$$

$$= \frac{60}{2\pi} \times \frac{1}{\cancel{N_R}} \times \left(\frac{\cancel{N_R}}{N_s}\right)P_g$$

$$= \frac{60}{2\pi N_s} P_g \Rightarrow \frac{60}{2\pi N_s} \times 3 I_2^2 \frac{R_2}{s}$$

$$= \frac{60 \times 3}{2\pi N_s}\left[\left[\frac{s^{\cancel{2}} E_2^2}{\left(\sqrt{R_2^2+(sX_2)^2}\right)^2}\right]\frac{R_2}{\cancel{s}}\right]$$

Power Input Torque $= \frac{180}{2\pi N_S}\left[\frac{S E_2^2 R_2}{R_2^2+(SX_2)^2}\right]$

Running Torque(or) F.L. Torque

$$\boxed{T = K \frac{S E_2^2 R_2}{R_2^2+(SX_2)^2}} \quad \text{— (1)}$$

The running torque is directly proportional to the Square of the supply voltage, because rotor induced EMF is proportional to supply voltage

- At standstill condition (or) starting torque

The torque developed by the motor at the instant of starting is called starting torque.

At standstill $S=1$, because $S = \frac{N_S-N_R}{N_S}$; $S=\frac{\cancel{N_S}-0}{\cancel{N_S}} \Rightarrow 1$ i.e; $N_R=0$

Sub $S=1$ in eq(1)

$$\boxed{T_{st} = \frac{K E_2^2 R_2}{R_2^2+X_2^2}}$$

Alternate Method for Torque Equation

$T \propto E_2 I_2 \cos\phi_2$ (or) $T \propto \phi I_2 \cos\phi_2$

E_2 = Rotor EMF/phase; I_2 = Rotor current/phase

Now $E_2 = SE_2$; $I_2 = \frac{E_2}{Z_2} \Rightarrow \frac{SE_2}{\sqrt{R_2^2+(SX_2)^2}}$; $\cos\phi_2 = \frac{R_2}{\sqrt{R_2^2+(SX_2)^2}}$

$T \propto \phi I_2 \cos\phi_2$ — (a)

Sub above equation in eq(a)

$$T \propto \phi \times \frac{SE_2}{\sqrt{R_2^2+(SX_2)^2}} \times \frac{R_2}{\sqrt{R_2^2+(SX_2)^2}}$$

constant, w.k.T $\therefore K_1 = \frac{3}{2\pi N_s}$

$$T = K\phi \frac{SE_2^2 R_2}{R_2+(SX_2)^2} \Rightarrow \frac{K_1 SE_2^2 R_2}{R_2^2+(SX_2)^2}$$

Condition for Maximum Torque.

We know that, The torque of a rotor under running conditions. from eq① $T = K \frac{SE_2^2 R_2}{R_2^2+(SX_2)^2}$

The condition for maximum torque may be obtained by diff the above expression w.r.to slip 's' and putting it equal to '0'.

i.e., $\frac{dT}{ds} = 0 \Rightarrow \frac{d}{ds}\left[\frac{K SE_2^2 R_2}{R_2^2+(SX_2)^2}\right] = 0$ $\quad \frac{d}{dt}\left(\frac{U}{V}\right) = \frac{VU'-UV'}{V^2}$

$$\Rightarrow \left[\left[R_2^2+(SX_2)^2\right](K E_2^2 R_2)\right] - \left[(K S E_2^2 R_2)(2SX_2^2)\right] = 0$$

$$\Rightarrow K E_2^2 R_2 \left[\left[R_2^2+(SX_2)^2\right] - (2S^2X_2^2)\right] = 0$$

$$R_2^2 - S^2X_2^2 = 0$$

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

$$\boxed{S_{T_{max}} = \frac{R_2}{X_2}}$$

Condition for maximum Torque (or) slip at which Max. Torque occurs

Substitute $S_{T_{max}} = \frac{R_2}{X_2}$ in eq① we get Maximum Torque

eq① $T = \frac{KSE_2^2 R_2}{R_2^2+(SX_2)^2}$

$$= \frac{K\left(\frac{R_2}{X_2}\right)E_2^2 R_2}{R_2^2 + \left(\frac{R_2}{\cancel{X_2}}\right)^2 \cancel{X_2^2}} \Rightarrow \frac{K \frac{\cancel{R_2^2}}{X_2} \times E_2^2}{2\cancel{R_2^2}}$$

$$\boxed{T_{max} = \frac{KE_2^2}{2X_2}}$$

In the above equation

NOTE

- Maximum Torque is independent of rotor resistance i.e, T_{max} does not depend on R_2
- T_{max} is directly proportional to the square of rotor induced EMF.

Relation (or) Ratio between Maximum Torque to Starting Torque

$$T_{max} = \frac{KE_2^2}{2X_2} \; ; \; T_{st} = K\frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

$$\frac{T_{st}}{T_{max}} = \frac{\left(\frac{KE_2^2 R_2}{R_2^2+X_2^2}\right)}{\frac{KE_2^2}{2X_2}} \Rightarrow \frac{\cancel{K}\cancel{E_2^2} R_2}{R_2^2+X_2^2} \times \frac{2X_2}{\cancel{K}\cancel{E_2^2}}$$

$$= \frac{2R_2X_2}{R_2^2+X_2^2} \Rightarrow \frac{2R_2\cancel{X_2}}{X_2^{\cancel{2}}\left[\left(\frac{R_2}{X_2}\right)^2+1\right]}$$

$$= \frac{2\left(\frac{R_2}{X_2}\right)}{\left[\left(\frac{R_2}{X_2}\right)^2+1\right]}$$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2} \qquad \because a = \frac{R_2}{X_2}$$

Relation between Full load Torque and Maximum Torque

$$T_{F.L} = \frac{KSE_2^2R_2}{R_2^2+(SX_2)^2} \; ; \; T_{max} = \frac{KE_2^2}{2X_2}$$

$$\boxed{\because \frac{T_{FL}}{T_{max}} = \frac{2aS}{S^2+a^2}} \quad \because a = \frac{R_2}{X_2}$$

$$\frac{T_{F.L}}{T_{max}} = \left(\frac{\cancel{K}S\cancel{E_2^2}R_2}{R_2^2+(SX_2)^2}\right)\times\left(\frac{2X_2}{\cancel{K}\cancel{E_2^2}}\right)$$

$$\frac{T_{FL}}{T_{max}} = \frac{2SR_2\cancel{X_2}}{X_2^{\cancel{2}}\left[\left(\frac{R_2}{X_2}\right)^2+S^2\right]} \Rightarrow \frac{2S\left(\frac{R_2}{X_2}\right)}{\left[S^2+\left(\frac{R_2}{X_2}\right)^2\right]} \Rightarrow \frac{2aS}{S^2+a^2}$$

Condition for obtaining maximum torque at starting

Obtaining Maximum Torque at starting means starting Torque equal to maximum Torque i.e., $T_{st} = T_{max}$.

$$T_{st} = \frac{KE_2^2 R_2}{R_2^2 + X_2^2} \quad ; \quad T_{max} = \frac{KE_2^2}{2X_2}$$

substitute $R_2 = X_2$ in T_{st} eq. we get

$$T_{st} = \frac{K E_2^2 X_2}{\cancel{X_2^2} + X_2^2} \Rightarrow \frac{K E_2^2 \cancel{X_2}}{2X_2^{\cancel{2}}}$$

$\because T_{st} =$
$S = 1$
$\because S = \frac{R_2}{X_2}$
$R_2 = X_2$

$$T_{st} = K \frac{E_2^2}{2X_2}$$

$$T_{st} = T_{max}.$$

In order to obtain $T_{st} = T_{max}$, the condition is $\boxed{R_2 = X_2}$

Equivalent circuit of an Induction Motor

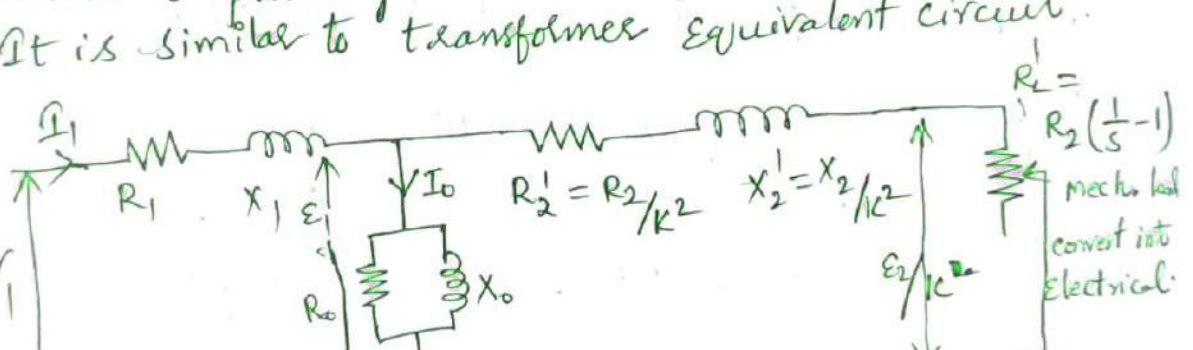
The energy is transferred from primary to secondary winding i.e., stator to rotor windings respectively entirely by induction therefore induction motor is essentially a transformer.

At standstill, the induction motor is actually a static transformer having its secondary (rotor) winding short circuited.

- Actually the rotor field does not exist alone but combines with the revolving field of stator to produce a resultant field. Just like a Transformer.
- Generally, In transformer load is electrical, and in an induction motor the load is mechanical which can be replaced by an electrical load of Resistance $R_L' = R_2\left(\frac{1}{s}-1\right)$

Now the equivalent circuit of an Induction motor referred to primary.

- It is similar to transformer Equivalent circuit.



In, transformer no load current 2 to 5% FL c/t but in an Induction motor no load current is 30 to 50% of Full load current. So that we can't neglect no load branch parameters.

- In the above equivalent circuit, where V_1 is applied Voltage, R_1 & X_1 are the stator resistance & leakage reactance per phase respectively. R_2 and X_2 are the rotor resistance and leakage reactance per phase respectively at standstill.

rotor current has the ... condition ...

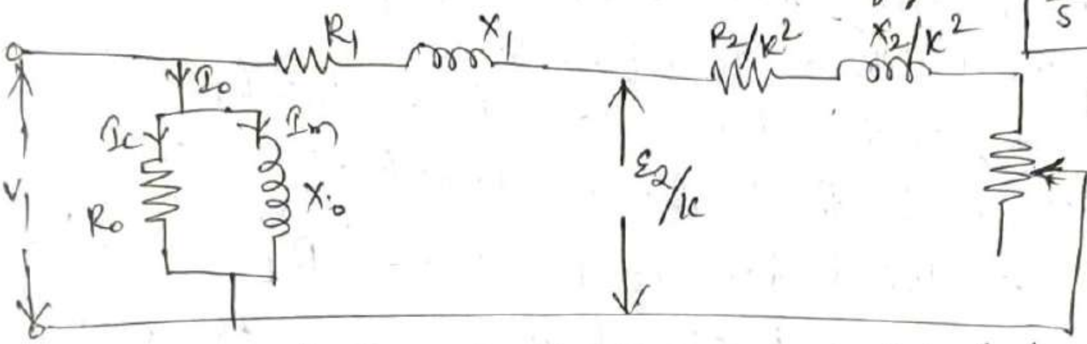
2

K = Turns ratio; R_o & X_o = No load Resistance and Reactance res

- At no load, the impedance drop very small. can be neglected.
- The no load current, which supplies core losses and copper losses of stator.

→ E_1 is induced Emf per phase in the stator and is equal to applied voltage. E_2 is Emf induced in the rotor. It is assumed that the mechanical load is replaced by Equivalent electrical load as shown above fig.

$$\boxed{\frac{R_2}{S} = R_2 + R_2\left(\frac{1-S}{S}\right)}$$



the Equivalent circuit can be simplified by transferring no load component current to the supply terminals

phasor diagram of an Induction motor

The phasor diagram of an Induction motor similar to transformer except no load current is high due to air gap (of high reluctance). So that I.M requires high magnetising current.

The induced Emf in the rotor w/g is $SE_2 = E_2'$

$$I_2 = \frac{SE_2}{\sqrt{(R_2)^2+(SX_2)^2}} \text{ (or) } \frac{E_2}{\sqrt{\left(\frac{R_2}{S}\right)^2+(X_2)^2}}$$

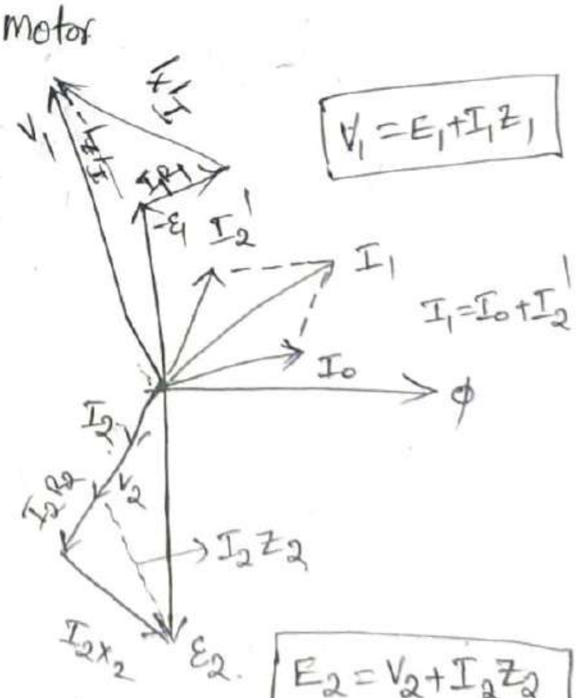


fig phasor diagram

As in transformer, an emf $E_1 = \frac{\omega_2}{K}$ in induced in the stator.
where $I_m + I_c = I_0$;. I_m, I_c – magnetising, working currents
• stator current I_1 - is phasor sum of I_1' and I_0.
i.e., $\boxed{I_1 = I_2' + I_0}$ where I_2' – Counter balancing secondary(r/r current and is equal to KI_2.
$I_1 R_1$ and $I_1 X_1$ are the resistive and reactance drops of Stator.

$$\boxed{V_1 = -E_1 + I_1 R_1 + I_1 X_1}$$

Torque slip and Torque speed curves

Torque developed by an Induction motor is given as

$$T = \frac{K S E_2^2 R_2}{R_2^2 + S^2 X_2^2}$$

From the above equation
i) when speed is synchronous i.e, when slip S is zero, the torque T is zero So the torque slip curve start from origin
(ii)

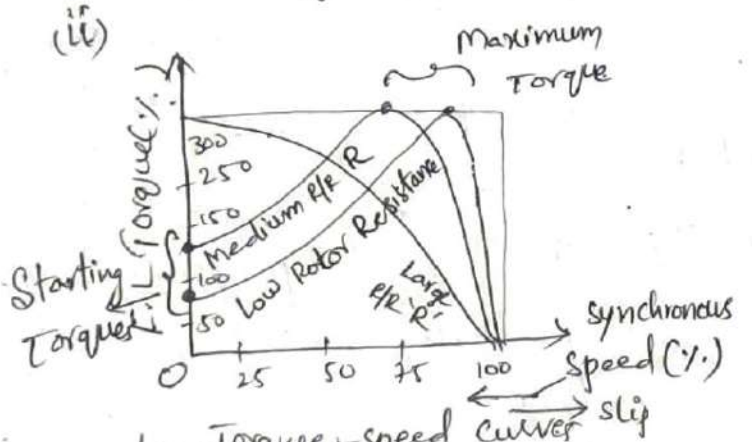


fig 1: Torque-speed curves

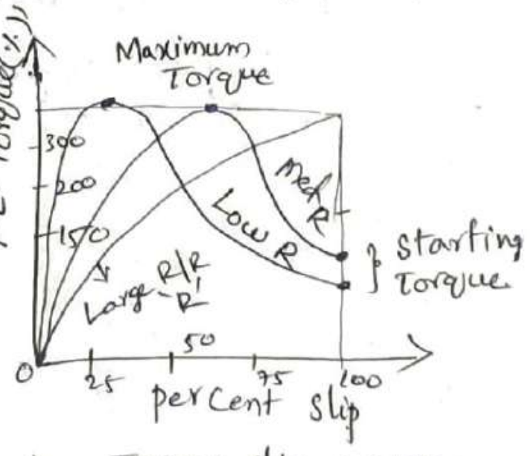


fig 2. Torque slip curves

Torque Speed and Torque slip curves are shown for different values of rotor resistance.

ii) when the speed is very near to synchronous speed N_S i.e, when slip is very low the value of term sX_2 is very small and is negligible in comparison with rotor resistance R_2.

∴ Torque is approximately proportional to slip 's'.

If rotor resistance R_2 is constant i.e., at speeds near synchronous speed the Torque speed and torque slip curves are approx. straight line as shown in fig.

(iii) As the slip increases i.e, as the speed drops with increase in load, Torque increases, reaches its maximum value when slip $s_m = \frac{R_2}{X_2}$.

The maximum Torque is also known as "Breakdown or pull out Torque". The slip corresponding to breakdown torque is called the breakdown slip 's_b'

(iv) with further increase in slip (or) drop in speed due to increase in load beyond the point of maximum Torque, the Torque begin to decrease. The result is that the motor slows down and eventually stops.

From fig 2. It is cleared that when $s=0$, $T=0$, hence the curve starts from origin $\because T \propto \frac{K \phi s E_2 R_2}{R_2^2 + (sX_2)^2}$

• At Normal speed close to synchronism, the term sX_2 is small and hence negligible w.r.to R_2 $\therefore T \propto \frac{s}{R_2}$ (or) $T \propto s$ if R_2 = const.

• Hence for low values of slip, the Torque/slip approx. straight line. As slip increases (for increasing load on the motor), the torque also increases and becomes maximum when $s = R_2/X_2$.

Therefore the torque is known as pullout (or) Breakdown (or) stalling Torque (T_b).

• As the slip further increases (i.e., motor speed falls down) (i.e, load)↑

• Large values of slip $\boxed{T \propto \frac{1}{s}}$. Torque/slip curve is Rectangular Hyperbola

Power flow diagram of an Induction motor

The power flow diagram for a typical Induction motor indicates how the electrical power supplied to the stator winding is converted into useful mechanical power available at the shaft.

- A part of this power is consumed in stator iron and copper losses. The remaining power is transferred inductively to the rotor through the air gap. This is called rotor input.

$$P_g = P_{in} - \text{Stator iron \& copper losses.}$$

- The rotor losses are dominantly copper losses, as rotor iron losses are neglected. because it is very small

$$P_m = P_g - \text{Rotor Cu losses}$$

i.e. P_m = mechanically power developed in the rotor.

A part of P_m is consumed as mechanical losses and the remaining is the power available to the load at the shaft this is called Net output power of the motor, P_{out}

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

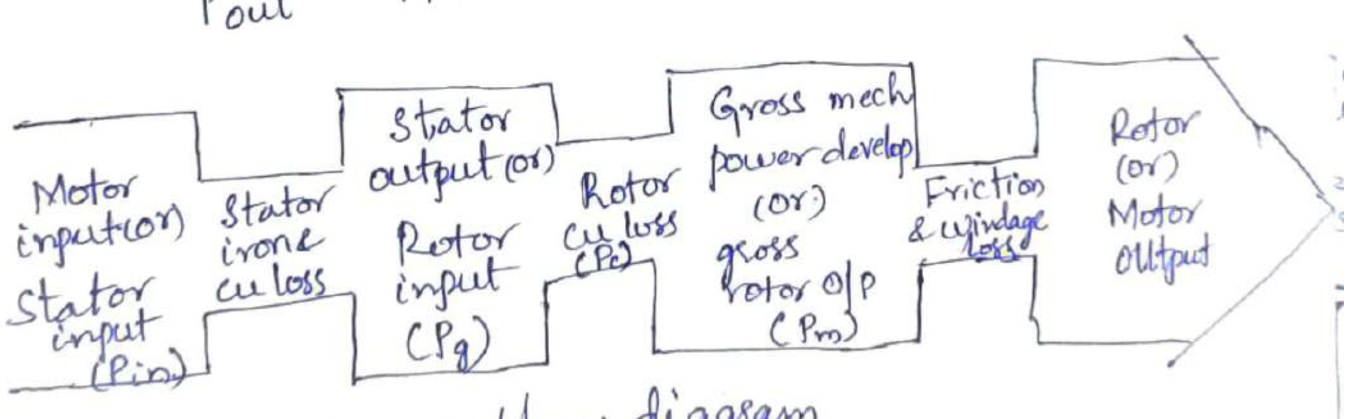


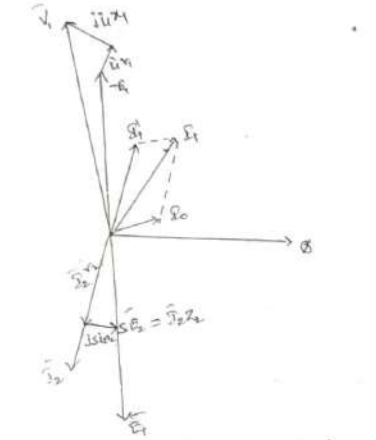
Fig. power flow diagram

- Finally we obtained the (about 88.5% of power input to the motor) is available at the motor shaft, called the mechanical power output.

... is the torque under running conditions

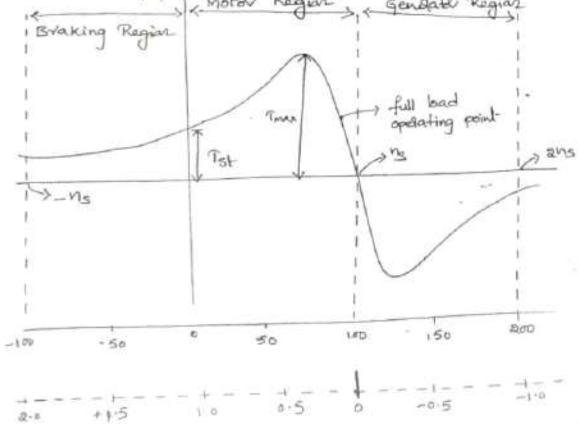
Power Stages of an Induction Motor

- Rotor input
  - Rotor output (or) Mechanical power developed
    - Rotor output
    - Windage & friction losses
  - Rotor copper losses
- Stator copper & iron losses



phasor diagram at full-load slip s.

Torque – slip characteristics :



(2)

$$T_{st} = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$$

$$T_{max} = \frac{K E_2^2}{2X_2}$$

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

the variation of torque with slip or speed of an induction motor can be plotted from above Eq. for different values of slip s and with the motor connected to constant-frequency voltage source. depending upon the value of slip an induction motor can have the following operating regions / modes.

a) Motoring mode ($1 \leq s \geq 0$)

Under normal operation, rotor revolves in the direction of rotating field produced by the stator currents. As such a slip varies from 1 at stand still to zero at synchronous speed i.e $1 \leq s \geq 0$. the rotor speed N_r is always less than the synchronous speed N_s. the corresponding speed values are zero $N_r = 0$ at slip $s = 1$. and synchronous speed N_s at slip $s = 0$. i.e $N_r = N_s$

b) Generating mode ($s < 0$)

In this operating mode, the rotor speed N_r is greater than the synchronous speed N_s ($N_r > N_s$). and slip is negative ($s < 0$). an induction motor will operate in this region only when its stator terminals are connected to constant frequency voltage source, and its rotor is driven above synchronous speed by a prime mover.

the connection of stator [illegible] is essential in order to establish the rotating air-gap field at synchronous speed. in case stator is disconnected from voltage source and rotor is driven above synchronous speed by the prime mover, now generating action would take place.

c) **Braking mode (S>1)**

In this mode, slip is greater than 1, A slip more than one can be obtained by driving the rotor, with a prime mover, opposite to the direction of rotating field. but such an use in practise is rare.

A practical utility of slip more than 1 (S>1) is obtained by bringing the rotor to a quick stop by braking action called plugging. for obtaining plugging, any two stator leads are interchanged. with this the phase sequence is reversed and therefore, the direction of rotating magnetic field becomes suddenly opposite to that of the rotor rotation. the electro magnetic torque Te, acting opposite to rotor rotation, produces the braking action. thus the motor can be quickly brought to rest by plugging, but the stator must be disconnected from the supply before the rotor can start in the other direction.

Effects of harmonic in I.M (7)

the components which has magnitude and frequency different or other then the fundamental are called as harmonics.

→ the main reason for production of harmonics are

→ Due to non-uniform air-gap (i.e air gap may have irregularities)

→ Due to rotor and stator slots

→ Due to the windings over hang

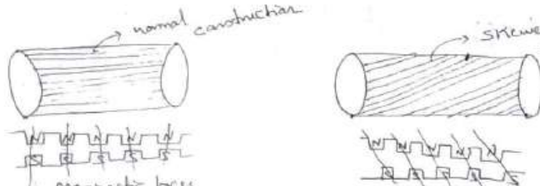
→ Due to saturation of magnetic circuit

→ If the applied voltage may be consist harmonics.

Cogging

Space (air gap) harmonic fields are developed by the windings, slotting, magnetic saturation, gap-length regularities. these harmonic fields induce Emf's and circulate harmonic currents in the rotor windings. these harmonic currents in the rotor interact with the harmonic fields and develop harmonic torques, vibration and noise.

with certain relationships b/w the no of poles & stator and rotor slots in cage rotor motors peculiar behaviour may be observed when the motor is started with the no. of stator slots S_1 equal to rotor slots S_2. when the magnectic locking take place b/w the stator and rotor at the time motor may refuse to start at all, a phenomenon called the "cogging"



these cogging phenomenon is more pronounced in case of squirrel cage induction motor as compared to slip ring induction motor because squirrel cage induction motor have the less starting torque (due to both ends are shorted together) as compared to slip ring I.M.

$\therefore \downarrow T_{st} \propto R_2 \downarrow$ (low)
(Squirrel cage)

$\therefore \uparrow T_{st} \propto R_2 \uparrow$ (due to External resistance
(slip ring I.M)

Crawling

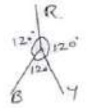
"With other ratios of rotor slot (S_2) to stator slot (S_1) the motor may exhibit a tendency to run stably at sub synchronous speed or other than the sub normal speed (N_s) (i.e constantly runs at $\frac{1}{7}$th of the synchronous speed), a phenomenon called the crawling"

In some cases excessive vibration may be set up at certain speeds below normal are, due to pulsations of mechanical force on the teeth, producing noise. the efficiency of the machine is also adversely affected because of stray load loss. these phenomena are much less prominent in wound rotor motors, because of their higher starting torques.

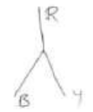
(8) A 3-ϕ winding carrying sinusoidal currents produces harmonics of the order of $n = 6m \pm 1$, where 'm' is an integer. the movement of harmonics is with & against the direction of rotation for positive and negative sign respectively. the no. of poles for the nth harmonic is n times the no. of poles of fundamental, and therefore, the synchronous speed of the nth harmonics is $\frac{1}{n}$th of the synchronous speed of the fundamental.

thus for m=1, a 3-ϕ winding will produce a forward rotating 7th harmonic rotating at speed of $\frac{1}{7}$th of synchronous speed

$\because n = 6m+1 = 6(1)+1 = 7^{th}$ order harmonic

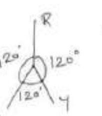


$\therefore 0°, 120°, 240°$



$\therefore 0°, 840°, 1680°$ same as fundamental

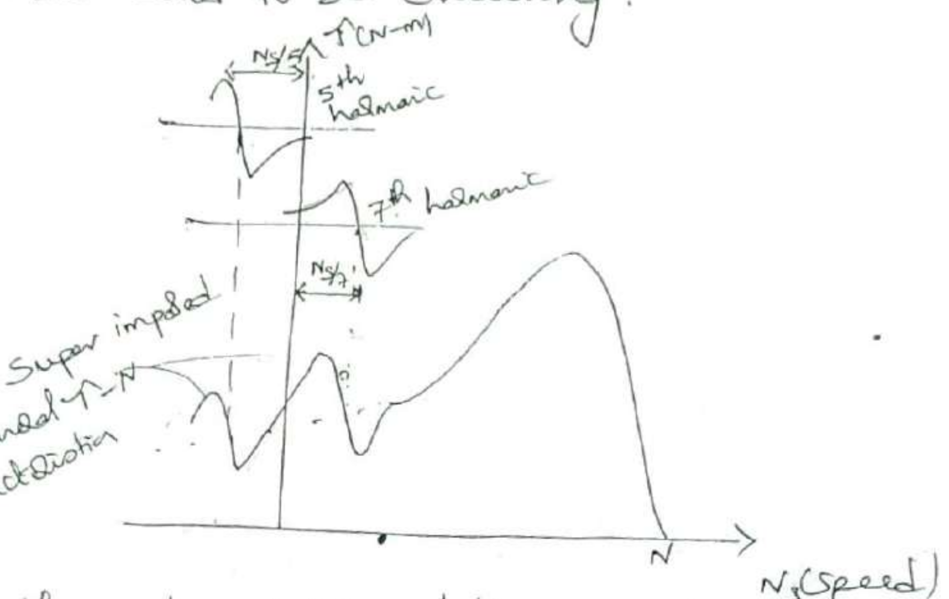
$\because n = 6m(+1) = 6(1)-1 = 5^{th}$ order harmonic



$\therefore 0, 120°, 240$

$\therefore 0°, 600°, 1200°$ anticlock wise to fundamental

A backward rotating 5th harmonic rotating at the speed of $\frac{1}{5}$th of synchronous speed. the 5th and 7th harmonic fluxes may be deemed as set up by sets of additional poles superimposed on the fundamental poles. they generate their emf's, currents and torque of the same general torque-speed shape as that of the fundamental but with ... speeds equal to 1/5 (backward) and 1/7 (forward). if the load torque is constant, the torque developed by the motor may fall below this load torque and when this occurs, the motor cannot accelerate to its full speed but continues to run at a speed a little lower than the 1/7th synchronous speed. the motor is now said to be crawling.



the order rotor slotting produces space harmonics of the order $\frac{S_2}{P} \pm 1$.

High torque cage motors

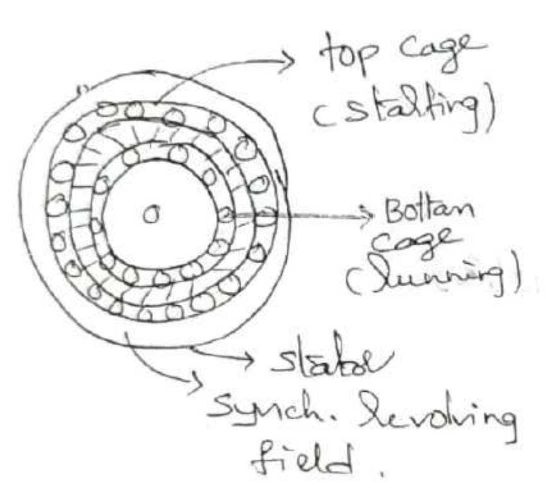
the great simplicity and Robustness of the cage motor are very characteristics of the motor from the st point of cost and maintance. the main draw back of a squirrel cage motor is its poor starting torque, because of its low ~~stat~~ rotor resistance.

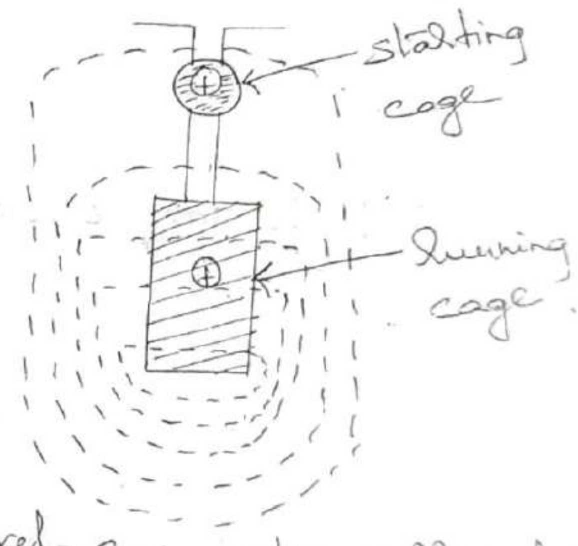
$$(\text{low}) \downarrow T_{st} \propto R_r \downarrow (\text{low})$$

If the rotor were made of high resistance to obtain a good starting torque with reasonable starting current. its rotor copper loss will increase and therefo

Double cage rotor motor

A rotor design, which through Expensive gives better starting and running characteristics than the deep bar design, is the double cage rotor. the double squirrel cage motor is designed to provide a high starting torque with a low starting current. the rotor is so designed that the motor operates with the advantages of high-resistance during starting and low-resistance under running conditions. Tst varies from 200 to 250% of full-load torque with starting current of 400 to 600% of full-load value. it is classed as a high-torque low starting current motor.





the rotor of a double squirrel-cage motor carries two squirrel cage windings Embedded in two rows of slots. the outer slots contains a high resistance and low leakage reactance are usually made up of manganese bars and the inner slots contain a low resistance and high leakage reactance winding are usually made up of red copper. the inner winding has greater cross-section than that of outer winding in order to have resistance 1/4th or 1/5th [illegible]

Circle diagram

It is a graphical method to analyse the performance of a 3-ϕ I.M. parameters like starting Torque, η, slip, p.f, max o/p & max. torque can be termined from the circle diagram

Construction

- the data available from no load and blocked rotor tests

1) the no load c/t and its p.f ϕ_0 can be obtained from the no. load test. the SC test current I_{sc} for v/t V_{sc} and its p.f angle ϕ_{sc} can be found out from the blocked rotor test. this c/t must be converted corresponding to the rated v/t V_1 of the motor. s/c current for normal voltage $I_{SN} = I_{sc}\left(\frac{V_1}{V_{sc}}\right)$

2) Draw a vertical line representing the rated voltage (V_1) reference phasor

3) select a suitable scale for current. Draw line OA lagging V_1 by an angle ϕ_0 equal to no. load current I_0.

4) Draw line OB lagging V_1 by an angle ϕ_{sc} equal to s/c current for normal voltage. Vector OB represents the rotor c/t I_2' as referred to stator

5. Join 'AB' represents the o/p line of the m/r.

6. A perpendicular bisector of the line AB is drawn cutting the horizontal line AD (drawn from A), at the point 'C', which is centre of the circle. Then with 'C' as centre and CA as radius, draw the semi circle ABD.

8) Draw a vertical line from the point 'B'. So as to meet the line 'AD' at the point 'F'. Divide BF in the ratio of rotor cu loss to stator cu loss at the point 'E' i.e.,

$$\frac{BE}{EF} = \frac{\text{Rotor cu loss}}{\text{Stator cu losss}}$$

* 1) Torque line

The line AE which ~~represents~~ separates the s/r & rotor cu loss is known as Torque line. (or) Rotor i/p line

- the rotor cu loss at standstill is BE

∴ starting torque = BE

2) Operating point (or) F.L point 'P'.

Draw a vertical line 'BL' represents the F.L o/p of the m/r. From the point 'L' draw a parallel line to the o/p line and it cuts the circle at two points 'O' & 'P'. Since the normal operating slip is small, the point 'p' will be oper. poin

3) F.L. c/t & p.f : Join 'Op' which represents the full load current of the m/r. Corresponding p.f angle $\phi_1 = \angle Y_1 OP$, gives the p.f at which the motor is operating.

4) F.L. η, slip & speed

Draw a vertical line from the point 'p'. then PM & PK respectively represents the o/p and i/p of the m/r. JK represent fixed losses

MN & NJ → R/r & S/r cu loss resp.

$$\eta = \frac{o/p}{i/p} \times 100 = \frac{PM}{PK} \times 1000$$

F.L slip $s = \frac{\text{Rotor cu loss}}{\text{Rotor i/p}} = \frac{MN}{PN}$

F.L rotor speed $N = N_s(1-s)$

Max. o/p ‖el. to AB tangent to the semicircle

Max torq: ‖el to the Torque line AE

slip at Max. torque.

$S_{max\ Torque}$ $S_m = \frac{TS}{RS}$

Maximum output: Draw a line ‖el to the o/p line 'AB' tangent to the semi circle. The actual point of contact 'H' is obtained by drawing a perpendicular to the tangent. Now HI is the max. o/p

(or)

- Draw vertical line from the star bisector touching to the semicircle and extends upto o/p line

Full load Torque = F.L. Rotor i/p = PN

Necessity of starter in an Induction motor

In a 3-ϕ I.M, magnitude of rotor induced emf is depends upon slip.

$$\text{Rotor current } I_2 = \frac{sE_2}{\sqrt{R_2^2+(sX_2)^2}} \quad \text{at start } s=1\,(\text{max})$$

→ At starting, the magnitude of rotor induced emf is maximum. This emf circulates very high c/t through the ro

- The I.M acts as a transformer having short circuited secondary at start.
- Hence a rotor current is high, consequently stator draws a very high current. of the order of 5 to 8 times full load current.
- Due to such high current at start their is a possibility of damage of the motor winding and can generate large line voltage drop, which may effect the working of other equipments connected to the same line.
- Therefore, starter is necessary to limit the current drawn by motor at start.

*→ starter not only limit the starting current but also provides protection to the motor against over loading and low voltage conditions

Functions : The functions of starter are

1) To start & stop the motor
2) To limit the starting (or in rush) current, when necess
3) [illegible] speed control will be possible.
4) To protect [illegible] from overload & low voltage condi

Starting Methods of I.M

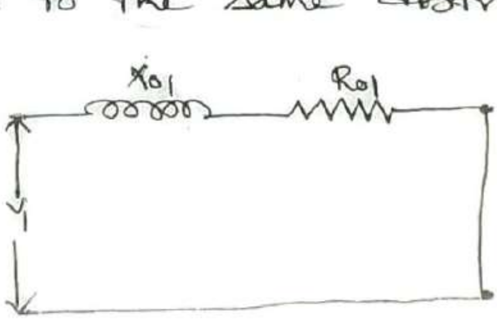
①

The 3-ø I.m has positive finite starting torque st when slip $s=1$. this means that 3-ø I.m is a elf-starting motor and begins to rotate on its own hen connected to a 3-ø source.

At the instant of starting, a 3-ø I.m behaves ike a transformer with short-circuit secondary. Consequently, a 3-ø I.m takes high starting current. nodern well-designed I.m will usually draw about 5 to 8% times the rated full load current at the starting instant if rated voltage applied to it. In order to limit this high starting current to reasonable values, some methods re adopted for the starting of 3-ø I.m's.

It is true that the starting of a squirrel cage I.m because of its rugged construction does not impose electrical stresses that are as severe as those experienced by commutator type motors, it is important that the starting current be minimised to such an extent that the line-voltage drop does not affect the operation of other equipment connected to the same distribution N/w.

∴ At starting of I.m



∴ starting current

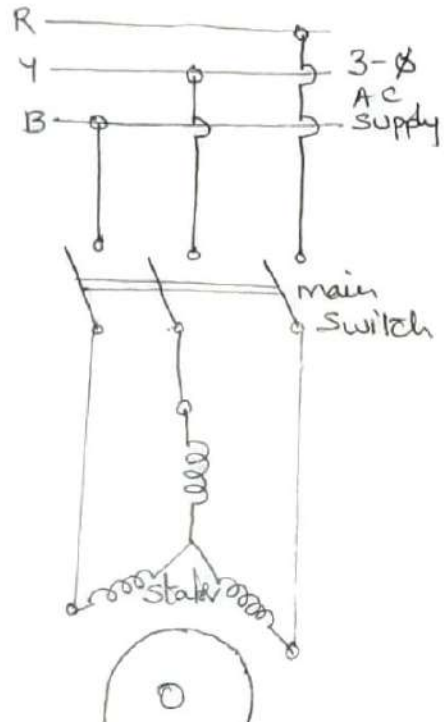
$$I_{st} = I_{s/c} = \frac{V_1}{Z_{01}}$$

∴ $I_{s/c}$ — short-circuit current.

→ Starting of Squirrel cage motor

the starting methods of squirrel cage I.M depends on
i) size and design of the motor
ii) capacity of the power lines
iii) type of the driven load.

A) Direct-on-line or full Voltage starting



As the name suggests, this method involves the direct switching of poly phase stator on to the supply mains. the motor takes low-power factor starting current of 5 to 7 times its full-load current, depending upon its size and design. Such large currents of short duration don't harm the rugged squirrel cage motor, but the high currents may cause objectionable voltage drop in the power supply lines feeding the I.M. these large voltage drops cause undesirable dip in the supply line voltage consequently the operation of other Equipments connected to the same supply lines is effected considerably. A common Example is the momentary dimming of lamp and tube-lights in the home at the instant a refrigerator motor starts.

Squirrel cage motors of capacity upto 1.5 kW are started by this method.

the Relation b/w starting torque T_{est} and full-load torque T_{efl} is now obtained. let I_{st} and I_{fl} be the per-phase stator currents drawn from the supply mains corresponding to starting and full-load conditions respectively. (7)

$\Rightarrow$ I/p power to rotor $= \tau w \Rightarrow$ Rotor Cu loss $= S \times$ i/p power to rotor

$\Rightarrow 3I_2^2 R_2 = S T_e W$

per phase : $T_e = \frac{1}{\omega_s} I_2^2 \cdot \frac{r_2}{s}$

$$\therefore \frac{T_{est}}{T_{e(fl)}} = \frac{I_{2(st)}^2 \, r_2}{I_{2(fl)}^2 \cdot \frac{r_2}{s_{fl}}}$$ at starting $s=1$

$$\therefore \boxed{\frac{T_{e(st)}}{T_{e(fl)}} = \left[\frac{I_{2(st)}}{I_{2(fl)}}\right]^2 \times S_{fl}}$$ $\because$ full load slip $- S_{fl}$

if V_1 is the per phase stator voltage and Z_{sc} is the stand still per phase leakage impedance referred to stator then per phase short-circuit current at stand still

$$\therefore I_{sc} = \frac{V_1}{Z_{sc}}$$ $\because Z_{sc} = (r_1+r_2) + j(x_1+x_2)$

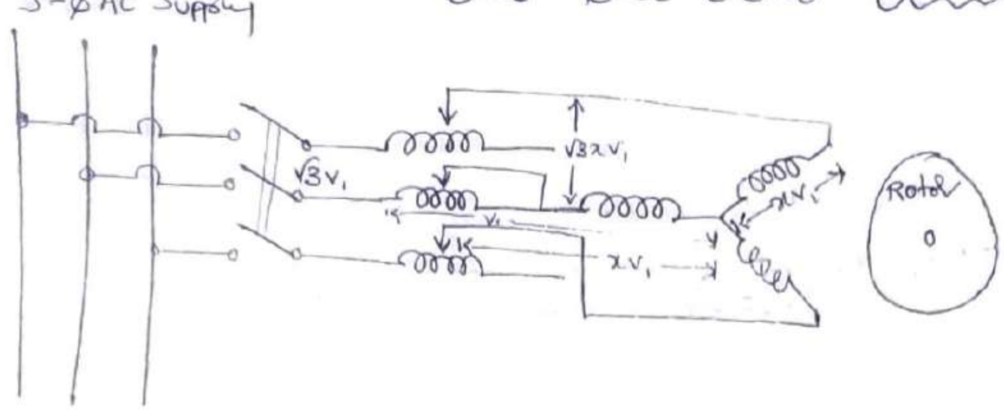
$$\therefore I_{st} = I_{sc} = V_1/Z_C.$$

the above Eq can be written as

$$\boxed{\frac{T_{e(st)}}{T_{e(fl)}} = \left[\frac{I_{sc}}{I_{fl}}\right]^2 \times S_{fl}}$$

the main draw back in this method is temperature rise is high and the motor may get damaged if the starting period is large. which may due to i) Excessive load (ii) in sufficient rotor resistance (iii) Excessive voltage drop in the supply lines.

→ Stator resistor (or) Reactor starting



In this method, a resistor & a reactor is inserted in between motor terminals and the supply mains as shown in fig. at the time of starting, some voltage drop occurs across the starting resistor or reactor and therefore, only a fraction x (less than 1) of the supply voltage appears across the stator terminals. this reduces the per phase starting current I_{st} drawn by the motor from the supply mains.

As the motor speeds up the reactor is cut out in steps and finally short-circuited when the motor speed is near to its operating speed. since per phase voltage is reduced to xV_1, then the per-phase starting current I_{st} is given by

$$I_{st} = \frac{xV_1}{Z_{sc}} = x I_{sc}$$

from D.O.L method $\frac{T_{e.st}}{T_{e.fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 \times S_{fl} = \left(\frac{x I_{sc}}{I_{fl}}\right)^2 \times S_{fl}$

$$\frac{T_{e.st}}{T_{e.fl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 \cdot S_{fl}.$$

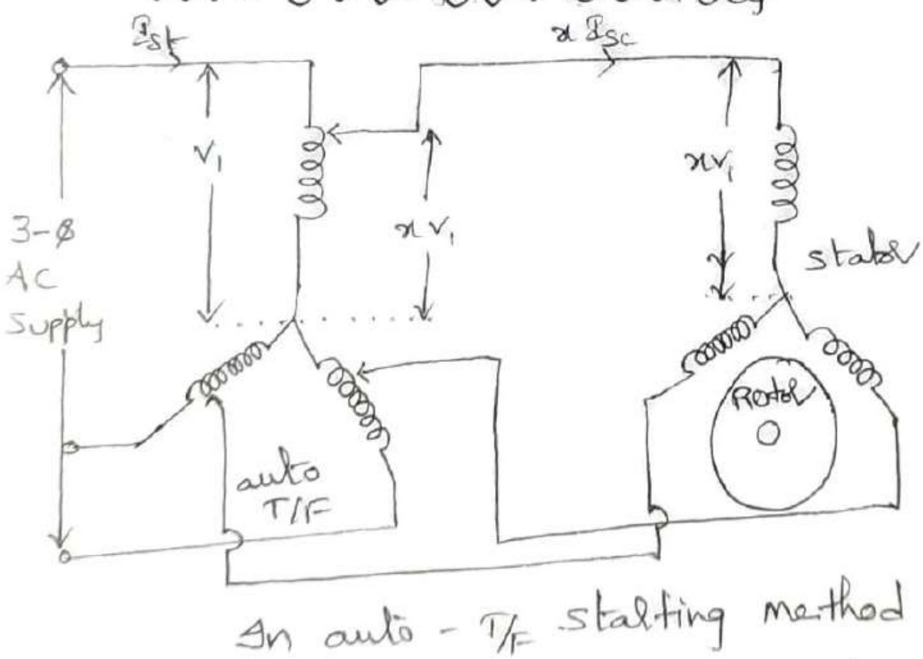
In an I.M torque $\propto$ (voltage)^2

$$\frac{\text{starting torque with reactor starting}}{\text{starting torque with direct switching}} = \left(\frac{x V_1}{V_1}\right)^2 = x^2$$

Series resistor method effects the efficiency due to the losses in resistor (i^2R). it can be avoided by using reactors.

Series reactor is more costly than the series resistor, but the former has lower energy loss and is more effective in reducing the voltage, the main draw back is the power factor at starting is quite low.

→ Auto-transformer starting



In auto-T/F starting method the reduced voltage is obtained by taking tappings at suitable points from a 3-ø auto T/F. as shown in fig. the auto T/F's are generally tapped at the 50, 60 and 80% points so that adjustment at these voltages may be made for proper starting torque requirements.

A fraction xV_1 of the supply voltage V_1 is applied to the stator terminals at the time of starting, by means of an auto T/F. this reduces the motor current and also the current drawn from the supply. after motor has accelerated near to its operating speed, auto T/F is disconnected and full line voltage is applied to the induction motor by connecting it directly across the supply mains. here x is less than one.

∴ with auto T/F, per phase starting current in motor winding

$$I_{st} = \frac{xV_1}{Z_{sc}} = x\, I_{sc}$$

if no-load current of auto T/F is neglected, then per phase output VA of auto T/F must be equal to its per phase i/p VA.

$$I_{st}\, V_1 = x V_1 \text{ (per phase starting current in motor winding)}$$

$$I_{st} \cdot \cancel{V_1} = (x \cancel{V_1})\,(x I_{sc})$$

∴ per phase starting current from the supply mains

$$I_{st} = x^2 \cdot I_{sc}$$

from the above Eq, that the motor starting current per phase is reduced only to x times the direct switching current I_{sc}, but the per phase starting current from the supply mains is reduced to x^2 times the direct switching I_{sc}.

$$\frac{T_{e(st)}}{T_{e(fl)}} = \frac{(x\, I_{sc})^2}{I_{fl}^2}\, s_{fl}.$$

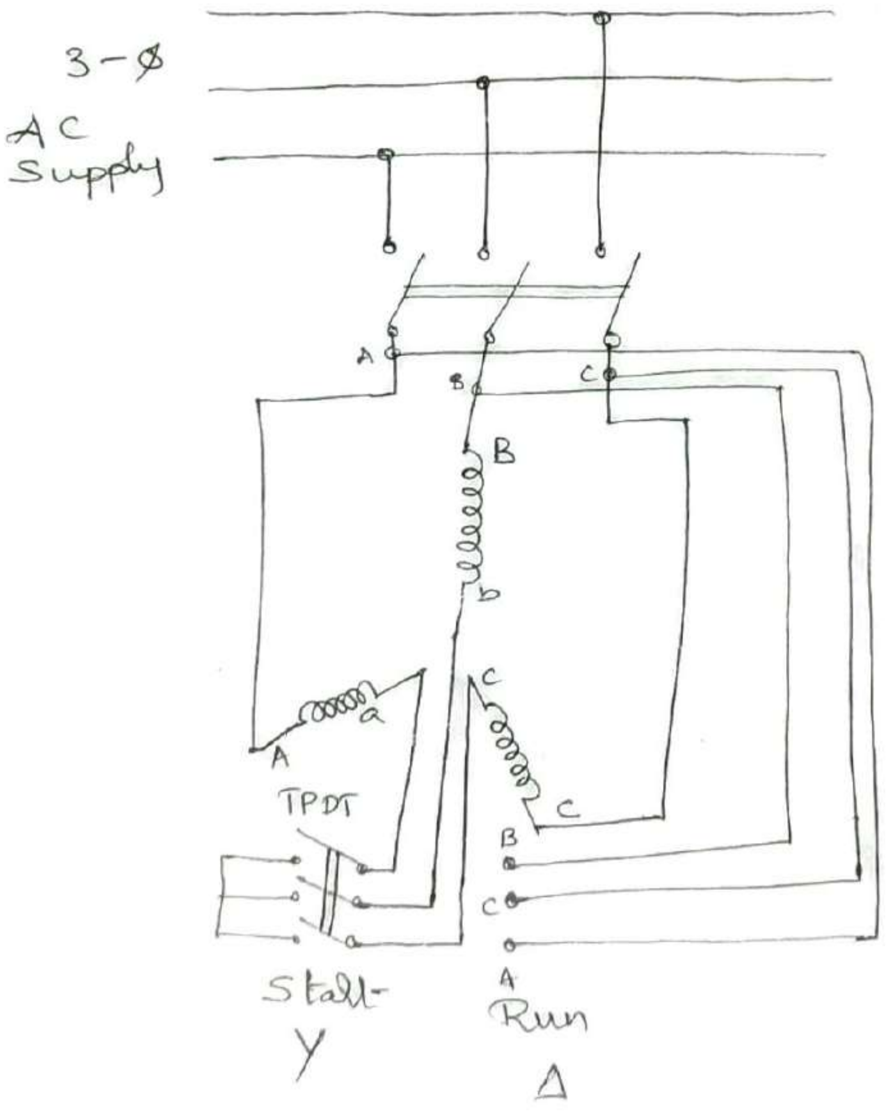
$$\frac{T_{e(st)}}{T_{e(fl)}} = x^2\left(\frac{I_{sc}}{I_{fl}}\right)^2 \times S_{fl}$$

for an I.M, torque α V^2

$$\frac{T_{e(st)} \text{ with auto T/F}}{T_{e(st)} \text{ with direct switching}} = \left(\frac{xV_1}{V_1}\right)^2 = x^2$$

It is seen from above that with an auto T/F, the starting current Ist from the mains and starting torque $T_{e.st}$ are reduced to x^2 times their corresponding values with direct-on-line starting. these motor Employed for > 20kw.

→ Star delta Starting



this method of starting of cage I.M is based on the principle that with 3 windings connected in star, the voltage across each winding is $1/\sqrt{3}$ i.e 57.7% of the line to line voltage where as the same winding connected in delta will have full line-to-line voltage across each.

the star-delta starter connects the three stator windings in star across the rated supply voltage at the starting instant. after the motor attains the speed the same windings, through a change over switch are reconnected in delta across the same supply voltage. the starter is also provided with a mechanical inter-locking device to prevent the handle from being put in the 'Run' position first.

since at starting instant, the stator windings are connected in star, so voltage across each phase winding is reduced to $1/\sqrt{3}$ of line voltage and therefore starting current per phase becomes equal to $I_{sc}/\sqrt{3}$.

starting line current by direct switching with stator windings connected in delta $= \sqrt{3}\, I$

$$\therefore \frac{\text{line current with Y-}\Delta\text{ starting}}{\text{line current with direct switching}} = \frac{I_{sc}/\sqrt{3}}{\sqrt{3}\, I} = 1/3$$

$$\therefore \frac{T_{e.st}}{T_{e.fl}} = \left(\frac{I_{sc}/\sqrt{3}}{I_{fl}}\right)^2 S_f = \frac{1}{3}\left(\frac{I_{sc}}{I_{fl}}\right)^2 S_f$$

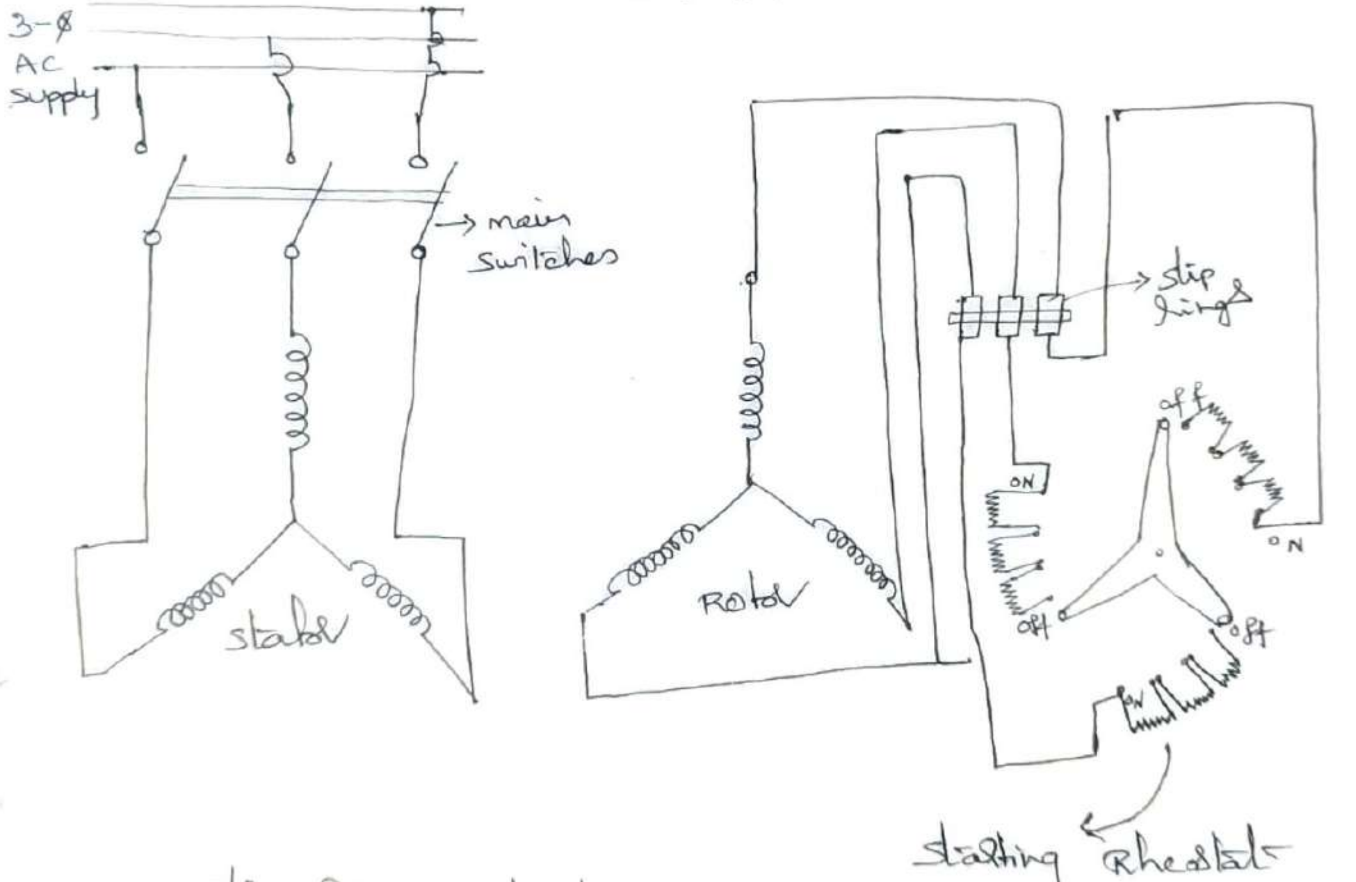
$$\frac{T_{e.st}}{T_{e.fl}} = \frac{1}{3}\left(\frac{I_{sc}}{I_{fl}}\right)^2 \times S_{fl}$$

5

Hence with Y-Δ switching, the starting torque is also (10) reduced to 1/3rd of starting torque obtained with direct switching. This method of starting of cage motors is simple, cheap, effective and efficient since no power is lost in auxiliary components.

This method needs a motor to be delta-connected for normal operation and all the six terminals of the 3-ø stator windings are to be brought out. The reduction in voltage is fixed and starting torque is also low. So this method is limited to application where high starting torque is not the essential requirement. Such starters are employed for starting 3-ø squirrel cage I.M's of rating b/w 4 and 20kw.

Starting of slip ring I.M.



Slip-ring induction motors are usually started with full-line voltage across the stator terminals and by introducing variable resistance in each phase of the rotor circuit

Advantages & disadvantages of stator Reactor method

Advantages

1) Smooth Acceleration 2. High power factor during start.
3). Less expensive than autotransformer in lower output rating.
4) closed transition starting
5) Available with as many as 7 accelerating points

Disadvantages

1) Resistors gives off heat
2) Low Torque efficiency.
3) Starting duration usually exceeds 5 seconds, so needs expensive resistors.

Advantages and disadvantages of Autotransformer Starting

1) Availability of highest Torque per Ampere of supply current
2) the Voltage is reduced by Transformation and not by dropping the voltage in resistor (or) reactor.
3) The internal losses of the starter itself are small during long starting periods.
4) Adjustment of starting voltage by selection of proper tap on the autotransformer.
5) Suitability for long starting periods.
6) Closed transition starting.
7) Motor current larger than supply current.
8) This method can be used for starting of Y-connected as well as Δ-connected motor.

Disadvantages

- this type of starters are low power factor and higher cost in case of low output rating.
- this method is used ab[illegible] [illegible].

Speed control method Abdul Ka... B.TEC

...In a no. of industries motors must satisfy strict speed characteristic requirements, both with ...ect to the range and smoothness of control and also ...h respect to economical operation.

...rious methods of speed control from stator side are
-> variation of supply frequency (f)
-> variation of applied voltage (V)
-> By changing the no. of poles (P)

...rious methods of speed control from rotor side are
-> By changing the resistance in the rotor circuit (R_r)
-> E.m.f injected method (E)
-> cascade connection.

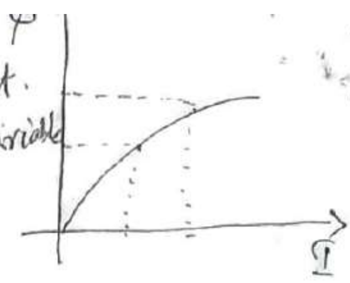
-> variation of supply frequency method

this method of speed control provides wide ...peed - control range with gradual variation of the speed ...rough out this range. the major difficulty with this ...ethod is how to get the variable supply frequency. ...e auxiliary equipment required for this purpose ...esults in a high cost, increased maintance and lowering ... the over all efficiency. these is the reason, this ...ethod is not employed for general-purpose speed control applications.

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

$$N_S \propto f$$

$\because \uparrow \phi \propto \dfrac{V}{f} \downarrow$



from the above Equation, it can be understood that a change of frequency will result in a change of flux level unless the induced Emf is changed in the same ratio. An imbalance in this ratio will cause either an Excessive flux and saturation or reduced flux and reduced torque per ampere of current.

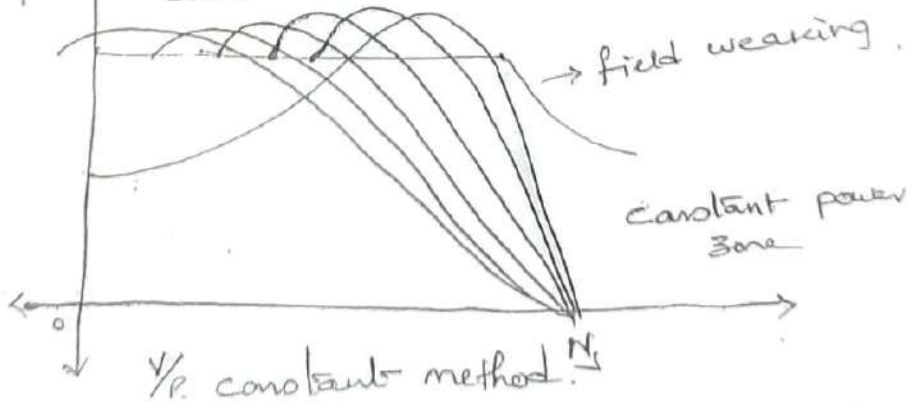
Excessive flux created due to reduction in frequency made for the purpose of reducing speed at constant voltage will cause increase in iron losses and increased iron losses along with reduced ventilation caused by the lower speed can result in Excessive heating.

$$\because E_S = j X_m I_m \Rightarrow I_m = \frac{E_1}{X_m} = \text{constant}$$

$$\because I_m = \frac{E_1}{2\pi f L_2} = \frac{E_1}{f} \text{ ratio remains constant.}$$

$\because E_1 \propto V$

constant flux per pole is approximated if the applied voltage per hertz V/f is maintained constant. because $V \simeq E_1$. under these conditions the maximum developed torque remain approximately constant and the o/p power varies approximately in direct propotion to the synchronous speed as shown in figure.



V/f constant method.

Speed control By variation of supply voltage : ② 7

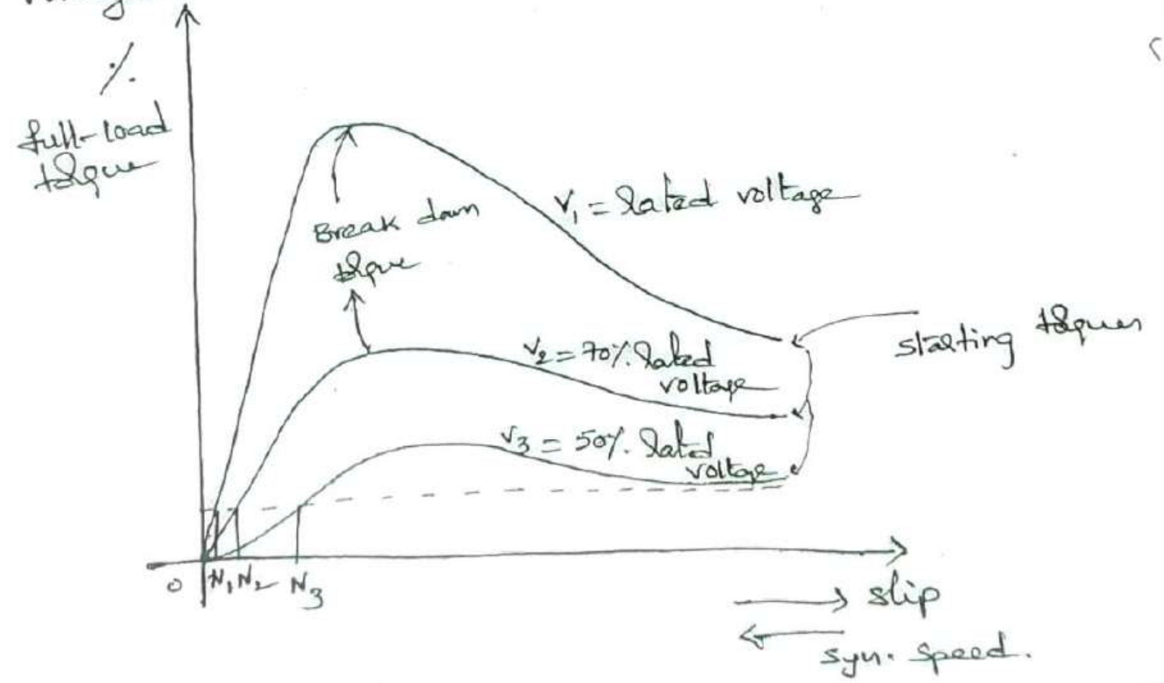
this is a slip - control method with constant frequency variable supply voltage. in this method of speed control of induction motors, the voltage applied to the stator is varied for varying the speed, the variable voltage may be obtained by means of either saturable reactors, variac or tap-changing transformers.

∴ torque developed by an induction motor is given by the equation

$$T = \frac{K S E_2^2 R_2}{R_2^2 + S^2 X_2^2}$$

$$\therefore T \propto E_2^2 \Rightarrow T \propto V^2 \qquad \because E_2 \propto V$$

It is seen that, from the above equation, the torque developed by an induction motor is directly propotional to the square of induced e.m.f in rotor, E_2 which is approximately propotional to the impressed voltage V thus torque developed is propotional to the square of supply voltage.



∴ rotor current is given by

$$I_2 = \frac{E_2}{\sqrt{\left(\frac{R_2}{s}\right)^2 + X_2^2}} \Rightarrow I_2 = \frac{V}{\sqrt{\left(\frac{R_2}{s}\right)^2 + (X_2)^2}} \qquad \because E_2 \propto V$$

around the rated speed, slip of the induction motor is so small that R_2/s is much greater than x_2 and x_2 can be neglected.

$$\therefore I_2 = \frac{sV}{R_2} \qquad \& \quad T \propto sV^2$$

if the slip is to be doubled for constant load torque, then the supply voltage must be reduced by a factor of $1/\sqrt{2}$ and consequently the rotor current I_2 will became $\sqrt{2}$ times of the full-load value. therefore the motor tends to get over heated. it is therefore necessary to take care, while using this method of speed control that the motor is not damaged due to excessive current at the reduced speeds.

→ limitations:

→ the operation at voltages exceeding rated voltage is restricted by magnetic saturation.

→ A large change in voltage is required for a relatively small change in speed.

→ Speed control By changing the no. of poles: (3)

this method is easily applicable to squirrel cage motors because a cage winding automatically reacts to create the same no. of poles as the stator. this method is not practicable with wound rotor motors because it would involve considalable complications of design and switching. Since the interconnection of both primaly and secondaly would have to be changed simultaneously in a manner to produce the same no. of poles in both windings. other wise negative torque will be developed by certain of the rotor conductor belts.

the no. of pole pairs in the stator can be changed as follows.

a> By using multiple stator windings

b> By using consequent pole technique.

c> By using pole amplitude modulation technique.

a → By using multiple stator windings:

In this method of speed control two or more completely (windings) independent windings, each wound for different no. of poles, are placed in the same stator slots :. the no. of stator winding poles are in this case in no way inter-related and can be albitralily chosen depending on the operating conditions of this motor.

for Example a two speed motor may have two stator windings, one wound for 4 poles another for 6 poles which will give syn. speeds of 15,00 rpm and 1000 rpm with a frequency of 50Hz. motors with four independents stator windings are also used some times and they giv four different syn. speeds. one winding is used at

(6) 11

$$\therefore F_Y' = F_{max}' \left[\cos\left\{ \left(\frac{P-n}{2}\right)\theta + \frac{2\pi}{3} \right\} - \cos\left(\frac{P+n}{2}\right)\theta \right]$$

$$\therefore F_B' = F_{max}' \left[\cos\left\{ \left[\frac{P-n}{2}\right]\theta - \frac{2\pi}{3} \right\} - \cos\left[\frac{P+n}{2}\right]\theta \right]$$

from above Equation it is found that the modulated mmf wave has (P-n) no. of poles and rotate in the direction opposite to that of the unmodulated field. it is concluded that if an unmodulated 8-pole motor is modulated with an mmf for which n=2. it will result in either a 10-pole & 6-pole motor. by this method of pole changing wide range of speed control is possible. it also allows great reduction in size and cost of the motor.

→ Speed control from rotor side

→ Rotor resistance control:

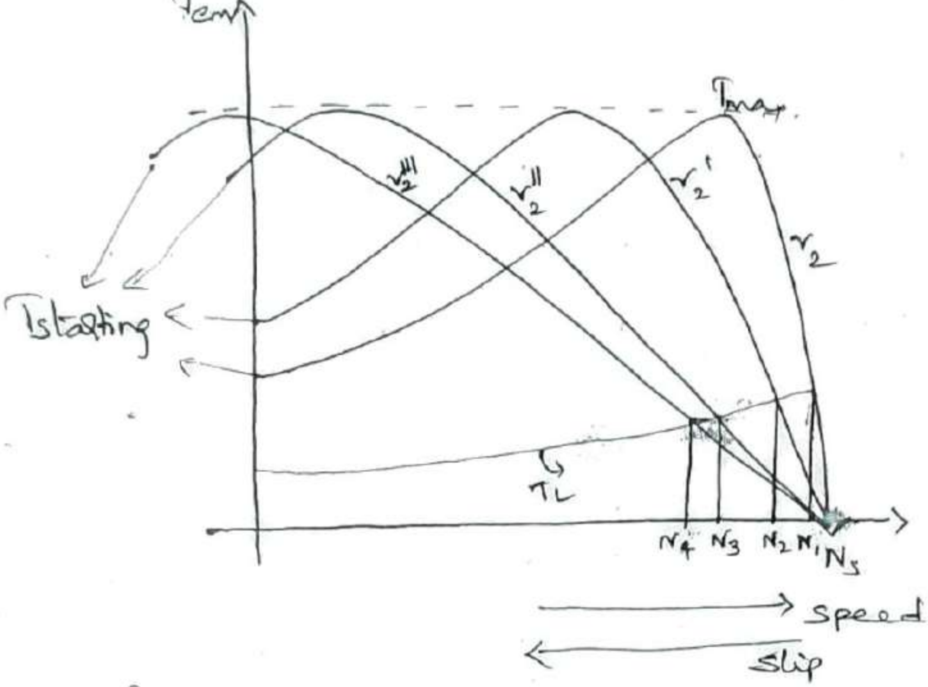
this type of control is only possible with wound rotor induction motors. i.e this method cannot be applied to squirrel cage motor. wound rotor motors are usually started by connecting starting resistances in the secondary circuit, which are cutted-out as the motor speeds-up if the ohmic values of these resistors are properly chosen and if these resistors are designed for continuous operation.

torque developed by an induction motor is given as

$$\therefore T = \frac{K S R_2 E_2^2}{R_2^2 + S^2 X_2^2}$$

when the speed is very near to syn. speed N_S. i.e (6)
when slip s is very low the value of the term sx_2 is very small and can be neglected as compared to R_2 and torque developed becomes proportional to

$$\therefore T_{em} \propto \frac{s}{R_2}$$



$$\therefore r_2''' > r_2'' > r_2' > r_2$$

from the above torque - slip characteristics, we can say that the speed of motor can be controlled by varying the rotor circuit resistance but maximum torque remains unaffected. So it is obvious that for a given torque, slip s can be increased by increasing the rotor resistance. Speed controlled will be below rated speed.

secondary resistance control is simple and low in initial as well as in maintenance cost and it is possible to have a large starting torque with low starting current and large pull-out torque at small values of slip.

→ disadvantages.

→ Reduction in speed is accompanied by Reduction in efficiency

→ the speed varies considerably with variation in torque

→ the External rotor resistors are comparatively bulky and Expensive as they have to dissipate a good deal of power with out getting overheated.

→ E.m.f injected method :

In this method, the speed of an induction motor is controlled by injecting a voltage of slip frequency in the Secondary circuit. if injected voltage is in phase with the induced E.m.f in the secondary circuit. it is Equivalent to decreasing of resistance in the Secondary circuit, therefore "slip decreases or Speed increases". it is possible to achieve super-synchronous speeds by injecting a voltage of slip frequency in phase with the induced Emf in the rotor circuit.

if injected voltage is in phase opposition to the induced Emf in the Secondary circuit. it is Equivalent to increasing of Resistance in the secondary circuit, hence resulting in increase in slip & reduction in speed. thus a large range of speed control is possible by this method by including frequency - converting Equipment in the rotor circuit.

In this method the disadvantages of lower efficiency and poor speed regulation are over come. but it requires more auxiliary machines to inject Emf

Induction Motor Test

No load Test : $P_i = \sqrt{3} V_0 I_0 \cos\phi$; $W = W_1 - W_2$; $\cos\phi$

No load p.f. $\cos\phi_0 = \dfrac{P_i}{\sqrt{3} V_0 I_0}$

→ Working Component current $I_c = I_0 \cos\phi_0 \Rightarrow I_0 \times \dfrac{P_i}{\sqrt{3} V_0 I_0} \Rightarrow \dfrac{P_i}{\sqrt{3} V_0}$

→ Magnetising Component on No load current

$$I_m = \sqrt{I_0^2 - I_c^2}$$

→ No load Impedance $Z_0 = \dfrac{(V_0/\sqrt{3})}{I_0}$

→ No load Resistance : $R_0 = \dfrac{(V_0/\sqrt{3})}{I_c} \Rightarrow \dfrac{V_0/\sqrt{3}}{\dfrac{P_i}{\sqrt{3} V_0}} \Rightarrow \dfrac{V_0^2}{P_i}$

→ No load Reactance $X_0 = \sqrt{Z_0^2 - R_0^2}$

Blocked Rotor Test : power $W = W_1 + W_2$; $\cos\phi > 0.5$

If V_s is the applied Voltage (line to line value) and causes current I_s in the stator w/g and P_s is the total input power at short circuit then short circuit current I_{sc} with normal voltage 'V' (line to line) applied across the motor is given by

$$I_{sc} = I_s \frac{V}{V_s}$$

p.f $\cos\phi_s = \dfrac{P_s}{\sqrt{3} V_s I_s}$

Since input on short circuit meets with stator & rotor cu l

i.e., $P_s = 3 I_s^2 R_{01}$

N

- Motor equi. ckt resistance per phase referred to stator:

$$R_{01} = P_s / 3 I_s^2$$

- " , impedance per phase " " ",

$$Z_{01} = \frac{V_s/\sqrt{3}}{I_s}$$

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

problems on starting of 3-ϕ Induction motor

1 Direct ON Line starting

$$\frac{T_{st}}{T_{FL}} = \left(\frac{I_{st}}{I_{FL}}\right)^2 S_{FL} \quad \text{(or)} \quad \text{starting Torque } T_{st} = T_{FL}\left(\frac{I_{sc}}{I_{FL}}\right)^2 S_f$$

$\because I_{st} = I_{sc}$

2. primary Resistor (or) Reactor starting

Starting torque (T_{st})

$$\frac{T_{st}}{T_{FL}} = \left(\frac{I_{st}}{I_{FL}}\right)^2 S_{FL}$$

$$\frac{T_{st}}{T_{FL}} = K^2\left(\frac{I_{sc}}{I_{FL}}\right)^2 S_{F.L} \qquad \because I_{st} = K I_{sc}$$

$= K^2$ (Torque obtained by switching the motor directly)

3. Auto Transformer Starting

Motor input current $I_{st} = K I_{sc}$

$$\frac{T_{st}}{T_{FL}} = \left(\frac{I_{st}}{I_{FL}}\right)^2 \times S_{F.L}$$

$$\frac{T_{st}}{T_{FL}} = K^2\left(\frac{I_{sc}}{I_{FL}}\right)^2 \times S_{F.L}$$

4) Star-Delta starting

Starting. Torque (T_{st})

$$\frac{T_{st}}{T_{FL}} = \left(\frac{I_{st}}{I_{FL}}\right)^2 S_{FL}$$

$$\frac{T_{st}}{T_{FL}} = \left(\frac{\frac{I_{sc}}{\sqrt{3}}}{I_{FL}}\right)^2 S_{FL} \Rightarrow \frac{1}{3}\left(\frac{I_{sc}}{I_{FL}}\right)^2 \times S_{FL}$$

---

1) A small 3-ϕ I.M has a short circuit current equal to 4 times the full load current. Determine the starting torque as a percentage of Full load Torque if full load slip is 2.5%.

Sol Given data $I_{sc} = 4 I_{FL}$; slip $= 2.5\% \Rightarrow 0.025$

Starting Torque $T_{st} = T_{FL}\left(\frac{I_{sc}}{I_{FL}}\right)^2 \times S_{FL}$

$= \tau_{FL} \left(\frac{\;\;}{I_{FL}} \right) \times 0.025 \Rightarrow \tau_{FL} \times 16 \times 0.025$

$\tau_{st} = 40\%$ of τ_{FL}.

2) A 3-ϕ I.M. has a short circuit current 5 times of F.L current and Full load slip is 5%. Determine the starting torque and starting current if starting resistance starter is used to reduce the impressed voltage to 60% of normal voltage.

Sol. starting current $I_{st} = 0.6 \times 5 I_{FL} \Rightarrow 3 I_{FL}$

Starting Torque $\tau_{st} = \tau_{FL} \left(\frac{I_{st}}{I_{FL}} \right)^2 S_{F.L}$

$$= \tau_{FL} \left(\frac{3 I_{FL}}{I_{FL}} \right)^2 \times 0.005$$

$$= 0.45\, \tau_{FL} \Rightarrow 45\% \text{ of Full load Torque.}$$

3. Calculate the reduction in starting current and starting Torque when the supply voltage to a cage rotor motor is 80% instead of 100%.

Sol starting current with normal voltage $= I_{sc}$

starting current with 80% of normal supply voltage $0.8 I_{sc}$

Reduction in starting current $= \frac{I_{sc} - 0.8 I_{sc}}{I_{sc}} \times 100 \Rightarrow 20\%$.

Starting torque with normal $\tau_{st} = \tau_{fl} \left(\frac{I_{sc}}{I_{FL}} \right)^2 S_{FL}$

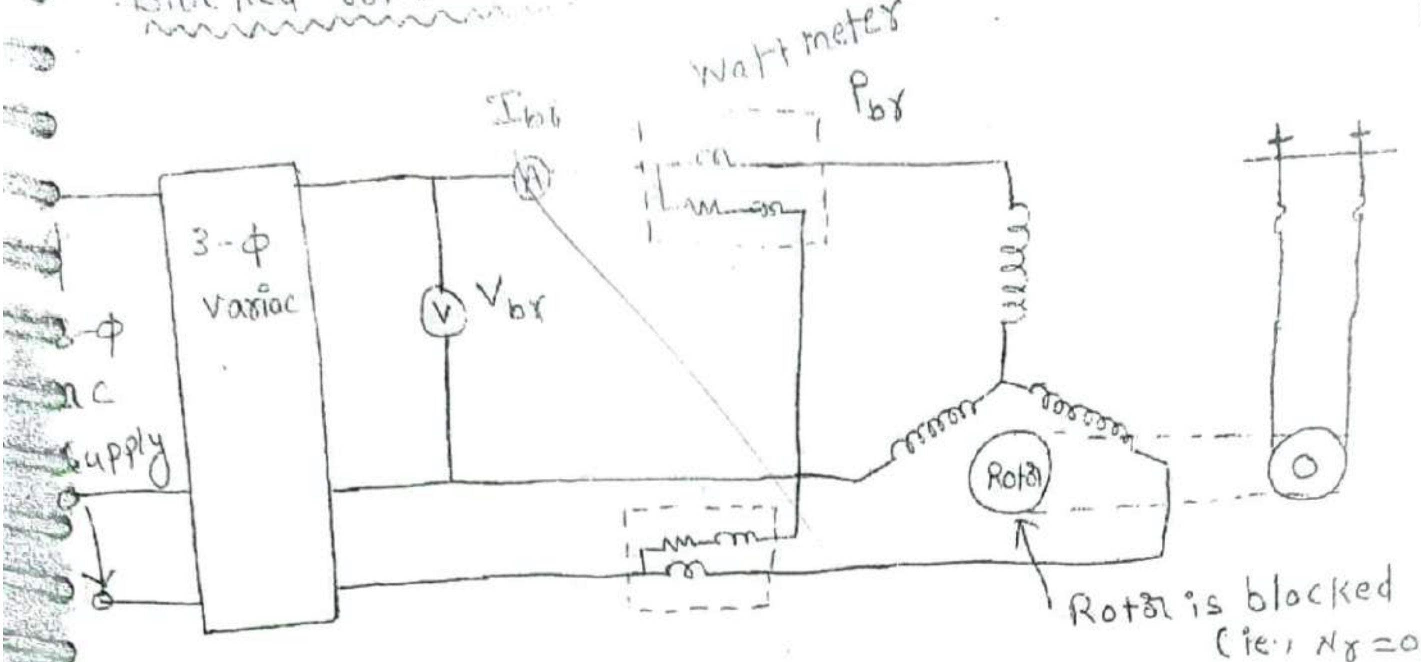
Starting torque with 80% of normal supply voltage.

$$= \tau_{FL} \left(\frac{0.8 I_{sc}}{I_{FL}} \right)^2 S_{FL}$$

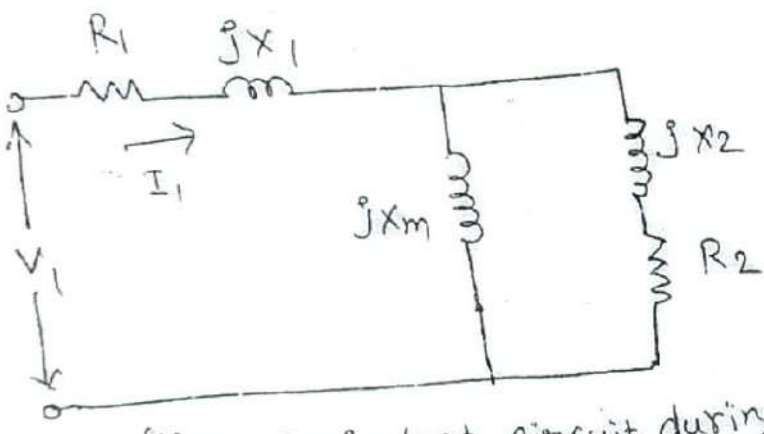
$= 0.64$ times starting torque with normal supply v/t.

Reduction in starting torque $(1 - 0.64) \times 100 \Rightarrow 36\%$.

Blocked-rotor test (S.C)



fig(iv) circuit diagram to conduct Blocked rotor test



During blocked rotor test, $N_r=0$

$S = \frac{N_s - N_r}{N_s} = 1$

fig(v) Equivalent circuit during blocked rotor test

Procedure:-

(i) Circuit diagram to conduct blocked rotor test is shown in fig(iv)

(ii) Initially rotor is blocked by connecting it to the external belt and pulley arrangement shown in fig(iv) and 3-ϕ variac in zero output voltage position.

(iii) Now adjust the 3-ϕ variac position until rated current flows through stator windings.

(iv) If ammeter reads rated current, then stop the adjustment of 3-ϕ variac and note down the readings of Voltmeter,

S.No	Voltmeter reading	Ammeter reading	Wattmeter reading
1.	V_{br}	I_{br}	P_{br}

TABLE ②:- Readings during blocked rotor test.

we know, $Z = \frac{V}{I} \Rightarrow Z_{br} = \frac{V_{br}}{I_{br}}$

and $R_{br} = \frac{P_{br}}{I_{br}^2}$ [since during blocked rotor test, total power required to over I^2R loss, hence $P = I^2R$]

and $x = \sqrt{Z^2 - R^2}$

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

Since $Z_{br} = R_{br} + jX_{br}$

from fig(V), $Z_{br} = R_{br} + jX_{br} = R_1 + jX_1 + (jX_m) \,//\, (R_2 + jX_2)$

Since $jX_m >> R_2 + jX_2$, neglect jX_m, then

$Z_{br} = R_{br} + jX_{br} = R_1 + jX_1 + R_2 + jX_2$

Equating real and imaginary parts, then

$\boxed{R_{br} = R_1 + R_2} \rightarrow ①$

and $\boxed{X_{br} = X_1 + X_2} \rightarrow ②$

$① \Rightarrow \boxed{R_2 = R_{br} - R_1}$

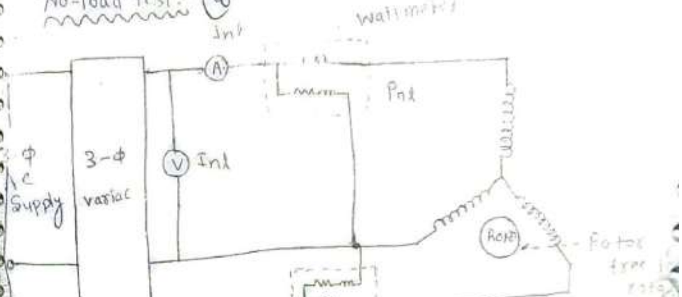
Assume $X_1 = X_2$, then,

$② \Rightarrow X_{br} = 2X_1 = 2X_2$

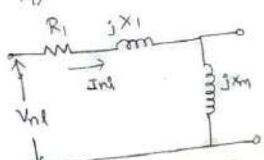
$\Rightarrow \boxed{X_1 = X_2 = \frac{1}{2} X_{br}}$

Hence from blocked rotor test, we calculated R_2, X_1 & X_2 values.

No-load test:- (OC)



fig(vi) circuit diagram to conduct No-load test



fig(vii) Equivalent circuit during no-load test

During no-load test, 's' value is very less
$\therefore \left(\frac{R_2}{s} + jX_2\right)$ is very high.
Since $\left(\frac{R_2}{s} + jX_2\right)$ and (jX_m) are in parallel, neglect $\left(\frac{R_2}{s} + jX_2\right)$

Procedure:-

① circuit diagram to conduct No-load test, is shown in fig.
② Initially rotate is made free to rotate and keep 3-Φ variac in zero output voltage position.
③ Adjust 3-Φ variac position until rated voltage is applied to Stator windings.
④ Whenever the voltmeter reach, rated voltage, (stop) the adjustment of 3-Φ variac and notedown the readings of voltmeter, ammeter and wattmeter

S.No	Voltmeter reading	Ammeter reading	Wattmeter reading
	V_{nl}	I_{nl}	P_{nl}

Table ③ during [illegible]

Since during no-load test, total power is required to overcome [No load rotational losses + ohmic losses],

$$R_{nl} = \frac{P_{nl}}{I_{nl}^2}$$

$$Z_{nl} = \frac{V_{nl}}{I_{nl}}$$

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

From fig(viii). $X_{nl} = X_1 + X_m$

$$\Rightarrow \boxed{X_m = X_{nl} - X_1}$$

Hence from blocked rotor test, we calculated 'X_m' value.

Conclusion:-

① Hence stator resistance 'R_1' is calculated from stator windings d.c resistance test as $R_1 = 1.2\ R_{dc}$

② From blocked rotor test, we calculated R_2, X_1 & X_2 values as

as $R_2 = R_{br} - R_1$

and $X_{br} = X_1 + X_2$, if $X_1 = X_2$, then $X_1 = X_2 = \frac{1}{2} X_{br}$

③ From No-load test, we calculated X_m value as

$$X_m = X_{nl} - X_1$$

Note:-

* Under No-load test, input power is required to overcome total losses

No-load input power = total losses = constant losses + variable losses

$\Rightarrow P_{nl}$ = Rotational losses + ~~stator~~ ohmic losses during no-load

$$\Rightarrow P_{nl} = P_R + I_{nl}^2 R_1$$

$$\Rightarrow \boxed{P_R = P_{nl} - I_{nl}^2 R_1}$$

rotational losses per phase

Explain procedure to draw circle diagram for induction motor.

Ans:-

Circle diagram for 3-φ Induction motor:-

Induction motor circle diagram is a graphical representation of it's equivalent circuit. This means that whatever information can be obtained from the equivalent circuit, the same can also be obtained from the circle diagram. (The advantages of circle diagram are it's simplicity and quick estimation of the induction motor operating conditions)

circle diagram is the locus of stator current.

circle diagram can be drawn by the following test data

(i) Stator windings dc resistance test

(ii) No-load test, and

(iii) Blocked rotor test.

No-load test:- From no-load test data, per phase values of P_{nl}, V_{nl} and I_{nl} are calculated, then

$$\cos\theta_{nl} = \frac{P_{nl}}{V_{nl} \cdot I_{nl}}$$

$$\Rightarrow \theta_{nl} = \cos^{-1}\left(\frac{P_{nl}}{V_{nl} \cdot I_{nl}}\right)$$

Blocked rotor test:- From blocked rotor test data, per phase values of V_{br}, I_{br} and P_{br} are calculated. Since during blocked rotor test, reduced voltage is applied, converting the blocked rotor test data, as if rated voltage per phase (V_1) is applied, then

$$I \propto V, \quad \frac{I_{sc}}{I_{br}} = \frac{V_{sc}}{V_{br}} \Rightarrow \boxed{I_{sc} = I_{br}\left(\frac{V_1}{V_{br}}\right)}$$

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and $P \propto V^2 \Rightarrow P_{sc} = P_{br}\left(\frac{V_1}{V_{br}}\right)^2$

and $\cos\theta_{sc} = \frac{P_{sc}}{V_1 \cdot I_{sc}}$

In general, $\cos\theta_{sc} = \cos\theta_{br}$; where $\cos\theta_{br} = \frac{P_{br}}{V_{br} \cdot I_{br}}$

$\therefore \theta_{sc} = \theta_{br} = \cos^{-1}\left(\frac{P_{br}}{V_{br} \cdot I_{br}}\right)$

Current scale and perphase power scale:-

Based on I_{sc} value, choose current scale as $1\,cm = x\,A$ or $\boxed{\text{current scale} = x\,A/cm}$ [In general choose scale so that $I_{sc} = 10$ ... value is obtained]

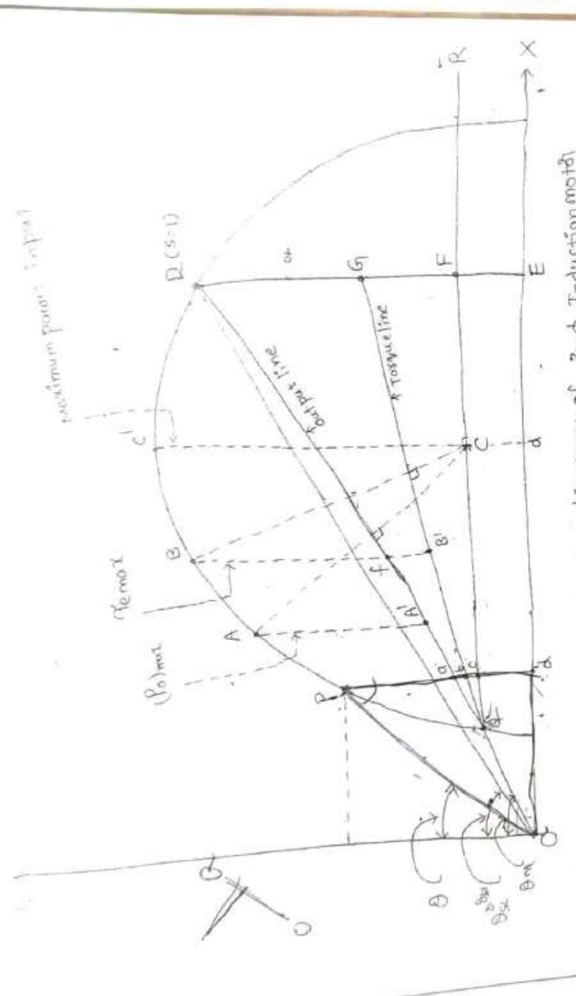
Then, $\boxed{\text{perphase power scale} = xV_1 \text{ watts/cm}}$

Procedure to draw circle diagram of 3-ϕ induction motor:-

(i) Take V_1 as reference draw along Y-axis.
(ii) Draw OX line along X-axis
(iii) Draw $OQ = I_{nl}$ at an angle θ_{nl} w.r.t V_1 (Y-axis)
(iv) Draw $OD = I_{sc}$ at an angle θ_{sc} w.r.t. V_1 (Y-axis)
(v) Join QD line.
(vi) Draw QR line parallel to OX (X-axis) line.
(vii) Draw perpendicular bisector to QD line. [Take rounder drawn an arc from Q & D, by taking length more than half of QD line]. This perpendicular bisector line meets QR line at 'C'.
(viii) Now 'C' as center, 'CQ' as radius, draw a circle. The circle passes through 'D' point.
(ix) Draw DE line perpendicular to OX line.
(x) Let 'G' be any point on line DF, such that $\frac{DG}{\ldots} = \frac{\text{Rotor ohmic loss at standstill}}{\ldots \text{ at standstill}} = \frac{R_2}{R_1}$:
(xi) Let 'P' be any operating point on the circle. Join OP. Draw 'Pd' line perpendicular to OX.

Results from circle diagram:

(i) Input current or full-load current = OP × current scale
(ii) Full load p.f or operating p.f, $\cos\theta = \frac{dP}{OP}$
(iii) Rotor output power perphase $\}$ = aP × perphase power scale
(iv) Rotor ohmic loss perphase $\}$ = ab × perphase power scale
(v) Stator ohmic loss perphase $\}$ = bc × perphase power scale
(vi) Rotational loss perphase $\}$ = cd × perphase power scale
(vii) Full load torque or operating torque $\}$ $= \frac{3 \times 60}{2\pi N_s} \times bP \times$ perphase power scale
(viii) Rotor input power perphase $\}$ = bP × perphase power scale
(ix) Full-load slip or slip $\}$ $= \frac{ab}{bP}$
(x) Efficiency, $\eta = \frac{aP}{dP}$
(xi) Stator input power perphase $\}$ = dP × perphase power scale
(xii) Starting torque, $T_{est} = \frac{3 \times 60}{2\pi N_s} \cdot$ DG · perphase ...



fig(i) Circle diagram of 3-φ Induction motor

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To obtain maximum power output:

Draw CA line, which in perpendicular to 'QD' line. From 'A' draw AA' perpendicular to OX, such that AA' in drawn upto ~~the~~ output line QD.

$$\left.\begin{array}{l}\text{Maximum power output}\\ \text{per phase}\end{array}\right\} = AA' \times \text{perphase power scale}$$

To obtain maximum tōrque T_{emax} and S_{mT} Values:-

Draw CB line perpendicular to tōrque line 'OG' line. From 'B' draw BB' upto tōrque line 'OG', such that BB' in perpendicular to OX.

$$T_{emax} = \frac{3\times 60}{2\pi N_s} \times BB' \times \text{perphase power scale.}$$

slip at which maximum tōrque occurs,

$$S_{mT} = \frac{fB'}{BB'}$$

To obtain maximum power input:-

Draw CC' line perpendicular to OX

$$\left.\begin{array}{l}\text{maximum power input}\\ \text{per phase}\end{array}\right\} = [cc' + cd] \times \text{perphase power scale}$$

1 - φ INDUCTION MOTOR:

- The name induction motor is given as the m/c is working based on the principle of mutual Induction.
- Also the speeds of the I.M. is always less than the synchronous speed and hence these are also called asynchronous motors.

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

constructional Details

- The construction of 1-φ induction motor is similar to the construction of 3-φ induction motor, the only difference is nature of supply.
- In this a 1-φ supply is given to stator winding
- The stator has punched slots which are made up of silicon steel material in order to reduce magnetic losses.
- The rotor is a round body and preferrably Squirrel cage rotors are used.
- The conductor in the rotor are skewed and short circuited by end rings on both sides.
- Generally cu conductors are preferred.
- The 1-φ I.M is not a self starting motor.

* Why 1-ϕ I.M. are not self starting motors:

For this we are using two theories

1) Double field Revolving theory.

A/c to this theory any alternating quantity can be resolved in 2 rotating components, which rotate in opposited directions and each having magnitude has half of the maximum magnitude of the alternating quantity.

ϕ_{1m} = stator alternating flux

→ A/c to this theory ϕ_{1m} is divided into 2 components as $\frac{\phi_{1m}}{2}$ which are rotating in opposite directions at the synchronous speed which is given as $N_s = \frac{120f}{P}$

→ let ϕ_f = forward flux, ϕ_b = Backward flux which are rotating in anticlockwise & clockwise.

→ The resultant of these two components gives the instantaneous resultant flux of the stator.

→ The below fig shows ϕ_1, ϕ_f, ϕ_b

→ At start both the components (ϕ_f & ϕ_b) are opposite to each other and the resultant flux is zero.

→ After 90° the 2 components are rotated such that the rotor conductors will cuts the flux.

→ Due to this an emf gets induced in rotor which circulates rotor c/t and hence results in flux.

→ This flux interacts with ϕ_f to produce a torque in anticlockwise direction.

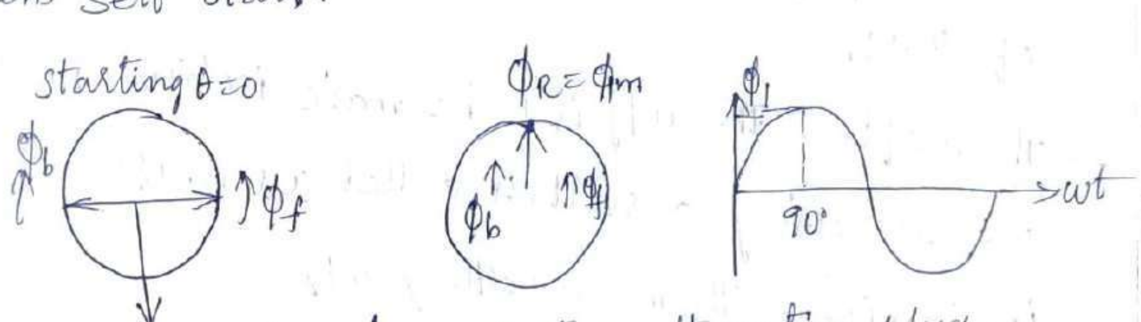
After 90° after 90° after After 90°

, while ϕ_b produces a torque which rotates clockwise direction.

→ If anticlockwise torque is considered as +ve and clockwise torque as '−ve' which are equal in magnitude results a net torque which is zero and hence a 1-ϕ I.M. are not self starting.

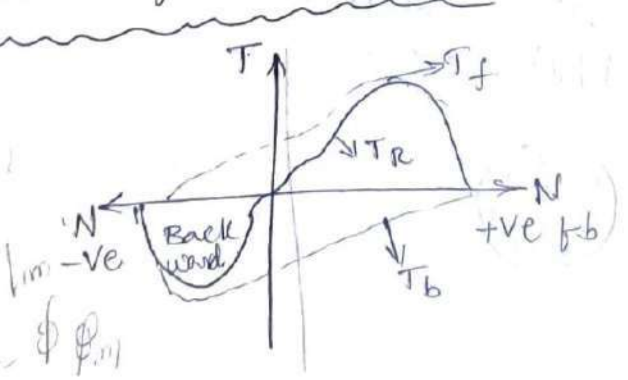
→ However if the rotor is given an initial rotation in any direction, the resultant average torque increases in the direction, at which the rotor is initially rotated and motor starts rotating in that direction.

→ But in practise it is not possible to give initial torque to the rotor externally and hence we need some modifications in the construction of 1-ϕ I.M to make them self start.



ϕ_{1m} = starting alternating flux.

Speed-Torque characteristics



2. Cross field theory

- In order to make the 1-ϕ Induction motors as self starting we are making some modifications in the w/g's

→ A/c to this 1-ϕ induction motors are
1) split phase I.M. 2. Capacitor start "
3. Capacitor start capacitor run I.M.
4. shaded pole I.M

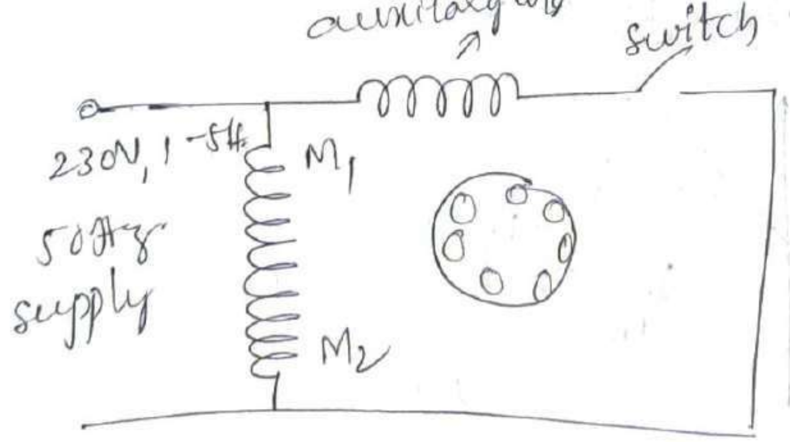
1) Split phase I.M (Resistance splitting)

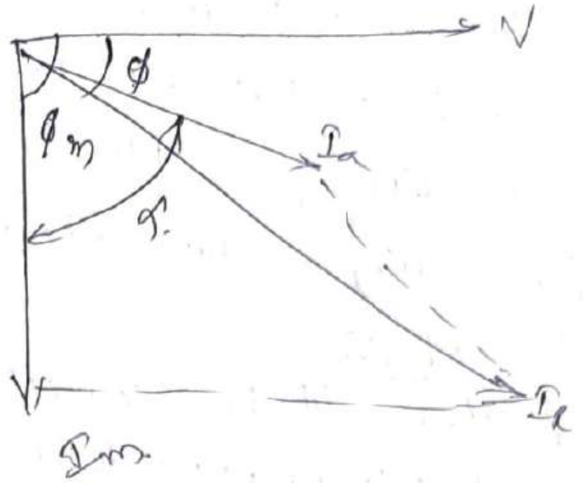
→ In this in addition to the main w/g, an extra w/g called starting w/g is used in order to split the main elt's and hence main flux.

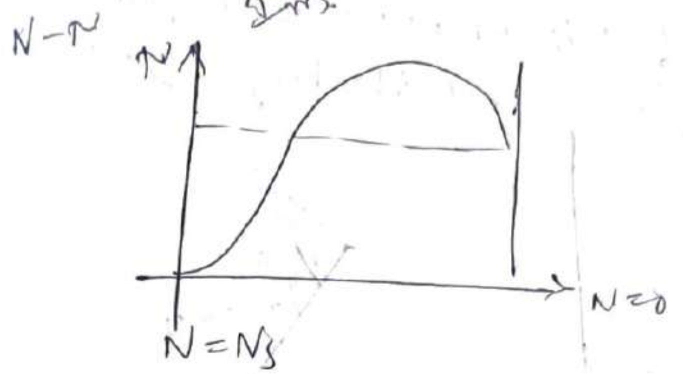
→ This w/g purpose is upto 70-80% of the rated speed of I.M.

→ Thereafter the w/g is to be make isolate. For this we are using a switch called centrifugal switch in series with the auxillary w/g.

→ The entire is etup is shown in fig.







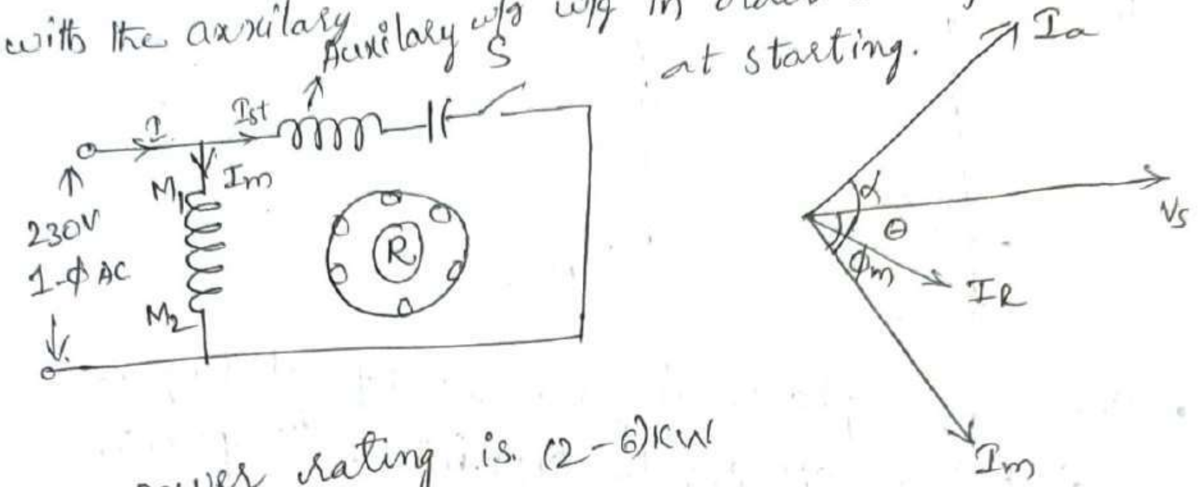
- the above phasor diagram shows of splitting on maintained c/t (stator c/t) into 2 components as I_m & I_a
- Due to this the starting torque is improved upto 125% to 150%

→ i.e. Due to the poor starting torque this type of I.M are limited less than ½ kVA.

This motors have low starting c/t and moderate starting torque and hence this motors are used in easily started loads like fans, blowers, Grinders centrifugal pump, washing machine etc.

Capacitor start method:-

In this a capacitor will be connected in series with the auxilary w/g in order to improve the p.f at starting.



· power rating is (2-6)KW

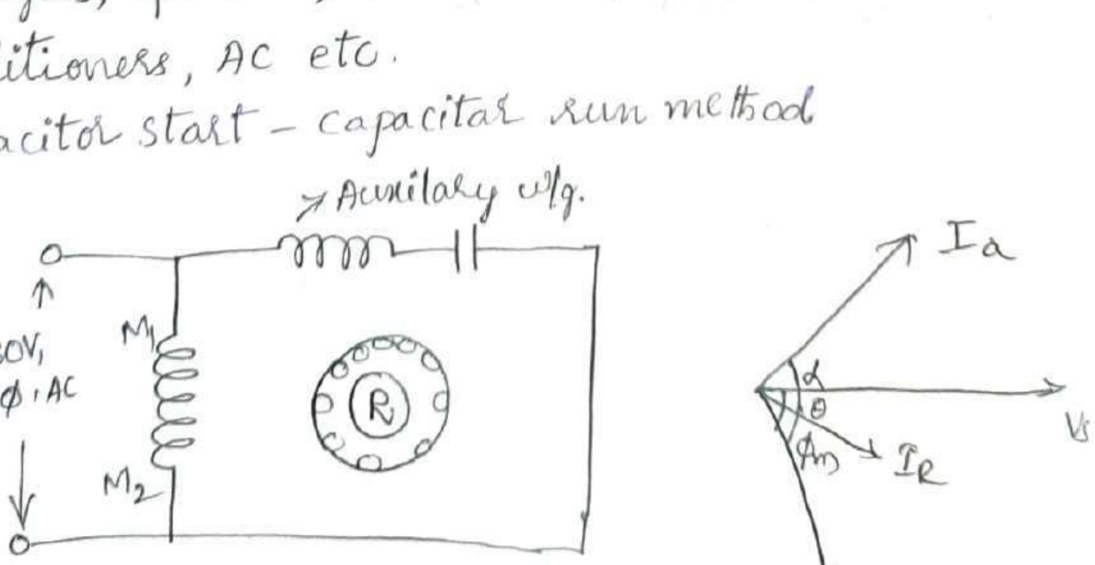
Starting torque ∝ to α'

α = Ist to Im

Application

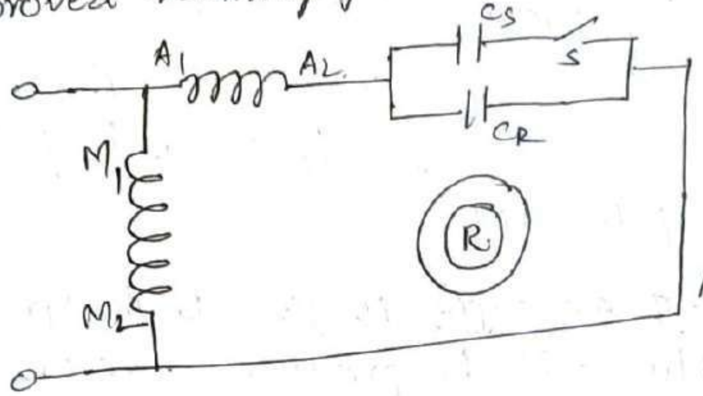
This motors have high starting torque and hence used for starting loads like compressor, conveyors, Grinders, fans, blowers, Refrigerators; air conditioners, AC etc.

Capacitor start - capacitor run method

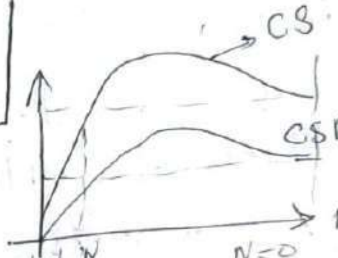


In this a capacitor will be kept permanently even at running condition also. This is because for improving p.f under running condition.

. The starting torque of this m/r about 100 to 150%. where as in capacitor start I.M, this value is 300-400%. . Hence in specific application in order to obtain both the characteristics of capacitor I.M (capacitor start & C.R I.M.). . Two value capacitor will be used to get high starting torque and improved running power factor



. power rating is upto -6KW

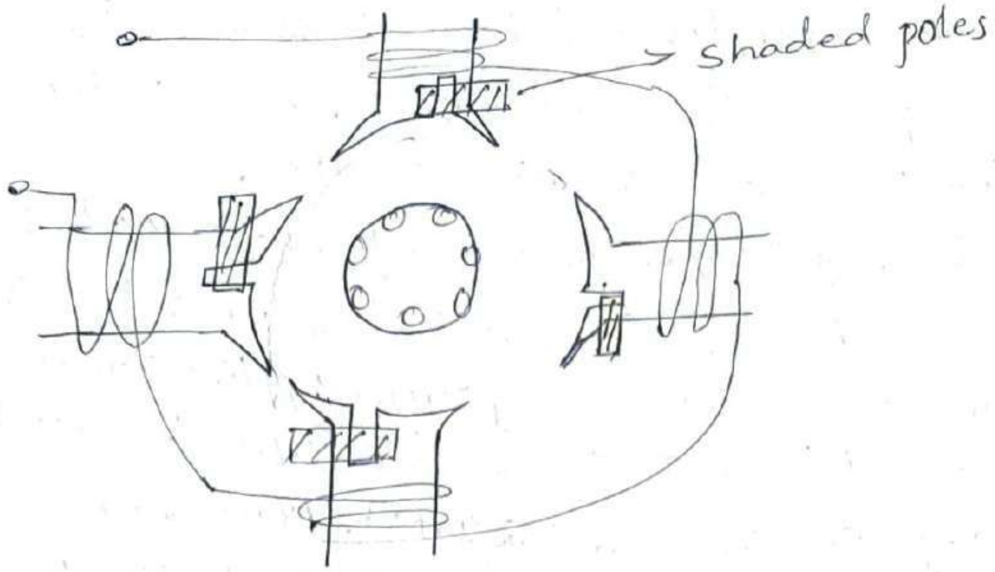


Application of C.S & C.R I.M

. Ceiling fans, blowers, air circulating etc.

SHADED POLE INDUCTION MOTOR.

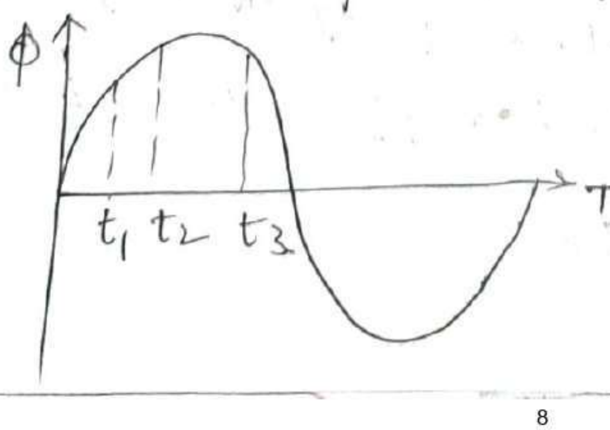
This type of m/r consist of squirrel cage m/r and stator consisting on salient poles i.e., projected poles. The poles are. shaded i.e., Each pole carries a copper band on one of its unequally divided parts called shading band. The below fig shows a four pole shaded pole construction.

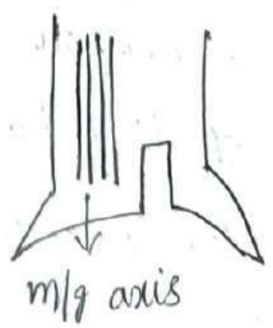


- when an 1-ϕ AC supply is given to the stator w/g.

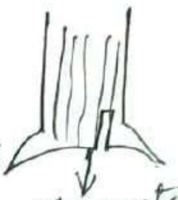
due to shading provided to the pole, a rotating m/g field is generated. The below procedure explains how a rotating m/g field is produced in the shaded pole I.M.

- when an 1-ϕ AC supply is given to the s/r w/g an alternating flux will be produced across the pole. which cuts the shading band as it is a closed ring. an emf will be produced in the ring simultaneously a current and flux will develop in the band. According to "Lenz law" the direction of the induced flux in the shading band is in opposite direction to the main flux. Hence due to opposition force. at $t=t_1$ instant the entire pole flux will be crouded towards the unshaded path of the pole. this is shown below



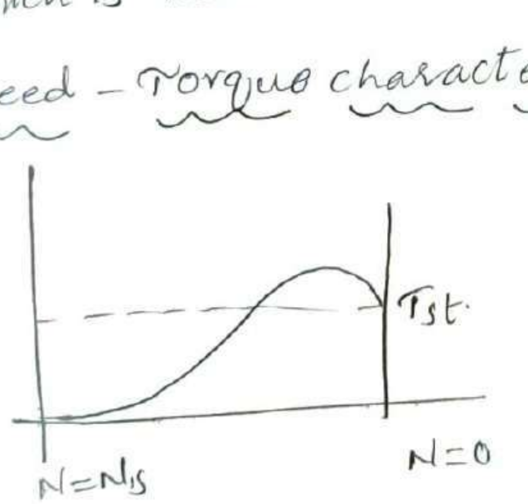


At $t=t_2$ position. the rate of rise of c/t is minimum and hence rate of rise of flux $\frac{d\phi}{dt}$ nearly equal to zero. Hence the EMF produced in the shaded band is minimum and opposing force to the pole flux is also minimum. Hence the main flux distributes entirely pole phase and magnetic axis will be as shown in below fig.



. At $t=t_3$ position, both c/t & flux decreases at higher rates and also the direction of main flux and shaded band flux is same and hence more resultant flux at shaded region of the pole. Hence the magnetic axis now shift towards shaded region. the similar process will results for the negative half cycle and hence by this procedure, It is clear that we are obtaining a rotating m/g field in the s/r. which is needed to make the 1-ϕ I.M as self started.

Speed - Torque characteristics :



DISADVANTAGES
. poor starting torque 2. low p.f. 3. I^2R losses more and hence decreasing η. 4. Speed revessal is difficult 5. less power ratings

Applications : Used in.

Small fans, Toy motors, Advertising display; film projector, Record player, Gram phones, hair dryers photocopying machine etc.

①

Equivalent circuit

The equivalent circuit of a 1-ϕ Induction motor can be developed based on two revolving field theory. To develop the equivalent circuit it is first necessary to consider standstill or blocked rotor conditions.

- The motor with a blocked rotor it acts like a transformer with its short circuited, the equivalent circuit shown (a). Em induced in the stator.

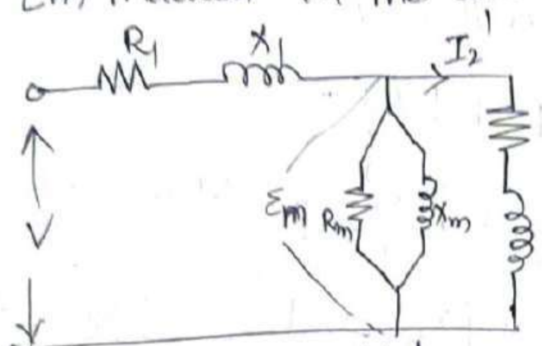


fig a) I.M at standstil

$$V(\text{or})\,E = E_{mf} + E_{mb}$$
$$= \phi_{m/2} + \phi_{m/2}$$

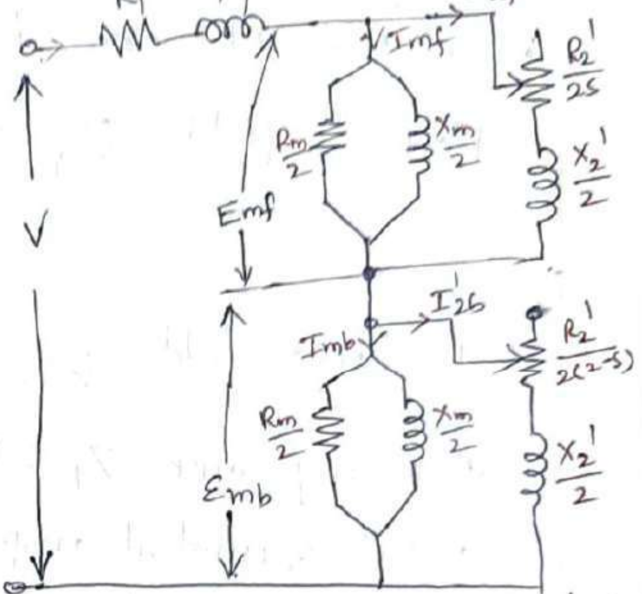


fig b. Equivalent ckt of I.M-under normal operating conditions

- The two flux components induce in the stator winding, the respective emf E_{mf} & E_{mb}.
- At standstill the two oppositely rotating fields are of same strength. The magnetizing and rotor impedance are divided into two equal halves connected in series
- when the rotor is running at speed N w.r.to forward field, the slip is 'S'
- (2-S) for backward rotating field(S_b)

$$S_b = \frac{N_s - (-N)}{N_s}$$
$$= \frac{2N_s - (N_s - N)}{N_s}$$
$$S_b = 2 - S$$

- In order to obtain approximate equivalent circuit the Core losses will be neglected. i.e., $\frac{R_m}{2}$ parameters.

Performance Characteristics

The performance characteristics of an 1-ϕ I.M, calculated when running with only its main winding.

- They determined from the equivalent circuit diagram
- In 1-ϕ I.M core losses will be taken rotational losses

Forward field $Z_f = R_f + jX_f \Rightarrow$

$$= \frac{R_2'}{2S} + j\frac{X_2'}{2} \text{ parallel with } \frac{jX_m}{2}$$

Backward field $Z_b = R_b + jX_b \Rightarrow \frac{R_2'}{2(2-S)} + j\frac{X_2'}{2} \parallel \frac{jX_m}{2}$

Stator impedance $Z_1 = R_1 + jX_1$

Total equivalent impedance $Z_{eq} = Z_1 + Z_f + Z_b$

Motor current $I_1 = \frac{V}{Z_{eq}} \Rightarrow \frac{V}{Z_1 + Z_f + Z_b}$

power factor $= \frac{R_{eq}}{Z_{eq}} \Rightarrow \frac{R_1 + R_f + R_b}{Z_1 + Z_f + Z_b}$

$E_{mf} = I_1 Z_f$; $E_{mb} = I_1 Z_b$

$$I_{2f}' = \frac{E_{mf}}{\frac{R_2'}{2S} + j\frac{X_2'}{2}} \Rightarrow \frac{I_1 Z_f}{\sqrt{\left(\frac{R_2'}{2S}\right)^2 + \left(\frac{X_2'}{2}\right)^2}}$$

$$I_{2b}' = \frac{E_{mb}}{\frac{R_2'}{2(2-S)} + \frac{jX_2'}{2}} \Rightarrow \frac{I_1 Z_b}{\sqrt{\left(\frac{R_2'}{2(2-S)}\right)^2 + \left(\frac{X_2'}{2}\right)^2}}$$

Airgap power for forward field $P_{gf} = (I'_{2f})^2 \frac{R'_2}{2s}$ in Watts

Airgap power for Backward field $P_{gb} = (I'_{2b})^2 \frac{R'_2}{2(2-s)}$ in watts

Mechanical power o/p forward field $P_{mechf} = (1-s) P_{gf}$

" " Backward field $P_{mechb} = [1-(2-s) P_{gb}]$

Mech power o/p = $P_{mech\,net}$ = $P_{mechf} - P_{mechb}$

Net Torque developed = forward field − Backward field

$$= \frac{9.55}{N_s} [P_{gf} - P_{gb}]$$

motor efficiency $\eta = \frac{\text{o/p power}}{\text{i/p power}} \times 100$

- power delivered to backward field = $P_{gb} - P_{mech\,b}$

  ↳ Two ways → one directly airgap
  → Convert into mech

- Backward field act as Generator.

Determination of Equivalent Circuit parameters

The performance (η, losses & p.f) of 1-ϕ I.M is obtained by applying load to it.. However to determine the constants of the machine it is necessary to perform tests

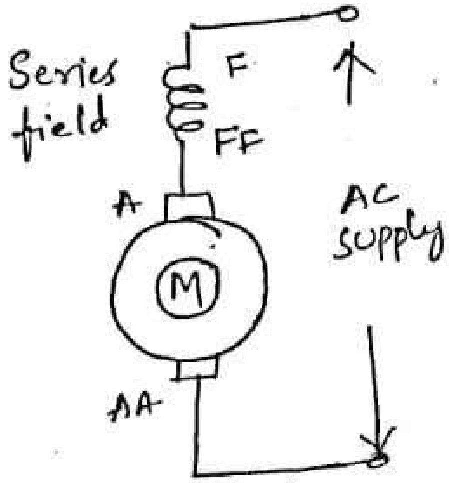
a) Measurement of stator winding resistance:

- Measurement of each stator winding is measured separately, but in case of capacitor start motor the condenser is omitted.

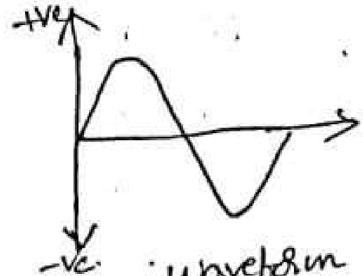
AC Series motor

An ordinary DC series motor will run in the same direction regardless of the polarity of the supply.

- If the line terminals be reversed, both the field and armature current are reversed, the direction of torque remains unchanged. Therefore the motor continuous to rotate in the same direction.



Schematic representation



waveform of alternating current

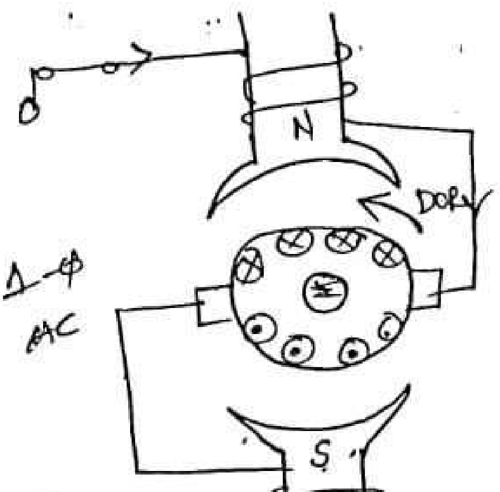


fig: current direction 1st half cycle

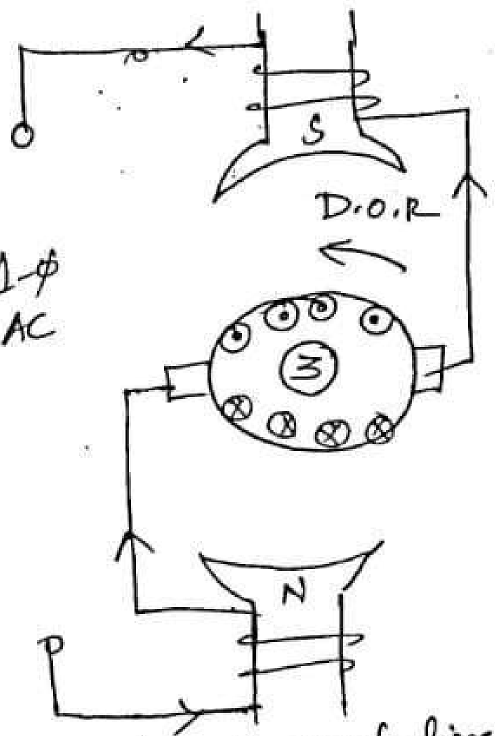


fig: current direction 2 other half cycle.

When normal DC series motor is connected to an AC supply both field and armature currents reverse simultaneously and unidirectional torque is produced in the motor.

Consider a two pole motor and let the alternating current be in its positive half.

The armature conductors carry inward direction (x) under north pole and outward direction (·) under south pole.

- By flemings left hand rule, it will be seen that the torque developed in the armature will try to rotate in anticlockwise direction.

- During the next instant, the alternating current goes through negative half cycle
  - Now the current through field and armature will also change as shown in fig 2.
- It will again the armature will tend to rotate in the same direction. Because of uniform torque produces the two halves of the cycle.

The performance of DC motor works on a.c. supply is not satisfactory due to the following reasons

1. The efficiency is low. Increases the core losses due to alternating flux. (field w/g has AC supply → Eddy ↑ → η ↓)
2. Armature and field winding offer high reactance to AC due to which operating p.f is very poor
   * $R+jX \rightarrow X\uparrow \rightarrow I\downarrow \rightarrow \phi\downarrow \rightarrow T\downarrow$

Modification in Design of AC series motor

- Yoke and poles should be fully laminated, to reduce eddy current losses.
- P.f. can be improved by reducing field & armature reactance. Field w/g. is designed with less number of turns. in order to reduce field reactance.
-

* Reduction in number of turns on the field winding would also reduces field flux. To keep the torque same, it is necessary to increase the armature turns proportionally. This increases A.R & armature reactance
* Compensating winding should be employed to lower the armature reactance as far as possible. It also reduces armature reactions
* The airgap is made very small, so that less field turns can be used per pole
* Size of pole reduces ↓ → field w/g turns ↓ → airgap small
* Voltage rating should be less, if $V\uparrow \rightarrow I\downarrow \rightarrow T\downarrow$

characteristics

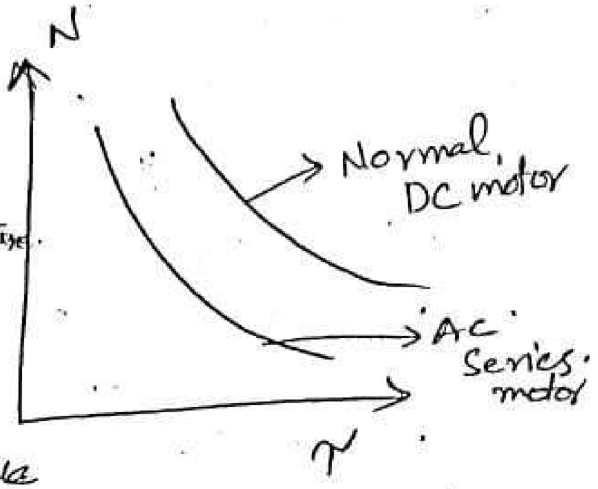
- the characteristic similar as Dc series motor

$T \propto I_a^2$

- Torque varies square of Armature current

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

T_{st} will 3 to 4 times of FL Torque



Application

Electric traction, locomotives

In DC $f=0$, $X_L = 2\pi f L$
$= 0$

* the axis of compensating winding is 90° (electrical) with main field axis.

In AC I^2R & I^2X_L losses increases

220V i/p — 180V AC. o/p appears.

$X_L = 2\pi f L \Rightarrow L\downarrow \rightarrow$ no. of turns decreases $- L\downarrow$

$\rightarrow \phi\downarrow \rightarrow T\downarrow$.

$$\boxed{T \propto K\phi I_A}$$

For overcome the above problem, Compensating winding is used 1) Conductively 2) Inductively

1) Conductively $\downarrow$ Series with Arm. w/g

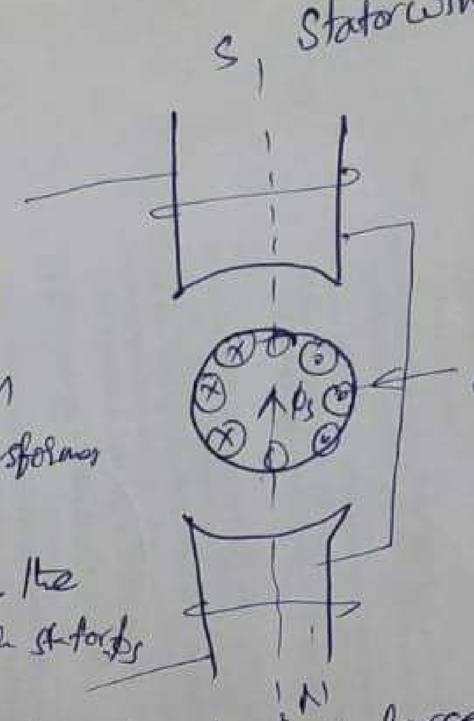
2) Inductively $\downarrow$ No connection

*

Cross field theory

1-ϕ I.M - Standstill rotor.

Stator w/g $\xrightarrow{\text{excite}}$ 1-ϕ AC supply



ϕ_S → along Stator w/g axis

Due to this emf induced in rotor conductors due to transformer Action.

- The direction of rotor oppose the Cause producing it, → which stator ϕ_s

Fleming LHR Used to know the direction of force experienced by the rotor conductor → Acts ϕ_S upward direction

- The conductor on left experience force from R to left
  Right " " Left to right

Hence overall experienced by the rotor is zero, So not starting

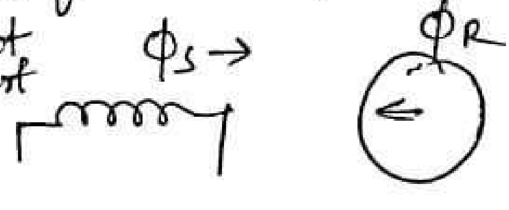
- Two fluxes produces RMF., ϕ_S → divides into two component mutually ⊥ar each other, One acts on S/r w/g axis other ⊥ar
- Initial push given → stator flux cut by rotor con, Speed emf i
- The axis of ϕ_R is at 90° to the axis of stator flux hence this rotor flux is called st cross field

Direction of RMF → direction of initial push

rotor experience for → same taking Direction of initial push as RMF

Cross field theory

why not Self start

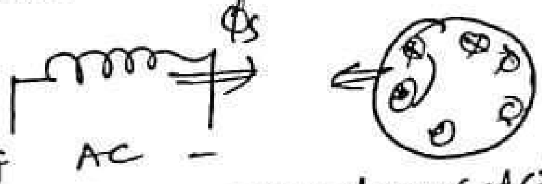
1) 

both field are opposite 180°

2) 

Net torque $= 0$

Case 1 : No push - No Rotation

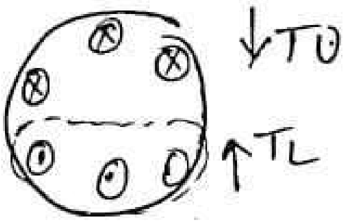


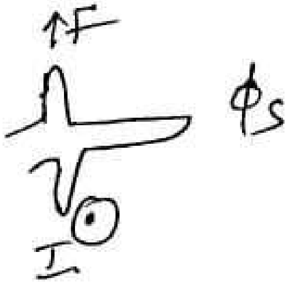
$\frac{d\phi}{dt} = \mathcal{E}$ induced

Transformer Action

Maxwell Thumb rule Thumb - flux, current - fingers

Fleming Right hand rule

FRH 



Electrical Machines - III

Construction and principle of operation of synchronous Machines:

ALTERNATOR:

Synchronous generator or AC generator is a device, which converts mechanical power in the form of AC.

It works on the principle of Electromagnetic induction and it is also called as Alternator.

An alternator consists of armature winding and field magnets, but the difference between the alternator and DC generator is that in the DC generator armature rotates and the field system is stationery. The alternator arrangement is just reverse of it, the armature is stationery called as stator and field system is rotating called as Rotor.

For generating EMF, three things are essential,

i) magnetic field ii) system of conductors

(iii) Relative motion between there two.

The conductors are mounted on the stators and field poles are mounted on the Rotor core. Relative motion between the stator conductors and the field is brought about rotating the field system.

The rotor is coupled mechanically to a suitable prime mover. when the prime mover runs, the rotor core also rotates and the field flux is cut by the stationary stator conductors and emf's are induced in them.

If a load is connected across the stator terminals, electric power would be delivered to it.

Advantages of stationary Armature:

1. The generated power can be easily taken out from the stator.
2. There is no possibility of the armature conductors flying of, when the machine runs at high speed, since they are housed in the stator slots.
3. There is no difficulty in insulating the armature (stationery) winding for very high voltages i.e as high as 30,000V or more.
4. Two slip rings are required for the supply of DC energy required for rotor field excitation since the exciting current is to be supplied at low voltage, there is no difficulty in insulating them.
5. Rotating field is competitively light and can run with high speeds.

parts of Alternator

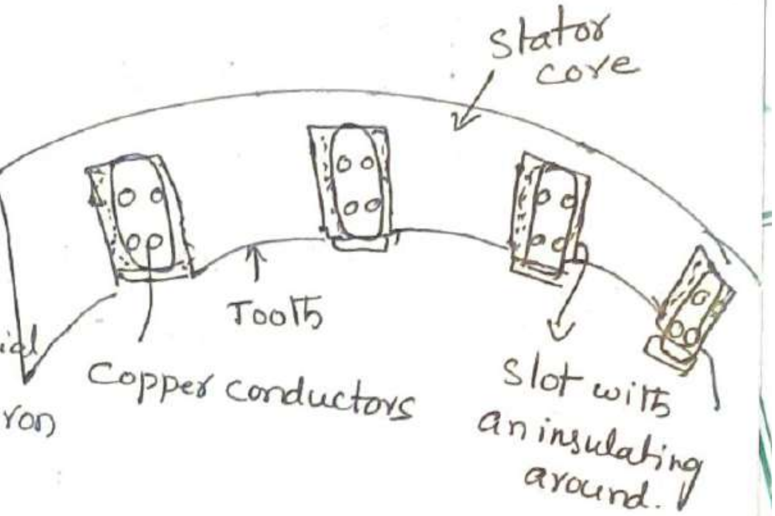
- Stator
  - Stator frame
  - Stator core
  - Stator winding
- Rotor

CONSTRUCTION:

An Alternator consists of mainly two parts 1. Stator 2. Rotor.

1. Stator:

The armature core is supported by the stator frame and is built up of laminations of special magnetic iron or steel iron alloy.



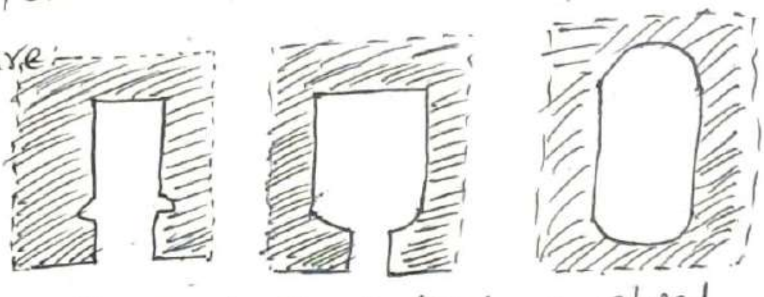
Stator frame : It is made of cast iron and gives mechanical support to the machine

Stator core: It is made of laminated Silicon steel, it has slots on its inner pheriphery to accommodate the Conductors.

The core is laminated to minimize the loss due to eddy currents. The laminations are stamped out in complete rings or segments. The laminations are insulated from each other and have space between them for allowing the cooling air to pass through.

The inner pheriphery of the stator is slotted and copper conductors which are joined to one another, constituting armature winding housed in these slots. The other ends of the winding are brought out are connected to fixed terminal from which the generator power can be taken out.

Different shapes of armature slots are shown in figure:-



wide open   Semi-closed   closed

The wide open slots used in DC machines, has the advantage of permitting easy installation of form-wound coils and their easy removal incase of repair, but it has the disadvantage of distributing the airgap flux into bunches that produce ripples in the wave of generated EMF. it gives least expenditure.

The semi closed type slots are better in this respect but dont allow the use of form wound coils.

The fully closed slots ~~are~~ do not distrub the airgap flux but they try to increase the inductance of the windings. The armature conductors have to be threaded through, there by increasing the intial labour and cost of the winding. Hence these are rarely used.

2. ROTOR: Depending upon the type of Application, there are classified into two types.

1). Salient- pole or projecting pole type

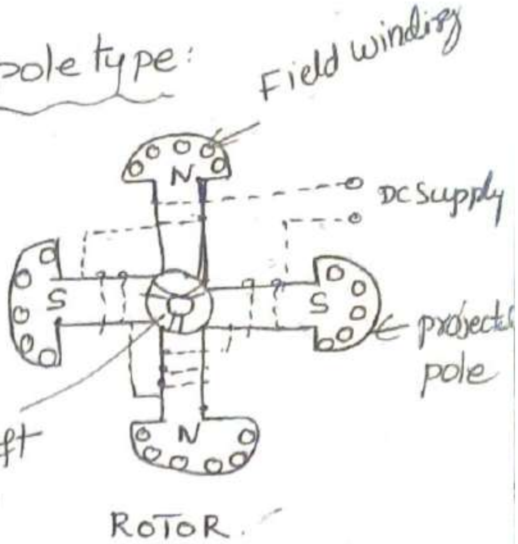
2). Non-Salient-pole or round rotor or cylindrical rotor.

The field excitation to the rotor is provided by a small dc shunt or compound generator. it is mounted on the same shaft of the alternator. The power rating is 0.3 to 1% of power rating of alt

Salient-pole or projecting pole type:

1) It is used for medium speed alternators, used in hydro & Diesel power generating station

2) The poles are made of laminated sheets and fixed to the rotor by dove tail joint.



3) Short circuited damper bars are placed in the slots provided on the pole surfaces.

4) These are used to prevent hunting and to provide Starting torque in Synchronous motors.

5) The field coils are placed on the poles shown in fig. they are connected in the Series and connected to a d-c source through slip-rings.

They have large diameter and short axial length. The pole shoes covers about two third of (2/3) of pole pitch.

→ It has non-uniform airgap

→ The diameter of the rotor is more than of the cylindrical rotor

→ The no-of holes is higher than that of the Non-salient pole rotor

→ Axial length is less

→ The prime mover speed is less and is driven in hydel turbines.

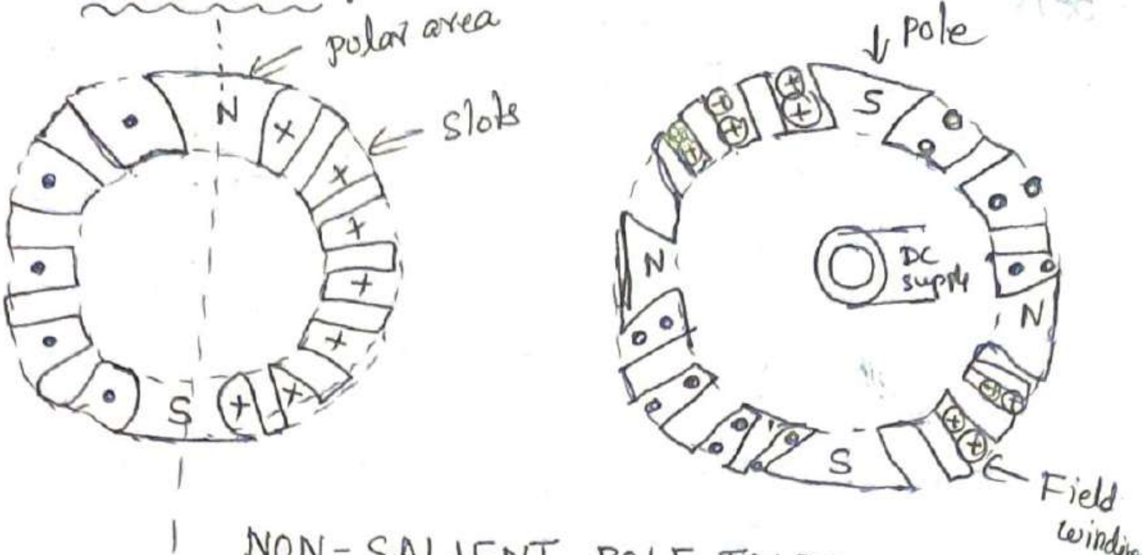
→ These generators are used in hydro electric Stations so these are called as hydro generators.

Sliprings: They are made of hard drawn copper. They are mounted on the shaft and insulated from it. They facilitate DC supply to field winding through brushes.

Brushes and Brush holders: are made of Carbon and placed over Slip rings. Brushes are placed in brush holders.

Non- Salient pole type or cylindrical type or

Round Rotor:



NON-SALIENT POLE TYPE

Slots are provided in between the poles and these slots are placed with field winding conductors.

Features: 1) No. of poles are less when compared to salient type

2) Diameter is less, good balancing & smooth operation

3) Axial length is more

4) Air gap is uniform

5). prime mover speed is more and is driven in Thermal turbines

6) These are used in Thermal stations, so these are called as turbo generators.

7) They have less windage losses

It is smooth cylindrical laminated core, having no. of slots on its outer pheriphery to accommodate field winding. They are designed for 2 pole or 4 pole alternator for a speed of 3000 rpm or 1500 rpm.

Spider: it is made of cast iron or cast steel. magnetic poles are fitted on it. it is mounted on the same shaft.

Frequency of the Induced emf:

let consider an alternator, whose rotor is driven at a constant speed N RPM.

let 'p' be no. of poles and 'f' is the frequency of the generated voltage.

No. of cycles of the induced EMF per second

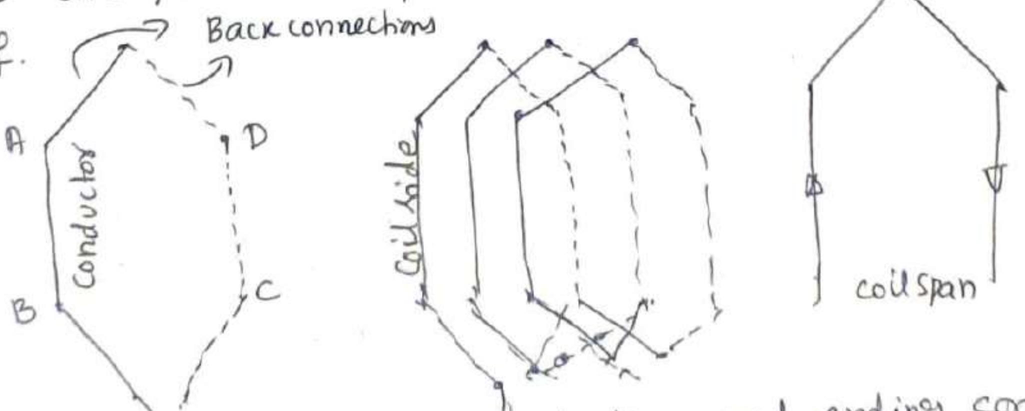
= No. of cycles per revolutions x No. of revolutions / sec

$$= \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120}$$

$$\boxed{\text{Frequency} = f = \frac{NP}{120}}$$

For a given alternator, the No. of poles is fixed. Hence inorder to generate power at a specified frequency, the machine is to be run at a definite speed which is termed as Synchronous speed.

Pole-pitch: Distance between two adjacent opposite main poles by the number of Armature conductors. It is the centre to centre distance between two ~~adjacent~~ adjacent poles. one pole is responsible for 180° electrical of induced emf.



Distance between two coils | starting and ending conductors

coil span = pole pitch → full pitch winding or integral slot winding

Coil span or coil-pitch (Y_s)

It is the distance, measured in terms of armature slots (or armature conductors), between two sides of a coil. If the pole span or coil pitch is equal to the pole pitch, then winding is called full-pitched winding. The distance between any two conductors is called slot angle (β)

Damper winding: most of the Alternators have their pole shoes slotted for receiving copper bars of a grid or damper winding also known as squirrel-cage winding. The copper bars are short circuited at both ends by heavy copper rings. These dampers are useful in preventing hunting (momentary speed fluctuations) in generators and ~~are~~ needed in synchronous motors to provide the starting torque. The damper windings also tends to maintain balanced 3-ϕ voltage under unbalanced load conditions.

Armature windings: windings in Alternator

In case of three phase alternators, the following types of windings are employed.

1. Lap winding 2. Wave winding 3. mush winding

Based on the pitch of the coil

1. Full pitched 2. Short pitched windings

Based on the number of Layers

1. Single layer 2. Double layer

AC Armature windings are usually symmetrically distributed in slots around the complete circum-ference of the armature.

AC armature windings are generally open circuit type i.e both ends are brought out. Armature windings in Alternators are different from those used in dc machines. The DC machines have closed circuit winding. Alternator windings are open, in the sense that there is no closed path for the armature currents in the winding itself. one end of the winding is joined to the neutral point and other is brought out (for a star connected armature)

Armature winding

- Concentrated winding
- Distributed winding
  - full pitched winding
  - Short pitched winding
    - Integral slot winding
    - fractional slot winding.

Note:
Short pitched windings are used to eliminate harmonics 3rd, 5th, 7th ----
Fractional Slot windings are used to eliminate slot tooth harmonics and higher order harmonics 11th, 13th, 15th.

AC Armature windings are generally distributed windings i.e they are symmetrically distributed in slots around the complete circum ference of the armature. A distributed winding has two principal advantages. First a distributed winding generates a voltage wave that is nearly a sinewave. secondly copper is evenly distributed, on the armature surface. therefore heating is uniform and this type of winding is more easily cooled.

AC Armature windings may use full pitch coils, or fractional pitch coils. A coil with a span of 180° electrical is called a full pitch coil. In this case two sides of coil occupy identical positions under adjacent opposite poles and the emf generated in the coil is maximum. A coil with a span of less than 180° electrical is called a fractional pitch coil. For example, a coil with a span of 150° electrical would be $150°/180° = 5/6$ pitch coil. Although emf induced in a fractional pitch coil is less than that of a full-pitch coil. Fractional pitch coils are frequently used in a.c machines for two main reasons. First, less copper is required per coil, Secondly the wave form of the generated voltage is improved.

most of ~~the~~ a.c machines use double layer armature windings. In double layer winding one coil side lies in the upper half of one slot, while the other coil side lies in the lower half of another slot, spaced about one pole pitch from the first one. This arrangment permits simpler end connections and it is economical to manufacture. Since most of a.c machines are of 3-phase type, the three windings of the three phases are identical,

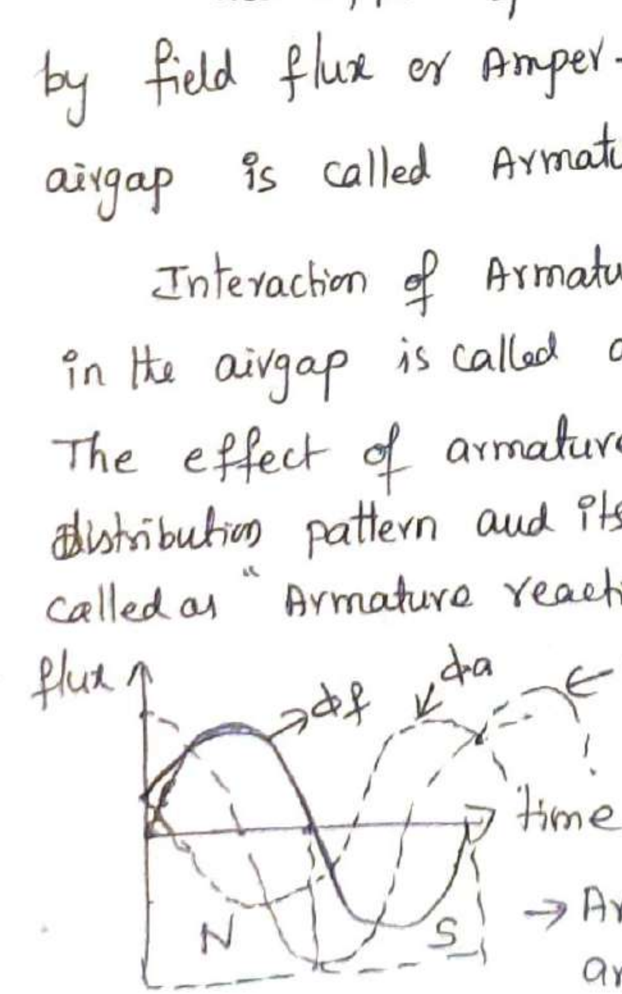
ARMATURE REACTION :

When an Alternator is running at NO-load, there will be no current flowing through the armature winding. The flux produced in the airgap will be only due to rotor Ampere-Turns (MMF). when the alternator is loaded, the three phase currents will produce a totaling magnetic field in the air gap. consequently the air gap flux is changed from the no-load condition.

The effect of armature flux on the flux produced by field flux or Amper-turns (MMF) (Rotor A-T) in the airgap is called Armature Reaction.

Interaction of Armature flux on the main flux (field flux) in the airgap is called as Armature reaction.

The effect of armature flux (AT), affecting the main flux distribution pattern and its magnitude in the airgap is called as "Armature reaction"



$\phi_f \rightarrow$ field flux (main flux ϕm)

$\phi a \Rightarrow$ armature flux

→ Armature reaction depends on the armature current.

The armature reaction in an alternator is mainly depends on i) the armature flux and the flux produced by rotor Amper Turns rotate at the same speed (Synchronous speed) in the same direction and therefore two fluxes are fixed in space relative to each other.

ii) The modification or changes of flux in the airgap due to armature flux depends on the magnitude of stator current and on the power factor of the load.

It is the load power factor, which determines wether the armature flux distorts, opposes or help the flux produced by rotor flux (A-T). To Explain armature reaction in an alternator, let consider the following cases:

(i) when load p.f is unity. (Purely resistive load)

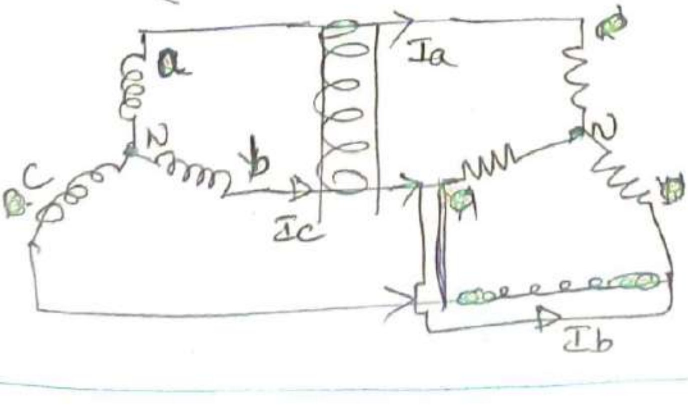
(ii) when load p.f is zero lagging (Purely Inductive load)

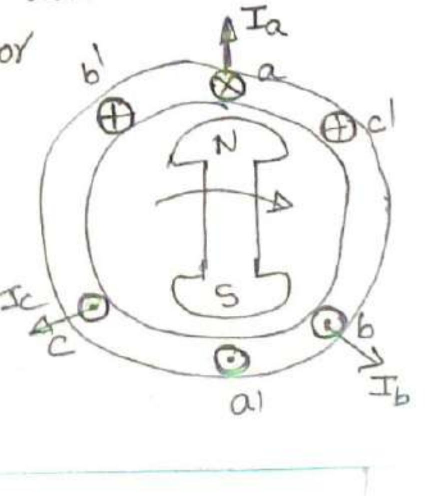
(iii) when load p.f is zero leading (Purely capacitive load)

(i) when the load power factor is unity:

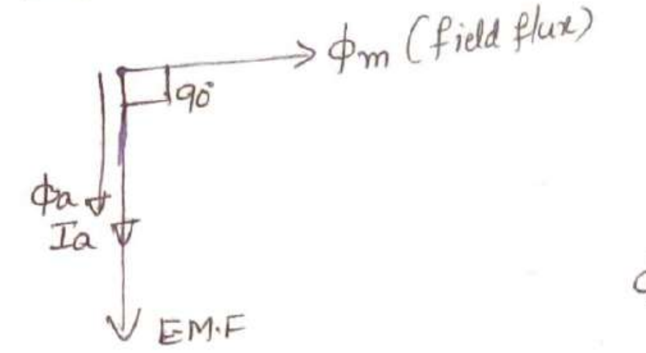
An alternator with no-load, the armature is on open circuit, there is no stator current and the flux due to rotor current is distributed symmetrically in the airgap. No armature flux is produced since no current flows in the armature winding.

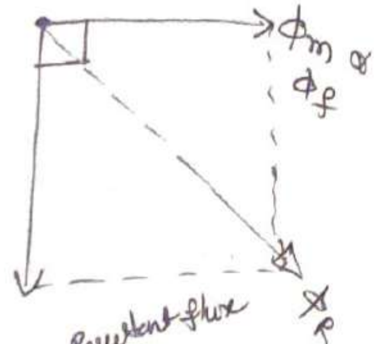
When resistive load is connected across armature terminals (at UPF p.f) of the alternator





phasor diagram



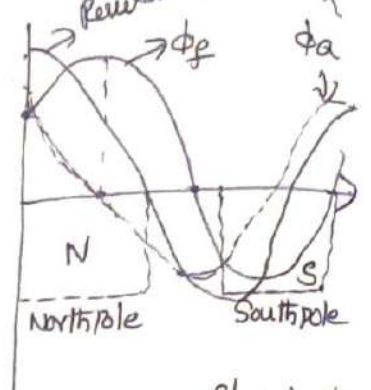


I_a - armature current

$I_a \propto \phi_a$

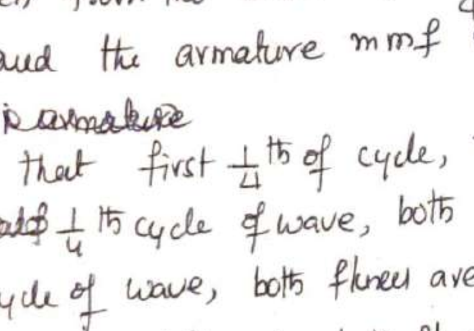
ϕ_m - main flux or field flux

The effect of the armature reaction for a unity power factor load, resulting in distortion of flux in the air gap is called "the cross magnetising effect".



Average flux in the air gap remains constant

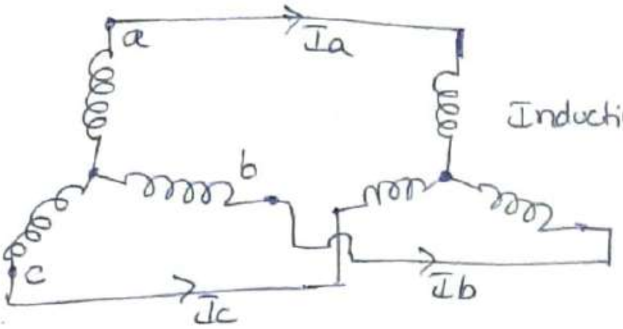
As seen from the above figures, the mmf of the main field ϕ_f and the armature mmf ϕ_a is behind it by 90°. It is seen that first $\frac{1}{4}$th of cycle, the two fluxes are aiding, next $\frac{1}{4}$th cycle of wave, both fluxes are opposing, next $\frac{1}{4}$th cycle of wave, both fluxes are aiding under South pole (S), further next $\frac{1}{4}$th cycle, both fluxes are opposing. For the period of 'T', the average flux in the airgap remains constant.

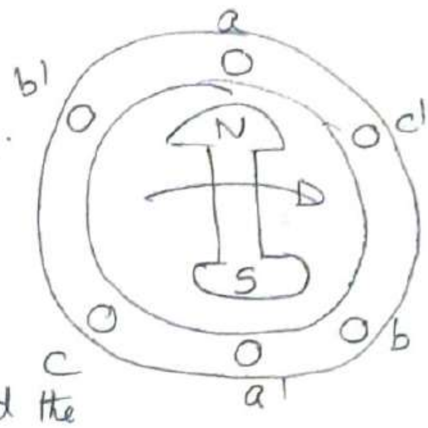


Cross magnetising effect

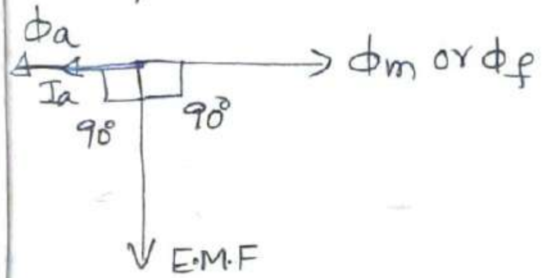
In the above case, the armature flux is cross-magnetising. The result is that the flux at leading tips of the poles is reduced while it is increased at the trailing tips. However these two effects nearly offset each other leaving the average field strength constant. Armature reaction for UPF is distorting ii). when the load p.f is zero lagging:

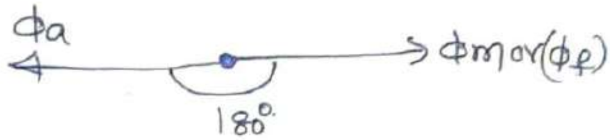
when Inductive load is connected across the armature terminals of a alternator,

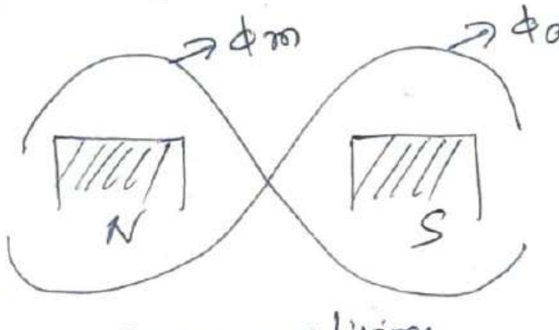




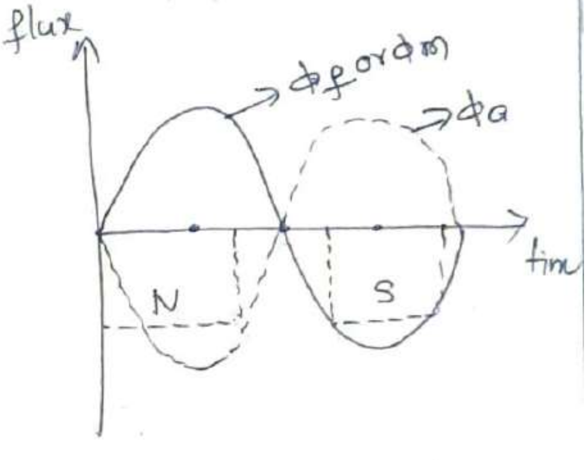
The armature current Ia lags behind the emf induced in stator and the armature flux ϕ directly proportional to the armature current as shown in phasor diagram. The armature flux ϕ_a is opposite to the field flux ϕ_f.





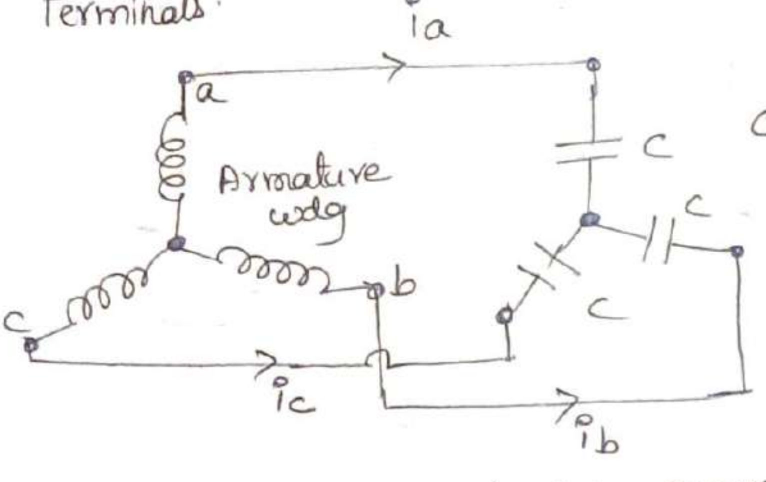


Demagnetising

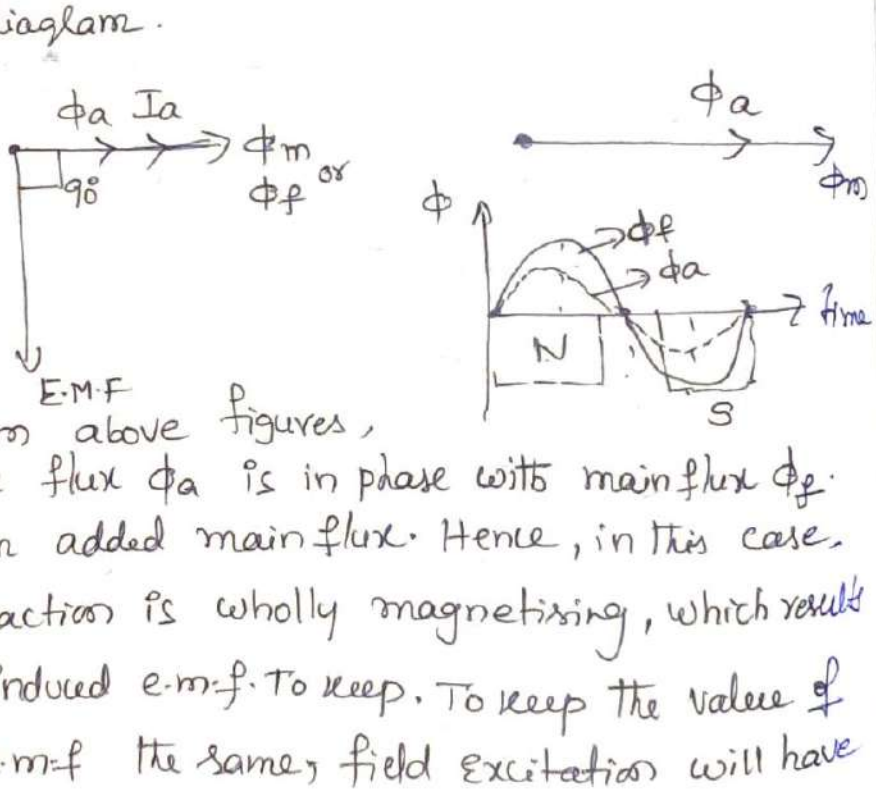


As seen from above figures, the armature flux ϕa is in direct opposition to the main flux ϕm or ϕf. hence the main flux is decreased. There fore it is found that armature reaction, in this case is wholly demagnetising, with the result, that due to weakening of the main flux, less e.m.f is generated. To keep the value of generated e.m.f the same, field excitation will have to be increased to compensate for this weakening (iii). When the load p-f is zero leading:

When capacitive load is connected across the armature terminals.

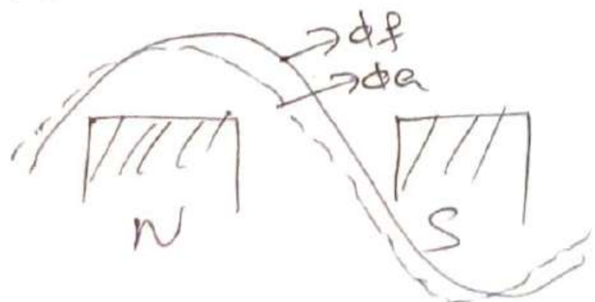


When capacitive load is connected across the terminals the armature current leads the e.m.f induced in a stator winding. Ia leads e.m.f by 90°. as shown in phasor diagram.



As seen from above figures,

The Armature flux ϕ_a is in phase with main flux ϕ_f. This results in added main flux. Hence, in this case, armature reaction is wholly magnetising, which results in greater induced e.m.f. To keep. To keep the value of generated e.m.f the same, field excitation will have to be reduced somewhat.



For intermediate p.f, the effect is partially distortional, and partially demagnetising.

Synchronous Reactance and Impedance:

The Sum of the fictitious armature reaction reactance accounted for considering armature reaction effet and the leakage reactance of the armature is called Synchronous reactance of the alternator denoted by X_s.

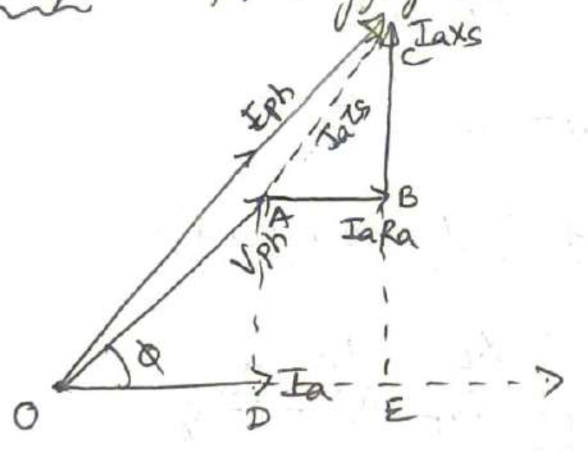
$$\boxed{X_S = X_L + X_{ar}}\ \Omega/\text{Phase}$$

The impedance is obtained by combining perphase value of Synchronous reactance and armature resistance is called Synchronous Impedance of the alternator denoted as Z_s.

$$\boxed{Z_S = R_a + jX_S}\ \Omega/\text{ph}.$$

$$|Z_S| = \sqrt{R_a^2 + X_S^2}\ \Omega/\text{ph}.$$

Phasor diagram: for lagging p.f loads.



$OA = V_{ph}$
$AB = I_aR_a$
$BC = I_aX_S$
$OC = E_{ph}$
$AC = I_aZ_S$

From Δ OCE

$$OC^2 = OE^2 + CE^2$$

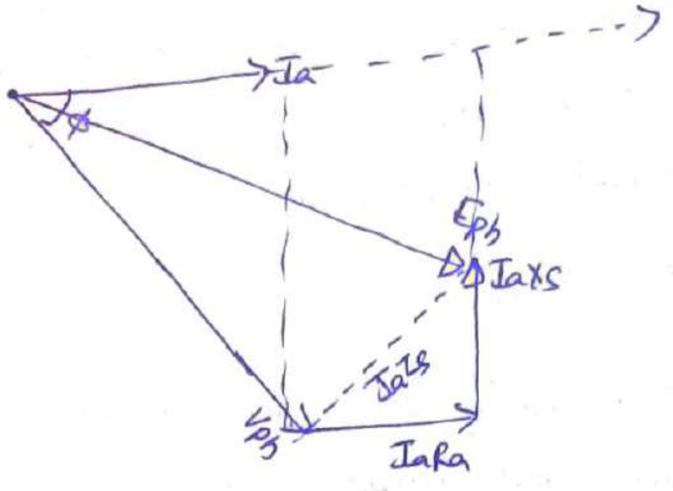
$$OC^2 = (OD+DE)^2 + (EB+BC)^2$$

$$E_{ph}^2 = (V_{ph}\cos\phi + I_aR_a)^2 + (V_{ph}\sin\phi + I_aX_S)^2$$

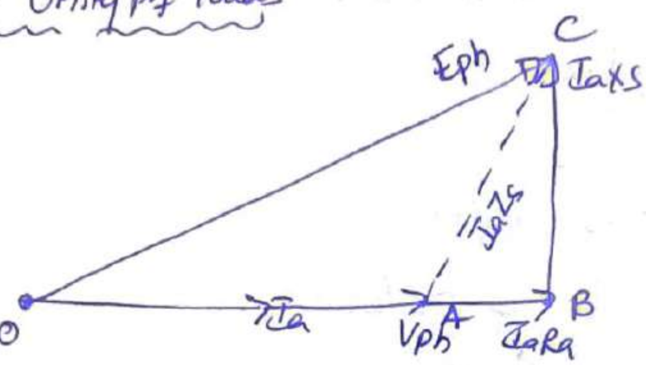
$$E_{ph} = \sqrt{(V_{ph}\cos\phi + I_aR_a)^2 + (V_{ph}\sin\phi + I_aX_S)^2}$$

for leading p.f^s

$$E_{ph} = \sqrt{(V_{ph}\cos\phi + I_a R_a)^2 + (V_{ph}\sin\phi - I_a X_s)^2}$$

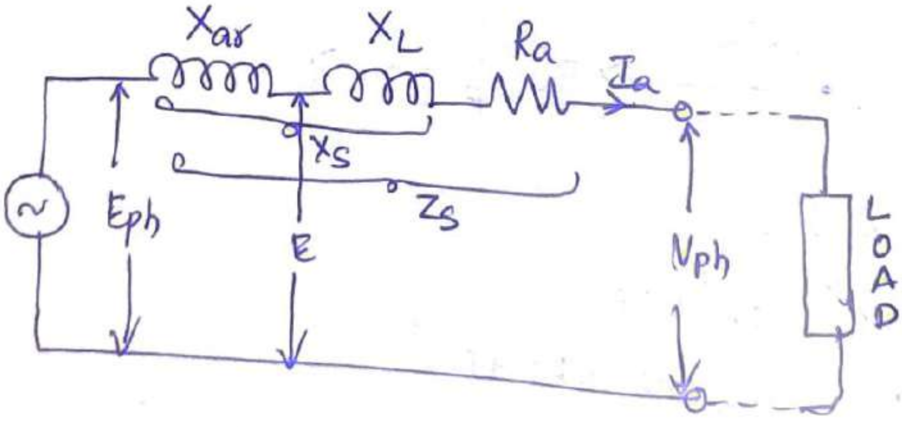


for unity p.f loads



$$E_{ph} = \sqrt{(V_{ph} + I_a R_a)^2 + (I_a X_s)^2}$$

Equivalent Circuit of Synchronous Alternator:



problems:

1. A 3 phase Star connected alternator supplies a load of 10 MW at 0.85 pf lagging and at 11 kV (terminal voltage). Its resistance is 0.1 Ω/phase and Synchronous reactance 0.66 ohms. Calculate the line value of emf generated?

Soln Full load Current $= \dfrac{10\times10^{6}}{\sqrt{3}\times 11{,}000 * 0.85} = 618A$

$I R_a$ drop $= 618\times0.1 = 61.8V$

$I X_s$ drop $= 618 * 0.66 = 408V$

Terminal voltage/phase $= 11000/\sqrt{3} = 6350V$

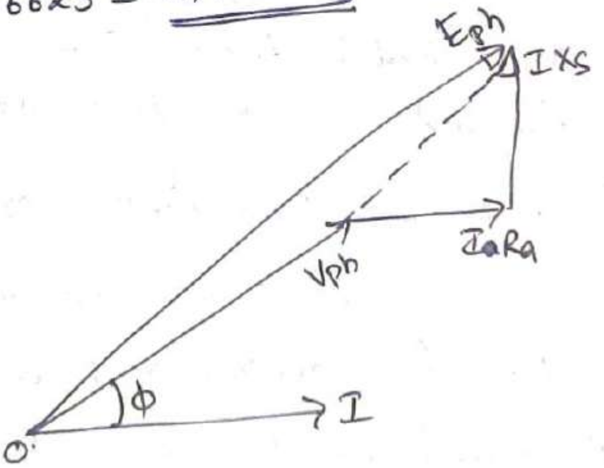
$\phi = \cos^{-1}(0.85) = 31.8^{\circ}, \ \sin\phi = 0.527$

$$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2}$$

$$E_0 = \sqrt{(6350\times0.85+61.8)^2 + (6350*0.527+408)^2}$$

$E_0 = 6625V$

Line emf $= \sqrt{3} * 6625 = \underline{11{,}486 \text{ volts}}$



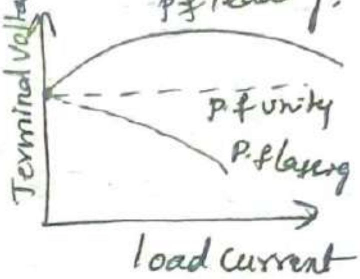
Voltage Regulation:

The Voltage regulation of an alternator is defined as " the rise in Voltage when full load is removed (field excitation and speed remaining same) divided by the rated terminal voltage."

$$\therefore \% \text{ regulation up} = \frac{E_0 - V}{V} \times 100$$

$|E_0 - V|$ is the Arithematic difference not Vector difference

In case of leading p.f, $E_0 < V$, % regn is -ve



Determination of Voltage Regulation:

The Regulation of alternator can be determined by Various methods. In case of Small capacity alternators, it can be determined by direct loading Test, while for large capacity alternator it can be determined by Indirect methods.

(i) Synchronous Impedance method or EMF method.

(ii) Ampere Turn method or MMF method

(iii) Zero power factor method or potier triangle method

(iv) ASA modification of MMF method:

1. Synchronous Impedance method:

This method is also known as EMF method. This method requires following data to calculate voltage regulation

1. The armature resistance per phase (R_a) : voltmeter-Ammeter meth
2. open Circuit characteristics (E_0 Vs I_f)
3. Short Circuit Characteristics (I_{sc} Vs I_f)

The Circuit diagram is shown below to conduct open Circuit test and short Circuit test.

prob: A 60-KVA, 220V 50Hz 1-ϕ alternator has effective armature resistance of 0.016 Ω and armature leakage reactance of 0.07Ω. Compute the voltage induced in the armature when the alternator is delivering rated current at a load p.f of (a) unity (b) 0.7 lag (c) 0.7 leading.

Soln

FL magnitude of current = $\frac{60000}{220} = 272.2A$

$IR_a = 272.2 * 0.016 = 4.3V$

$IX_L = 272.2 * 0.07 = 19V$

(a) UPF: $E = \sqrt{(V+IR_a)^2 + (IX_L)^2} = 225V$

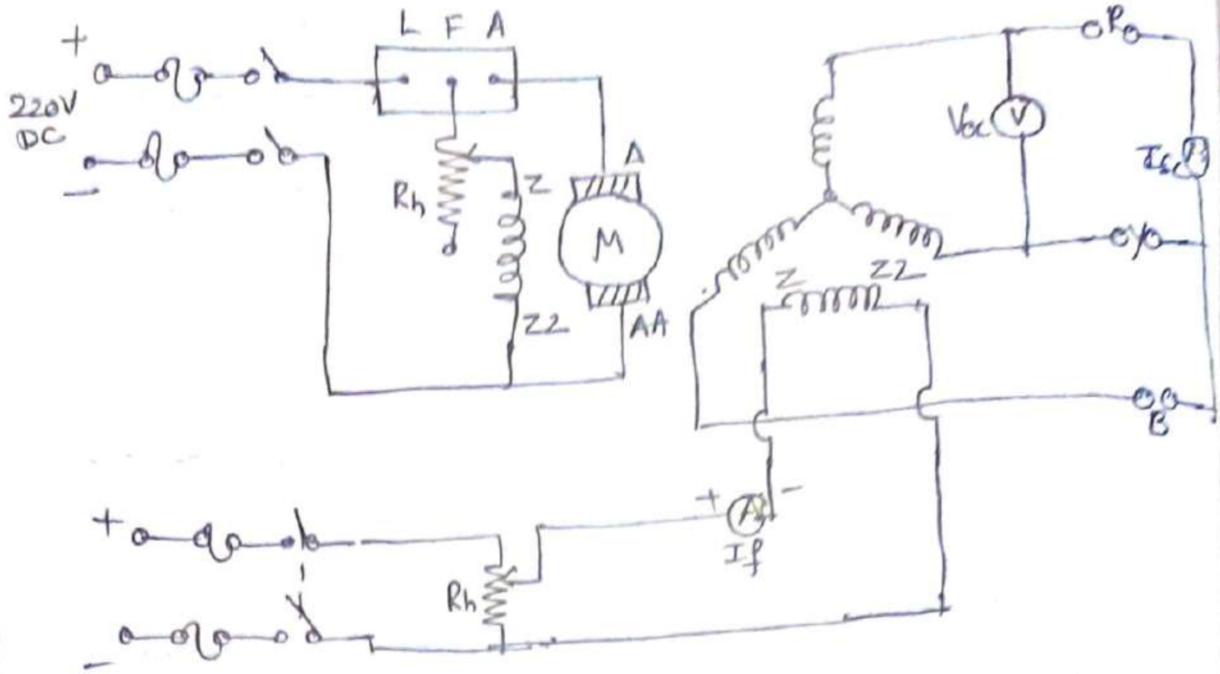
(b) 0.7 lagging $E = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_L)^2}$

$= \sqrt{(220\times 0.7 + 4.3)^2 + (220\times 0.7 + 19)^2} = 234V$

(c) 0.7 leading $E = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi - IX_L)^2}$

$\sqrt{(220(0.7)+4.3)^2 + (220(0.7)-19)^2} = \underline{208V}$

Circuit diagram



1. Start the alternator and adjust the speed to synchronous speed and open circuit the load terminals.
2. Keep the field rheostat maximum position and switch on DC supply.
3. The field Rheostat is varied, in such way that field current is varied from the minimum value to rated value. The voltmeter reads line value of open circuit voltage.

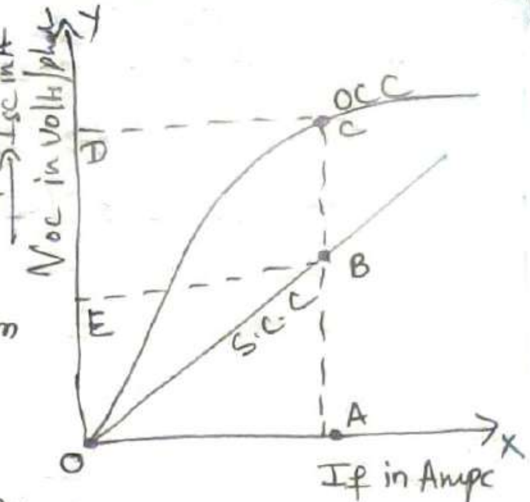
Tabulate the readings as shown in below.

S.NO	If(A)	Vo(Line) V	Voc (ph) = $\frac{V_{oc}}{\sqrt{3}}$

The open circuit characteristics are drawn between If and Voc phase as shown in below fig

Short Circuit Test

1. After completion of open circuit Test, The field Rheostat is brought to maximum position, Such that field current is reduced to minimum value.



2. Now TPST switch is closed, As Ammeter has negligible resistance, the armature gets short circuited.

3. Field Excitation is varied in such way that rated current is flows through Ammeter winding, which is read by Ammeter as I_{sc}.

Tabulate the reading as follows.

S.NO	If(A)	Isc(A)
1.		

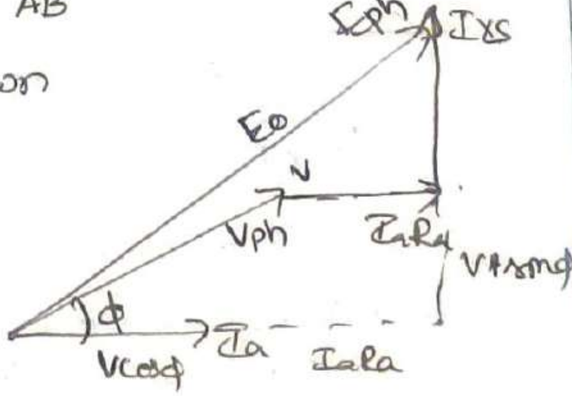
The Short Circuit characteristics are draw on the same graph between I_f and I_{sc} as shown in above fig.

From the Graph $Z_s = \left.\dfrac{V_{oc}}{I_{sc}}\right|$ for same I_f

$$= \frac{AC}{AB}$$

The phasor diagram is shown

$$\% \text{regn} = \frac{E_0 - V}{V} \times 100$$



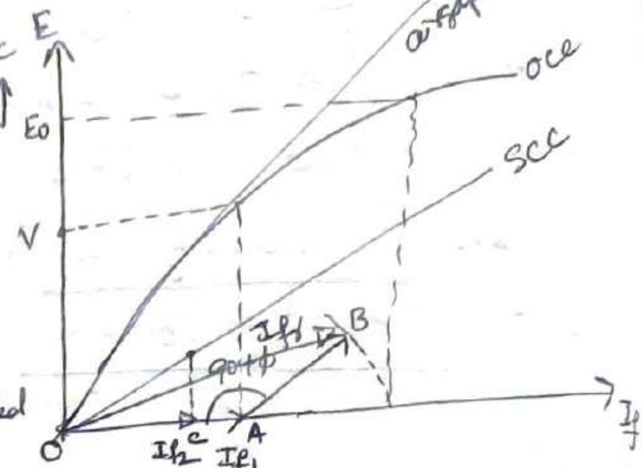
A 100KVA, 3000V, 50Hz 3ph Star connected alternator has effective Ra 0.2Ω, If-40A produces Isc = 200A oc emf 1040 (line) FL Regulation at 0.8 pf lag & lead draw phasor diagram

2.2%
-1.8%

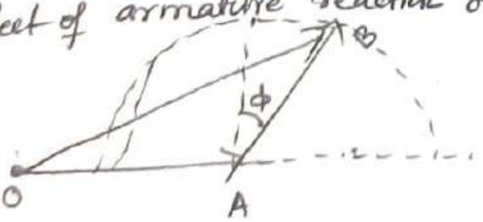
② Rotherts Ampere-Turn (AT) method or MMF method:

Assumptions: $X_s = X_l + X_a$ (flux phenomenon) or MMF method

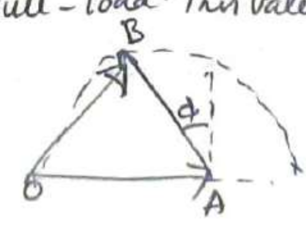
This method is also known as Amp-Turn method. In this method the all emf's produced rotor and stator are replaced by their equivalent mmFs (fluxes) and hence called



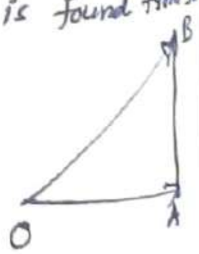
mmF method, In this method both reactance drops are replaced by their equivalent mmf's. The figure shows the complete phasor diagram for the mmf method. Similar to emf method OC & SC Characteristics are used for the determination of regulation by mmF method. I_{f1} = OA field AT required to produce V on noload. This can be found from OCC and I_{f2} = OC Field AT required to overcome demagnetising effect of armature reaction on Full-load. This value is found from SC



log p.f



leading pf



UPF

The above figure shows the complete diagram along with OC and SC Characteristics. OA represents field current for normal Voltage V. OC represents field current required for producing full load current on short-circuit

Vector $AB = OC$ is drawn at an angle of $(90° + \phi)$ to OA (if the p.f is lagging). The total field current is OB for which the corresponding OC voltage is E_0

$$\therefore \% \text{ regn} = \frac{E_0 - V}{V} \times 100.$$

Note: This method gives results which are less than the actual results, that is why it is sometimes referred to as optimistic method.

Prob: A 3.5 MVA, Y-connected alternator rated at 4160 volts at 50Hz has the open circuit characteristics given by the following data.

Field current (Amps)	50	100	150	200	250	300	350	400	450
E.M.F (volts)	1620	3150	4160	4750	5130	5370	5550	5650	5750

A field current of 200A is found necessary to circulate full load current on short circuit of the alternator. Calculate by (i) Synchronous Impedance method (ii) Ampere Turn method the full load voltage regulation at 0.8 p.f lagging. Neglect resistance. Comment on the result obtained.

Soln (i) EMF method.

As seen from the given data, a field current of 200A produces OC voltage of 4750 (line value), full load current on short circuit which is

$$I_{FL} = I_{SC} = \frac{3.5 \times 10^6}{\sqrt{3} * 4160} = 486A.$$

$$Z_s = \frac{\text{OC voltage/phase}}{I_{SC}} = \frac{4750/\sqrt{3}}{486} = \frac{2740}{486} = 5.64\,\Omega/\text{phase}$$

Since $R_a = 0\,\Omega$, $X_s = Z_s$ $\therefore IR_a = 0V$, $IX_s = IZ_s = 486 * 5.64 = 2740V$

$$\text{F.L voltage/phase} = \frac{4160}{\sqrt{3}} = 2400V,\ \cos\phi = 0.8,\ \sin\phi = 0.6$$

$$E_0 = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_s)^2} =$$

$$\left[(2400 \times 0.8 + 0)^2 + (2400 \times 0.6 + 2740)^2\right]^{1/2} = 4600V$$

$$\therefore \% \text{ regn} = \frac{E_0 - V}{V} \times 100 = \frac{4600 - 2400}{2400} \times 100 = 92.5\%$$

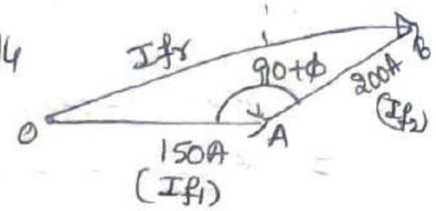
ii) AT-Method

It is seen from given data that, for normal voltage of 4160V, field current needed is 150A. → I_{f1}

Field Current necessary to circulate FL current on short-circuit is 200A → I_{f2}

Fig represents $\vec{OA}$ 150A,

the vector AB represents 200A, is vectorially added to OA at $(90^\circ+\phi) = (90^\circ+36.5^\circ)$ $= 126.5^\circ$.



Vector OB represents excitation necessaly current to produce terminal voltage of 4160V at 0.8 p.f lagging load.

$$OB = \sqrt{150^2 + 200^2 + 2 * 150 * 200 \cos(180^\circ - 126.5^\circ)} = 313.8A$$

The generated phase EMF, E_0 corresponding to this excitation as found from O.C.C (if drawn) is 3140V.

Line value is $3140 \times \sqrt{3} = 5440V$

$$\%\ regn = \frac{E_0 - V}{V} \times 100 = \frac{5440 - 4160}{4160} \times 100 = \underline{30.7\%}$$

Prob: (2): The following test results are obtained on a 6600V alternator.

Open Circuit (voltage)	3100	4900	6600	7500	8,300
Field Current (Amps)	16	25	37.5	50	70

A field current of 20A is found necessary to circulate full load current on short circuit of the armature. Calculate by (i) The AT method (ii) The Syn. Impedance method the full load voltage regulation at 0.8 p.f (lag). Neglect resistance & leakage reactance. State the drawbacks of each of these methods.

Ans: i) 15.16%
ii) 38.7%

prob③: The open and S.C Test readings for a 3-phase star connected 1000 KVA, 2000V, 50Hz Syn-Generator are:

Field Amps	10	20	25	30	40	50
O.C Terminal V	800	1500	1760	2000	2350	2600
S-C in A	—	200	250	300	—	—

The armature effective resistance is 0.2Ω/phase, Draw the characteristic curves and estimate the FL percentage regulation at (a) 0.8 p.f lagging (b) 0.8 p.f leading.

Soln The o.c.c and s.c.c are plotted in Graph.

prob: ④ The following test results are obtained on a 6600V alternator.

open circuit Voltage	3,100	4,900	6,600	7,500	8,300
Field Current Ampere	16	25	37.5	50	70

A field current of 20A is found necessary to circulate full-load current on short-circuit of the armature. Calculate by (i) A-T method and (ii) the Syn-Impedance method, the FL regulation at 0.8 p.f (Lag). Neglect resistance and leakage reactance. State the draw back of each method.

OCC - has to be drawn.

(i) Ampere-Turn method: From OCC curve, drawn from given data, the field current required to give normal emf of 6,600 volts on open circuit is 37.5A.

The field current required to give full load current on short circuit is 20A.

$$I_f = \sqrt{(37.5)^2 + (20)^2 - 2 * 37.5 \times 20 * (-0.6)} = 52A$$

The generated emf, corresponding to this excitation of 52A, as found from OCC is 7600V. $\%\, regn = \frac{E_0 - V}{V} \times 100 = \frac{7600 - 6600}{6600} \times 100 = 15.15\%$

ii) Syn-Impedance method: let 6,600V be taken as 100%

FL or 100% armature current is produced on S.C by field current of 20A. If 100% i.e 37.5A of field current applied on S.C, the S.C current would be $100 * \frac{37.5}{200} = 187.5\% \Rightarrow \frac{100}{187.5} \times 100 = 53.3\%$

ZPF Method or potier method: More Accurate method.

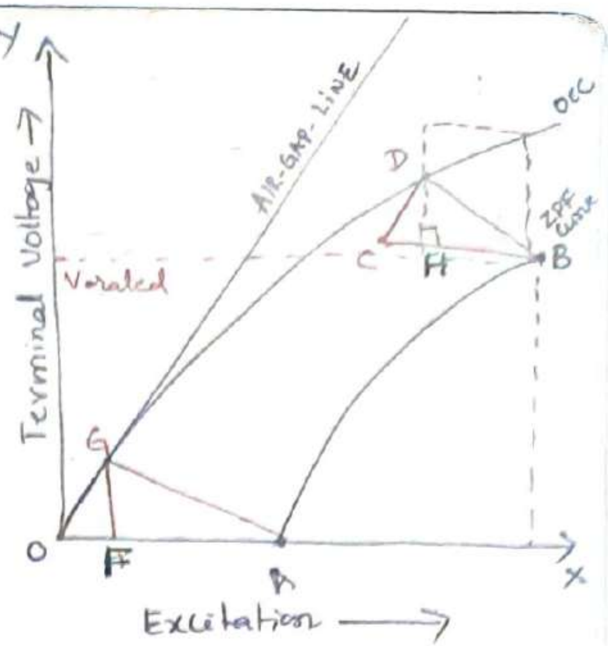
The regulation obtained by mmf and emf methods is based on the total synchronous reactance. ZPF method is based on the separation of reactances due to leakage flux and due to armature reaction flux. therefore it is more accurate.

For determination of voltage regulation by this method, the data required are (i) effective resistance of armature winding (ii) open circuit characteristics (iii) field current to circulate full load current in the stator (iv) zero-power factor full load voltage characteristics - a curve between terminal voltage and excitation while the machine is being run on synchronous speed and delivering full load current at zero power factor.

The zero power factor characteristics curve can be obtained as follows:

The machine is run at rated synchronous speed by a primemover. A purely inductive load is connected across the armature terminals and the excitation or field current is raised so as to cause flow of full load current (armature): The value of reactance is then increased step by step in such way that the excitation current is adjusted to a value that causes full load rated armature current to flow. The armature terminal voltage are varied from 125% to 25% of rated voltage in steps, maintaining the speed and armature current constant throughout the test. The Armature terminal voltage and excitation currents are noted at each step. The curve drawn between terminal voltage and excitation current gives the zero power factor (lagging) characteristic, as shown in below fig.

The Zero power factor (lagging) characteristic is to be used only for obtaining the potier reactance, it is sufficient to determine the point representing rated armature current and rated voltage. This is indicated by point "B".



The ZPF curve is of exactly the same shape, as the OCC but it is shifted vertically downward by leakage reactance drop IX_L and horizontally by the armature reaction MMF.

ZPF Curve can be drawn by knowing two points A and B. Point 'A' is obtained from a short circuit test with full load armature current. hence OA represents excitation (field) current, required to overcome demagnetising effect of armature reaction and to balance leakage reactance drop at full load.

Point 'B' is obtained when full load current flows through armature and wattmeter reads zero.

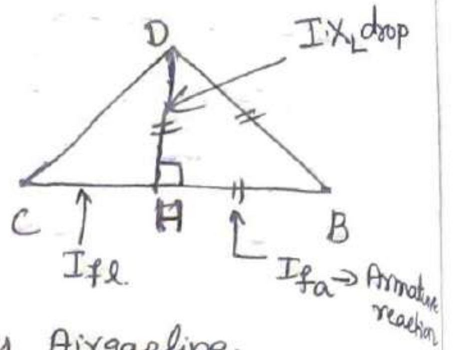
From B line BC is drawn equal and parallel to AO. Then a line is drawn through 'C' parallel to initial straight part of OCC (parallel to OG), intersecting the OCC at 'D'. BD is joined and a perpendicular DF is dropped on BC. The triangle BFD is imposed at various points OCC to obtain corresponding points on the zero power factor curve.

In Δ BDF, the length BF represents armature reaction excitation and length DF represents leakage reactance drop (IX_L^*). This is known as potier reactance voltage drop, triangle is known as potier Δle.

From the potier triangle, the emf generated E_0 can be calculated as follows.

Δ DHB is potier triangle.

leakage Reactance $X_l = \frac{DH}{I_a}$



General steps to draw potier Δle

i) Draw OCC & ZPFC & Tangent to the OCC curve, which is known as Airgapline.

ii) At V = Vrated draw horizontal line to ZPFC, to meet at "B"

iii) Draw BC = OA

iv) Draw CD parallel to airgapline

v) Join BD

vi) Draw DH perpendicular to BC

vii) The Right angled triangle BHD is called as potier triangle.

viii) Then calculate leakage reactance $X_l = \frac{DH}{I_a}$

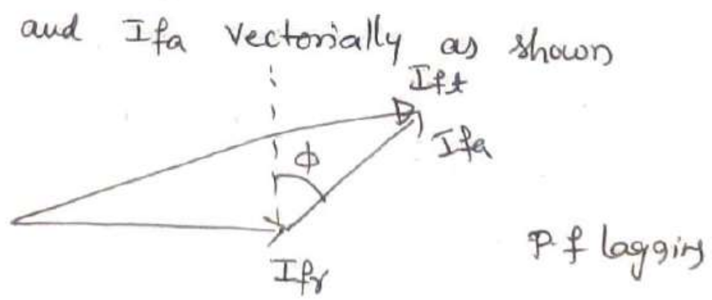
ix) Calculate $\bar{E}_r = V + IR_a + jIX_L$

$$|E_r| = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi \pm IX_L)^2}$$

(+ lag, − lead)

(x) From OCC curve, mark Er, corresponding Ifr can be calculated.

xi) Add "Ifr" and "Ifa" vectorially as shown



Calculate Ift → total field current.

(xii) from OCC curve corresponding Ift value, Determine Eo from OCC at Ift.

From the Graph:

$$BH = 3\times 5 = 15\,AT = 15000\,AT = I_{fa}$$

$$CH = \frac{1}{2}\text{unit} = 2.5\,AT = 2500\,AT = I_{fl}$$

$$DH = 1kV = IX_L$$

$$I = \text{F.L Current} = \frac{15000\times 1000}{\sqrt{3}\times 11000} =$$

$$X_L = \text{Leakage Reactance} = \frac{1000\times 11000\times\sqrt{3}}{15000\times 1000} = 0.843\Omega$$

$$E_r = \sqrt{(V\cos\phi + IR_a)^2 + (V\sin\phi + IX_L)^2} \qquad \cos\phi = 0.8\text{ lag.}$$

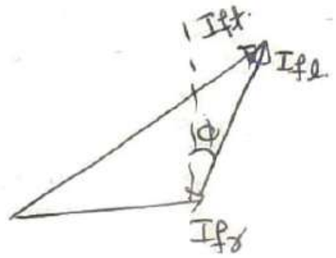
$$= \sqrt{\left(\frac{11000}{\sqrt{3}}\times 0.8 + 0\right)^2 + \left(\frac{11000}{\sqrt{3}}\times 0.6 + \frac{15000\times 1000}{\sqrt{3}\times 10000}\times 0.843\right)^2}$$

$$E_r = 11{,}700\,V$$

from occ curve, the correspo[n]ding AT for E_r 11,700V is 34 AT

which $I_{fr} = 34\,AT$

$$I_{ft} = 43.5\,AT$$



Induced voltage from occ

$$E_0 = 13.2\,kV$$

$$\%\,\text{regn} = \frac{E_0 - V}{V}\times 100$$

$$= \frac{13.2 - 11}{11}\times 100 = \frac{2.2}{11}\times 100$$

$$\boxed{\%\,\text{regn} = 20\%}$$

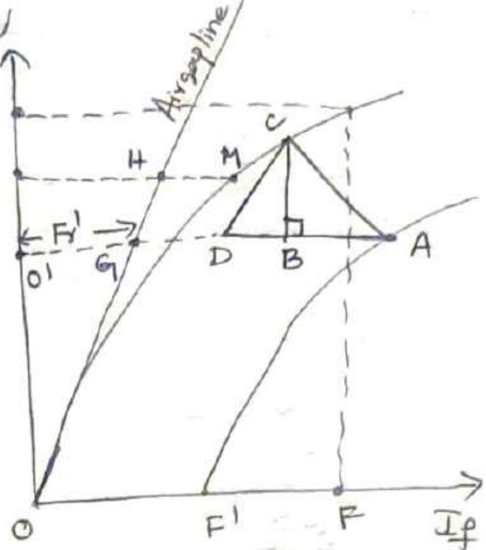
problem: Test on a 15000 kVA, 11000 Volt, 3 phase 50Hz Star connected Alternator gave the following results.

Field AT per pole, thousands	10	18	25	30	40	45	50
Open Circuit line emf in kV	5	8.4	10.0	11.2	12.8	13.3	13.65
FL Current Zero power factor test in kV	–	0	–	–	–	10	–

find the armature reaction AmpereTurn, the leakage reactance and the regulation for FL at 0.8 p.f lagging. Neglect resistance.

ASA Method: American Standard Association method'

In this method, the effect of saturation is also considered. it is combination of ZPF & MMF method. modification of MMF method to give best result for both cylindrical rotor and salient pole Synchronous Generators. This is newly developed method.

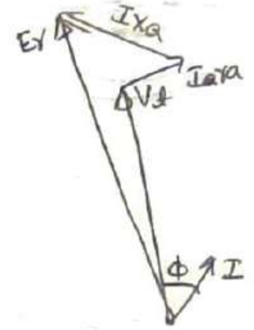


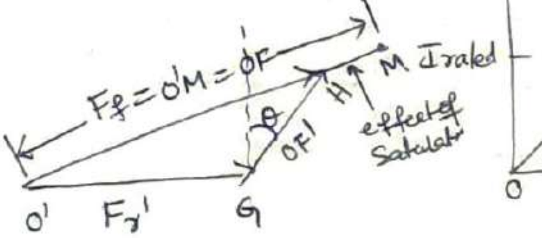
The following procedure

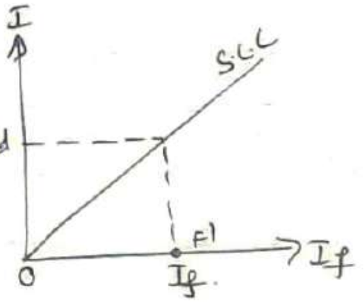
i) Requires OCC Curve & ZPFC

ii) To get point 'A', Load the over Excited Synchronous generator by under excited synchronous motor till full load armature current at rated voltage is flows.

iii) To get F', field current to circulate Full load current, when an alternator short circuited. (S.C.C)







iv) The value of X_L can be obtained from potier triangle,

$$CB = IX_L \text{ drop}, \quad \boxed{X_L = \frac{CB}{I}}$$

v). $E_Y = \sqrt{(E\cos\phi + I_aR_a)^2 + (E\sin\phi \pm I_aX_L)^2}$

once E_Y is obtained, in the Graph, draw a line HM corresponding E_Y on Y-axis as shown in above.

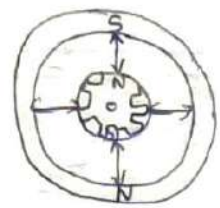
vi). $OF = O'M$ from the phasor, mark point F on a graph, with length $OF = O'M$ and corresponding F on OCC curve gives the no load induced emf E_0 on Y-axis.

vii) Calculate Voltage Regulation $E_0 - V / V \times 100$.

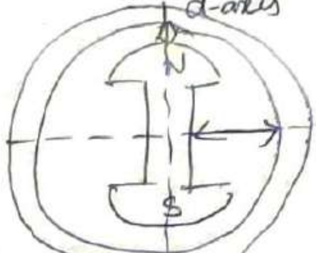
TWO REACTANCE CONCEPT FOR SALIENT POLE SYNCHRONOUS MACHINE:

In previous discussion, the armature reaction is inversely proportional to airgaplength and the flux (ϕ) $= \frac{MMF}{R} = \frac{NI}{R}$, the flux ($\phi$) is inversely proportional to reluctance (R). The Reluctance is opposition to flow or passage of flux. When the airgap length increases, the reluctance increases, then the flux flow reduces. With the result, the effect of armature flux on the main flux decreases therefore armature reaction is inversely proportional to airgap length.

Cylindrical m/c



Salient pole m/c



In cylindrical rotor machine, the airgap between stator and rotor is uniform, irrespective of rotor position as shown in above. hence the armature flux on the main flux equally distributed. In other words the armature Reaction is uniform. Single reactance is sufficient to represent the effect of armature reaction.

Let consider Salient pole Synchronous machine, with 2 poles as shown in above, the axis along with N-S pole, the main flux comming is d-axis (direct) and second axis is quadrature with d-axis is called as q-axis as shown in above fig.

The airgap in a salient pole Synchronous machine is non-uniform, along d-axis the airgap is minimum, and along q-axis, the airgap is maximum. For the given armature current, the flux ϕ for the d-axis, the reluctance is low, because airgap is minimum, the armature flux is more the armature reaction is more. with the result, the armature reaction reactance along d-axis is more i.e X_{ad} is more. After some time, the rotor will rotate, there will be ~~two~~ more airgap ~~be~~ along q-axis. when the airgap is more, automatically the reluctance is more, the armature flux decreases, and the armature reaction decreases along q-axis. The armature reaction is represented by a reactance in the quadrature axis is X_{aq} decreases. The value of X_{ad} is not equal to X_{aq} and the value of X_{ad} is greater than X_{aq}.

Generally $\quad X_{ad} > X_{aq}$

$$X_{ad} \simeq 1.6 \text{ times } X_{aq}.$$

$\therefore$ In two reactance theory, two symmetries are in Non-Salient pole Synchronous machines, as in case of only one symmetry in Salient pole machines. So two reactance theory tells that, one symmetry component of along direct axis and another symmetry component of reactance along quadrature axis. The Reactance can be divided into two components namely X_d & X_q.

In ~~a~~ previous armature reaction, the total synchronous reactance (X_s) is consists of leakage reactance X_l and armature reaction reactance X_{al}. In two reactance theory, the leakage reactance X_l is independent of the rotor position. therefore the X_L is same for cylindrical & ~~non~~-Salient pole machines.

The total reactance along d-axis can be written as

$$X_{ad} + X_l = X_d.$$ which is known as direct axis synchronous Reactance.

and in similar way, ~~also~~ the total reactance along q-axis can be written as

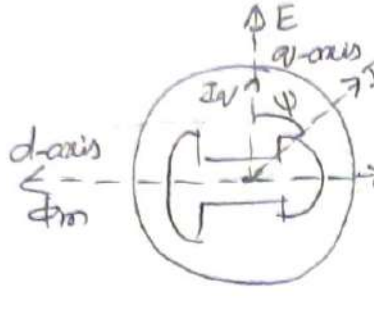
$$X_{aq} + X_l = X_q$$ which is known as quadrature axis Synchronous Reactance.

$$X_d = (1.5-2)X_q$$

$(X_d - X_q)$ = Saliency reactance.

In case of cylindrical rotor m/c, $X_d = X_q$, therefore the saliency is zero

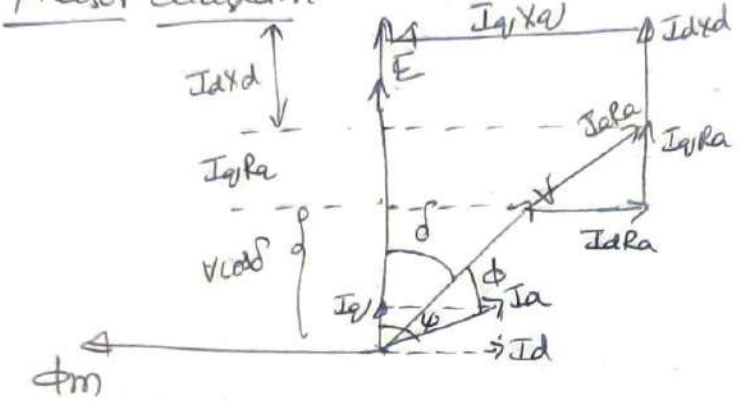
Phasor diagram for salient pole machine:



$I_d = I_a \sin\psi$ $\psi \rightarrow$ internal P.f angle.

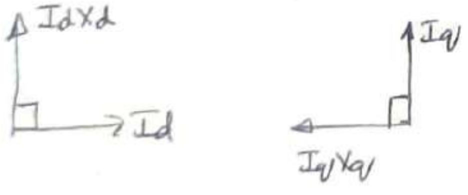
$I_q = I_a \cos\psi$

Phasor diagram



$$\boxed{E = V\cos\delta + I_qR_a \pm I_dX_d}$$

\+ lag
\- lead

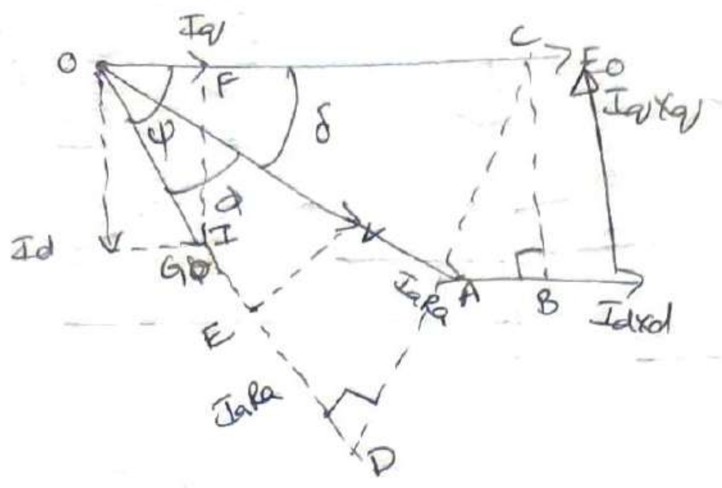


$$\boxed{\psi = \delta + \phi}$$

IIT-Kanpur

$$\boxed{\tan\psi = \frac{V\sin\phi \pm I_aX_q}{V\cos\phi + I_aR_a}}$$

NIT-W
ECE
\- Trichy
\- Surat
\- Jaipur
\- Rourkela
\- Calicut
\- Nagpur
\- Bhopal


O
Iq
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PARALLEL OPERATION OF ALTERNATORS :

The operation of connecting an alternator in parallel with another alternator or with common bus-bar is known as synchronizing. Generally, alternators are used in a power system where they are in parallel with many other alternators. The alternator is connected to a live system of constant voltage and constant frequency. If many alternators connected in parallel in the power system in order to share a load (common), then it is said to be connected to "Infinite" bus-bar having large inertia.

Advantages of parallel operation are:

1. In the absence of several machines, for maintenance or some other reason, the power station can be operated with the remaining units.
2. Depending on the load, generators may be brought on line, or taken off, and thus result in the most efficient and economical operation of the station.
3. For future expansion, units may be added on and operate in parallel.

A synchronous generator may be connected in parallel, with a system or bus, the following necessary conditions must be fulfilled -

1. The frequency of the incoming generator must be same as the frequency of the power system to which the generator is to be connected.

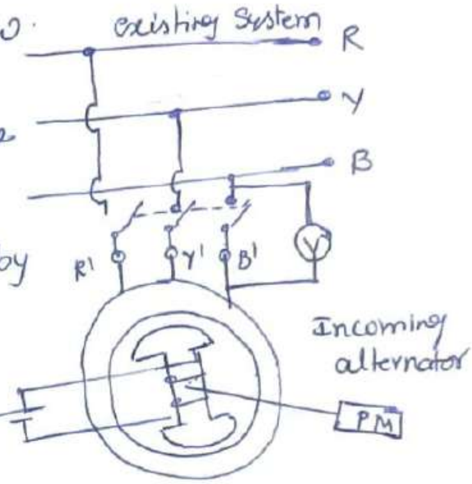
2. The magnitude of the voltage of the incoming generator must be same as the system or bus bar terminal voltage

3. With respect to external circuit, the voltage of the incoming generator must be same phase as system voltage at the terminals.

4. In a 3-phase system, the generator must have the same phase sequence as that of the bus.

Methods for synchronizing alternators:

1. The magnitude of the voltages can be measured by a voltmeter method between existing system and incoming alternator as shown in below.



2. The frequency and phase sequence can be checked between existing system and incoming alternator by synchronizing lamp methods in association with synchroscope.

Synchronizing methods

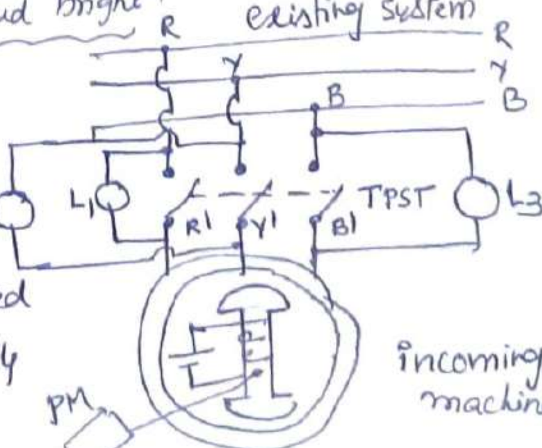
1) Lamp based method:

i) Three Lamps simultaneously dark and bright

ii) one Lamp dark and 2 Lamps simultaneously bright.

iii) Synchro scope.

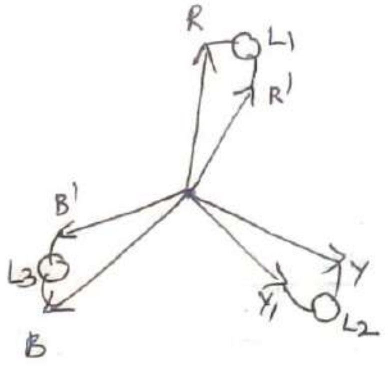
i) 3 Lamps Simultaneously dark and bright:



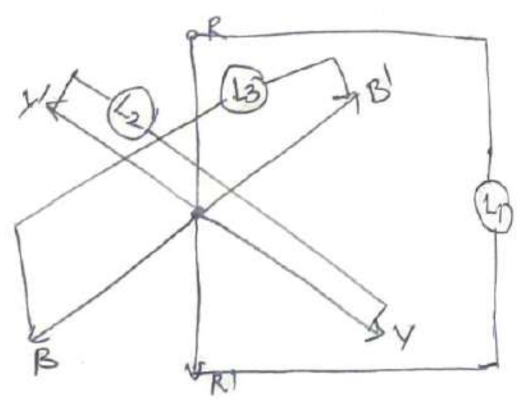
The connection diagram is shown in figure. A TPST switch is placed between incoming machine and existing system. 3 Lamps are connected across a switch in parallel. Generally the lamp L_1 is connected across

R and R' and the Lamp L_2 is connected between Y and Y' and the Lamp L_3 is connected across B and B'. Under running condition of incoming alternator, brought up to rated speed, by using voltmeter, check the incoming generator voltage is same as that of Existing system voltage, under this conditions, the flickering of the lamps L_1, L_2 & L_3 will be proportional to frequency $(f'-f)$.

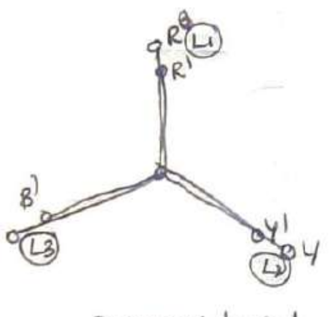
let Assume the phase sequences are same, then the



medium brightness



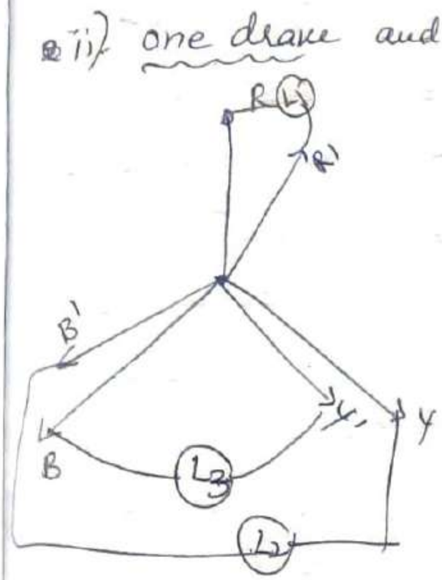
maximum bridgtness



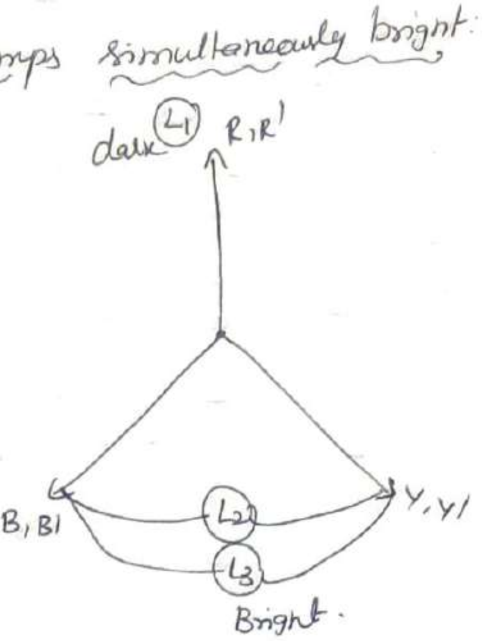
Darkness period.

Voltage applied for the Lamps L_1, L_2 & L_3 are shown in above figures with different instants of times. The measurement of frequencies and phase difference can be carried out by above three lamps. The frequent flickering of the lamps takes place simultaneously, the lamps L_1, L_2 and L_3 are in maximum brightness for some time, slowly changes to darkness period for 3 lamps simultaneously, when the phase sequences are same and frequencies are same, At that instant, the TPST switch is closed so that incoming alternator is connected in palallel with existing system which is known as Synchronization.

ii) one dark and 2 lamps simultaneously bright.



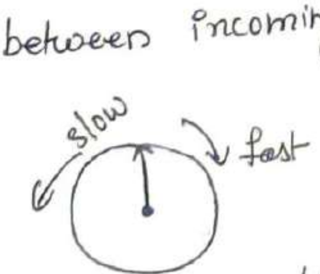
when two phase sequences are different.



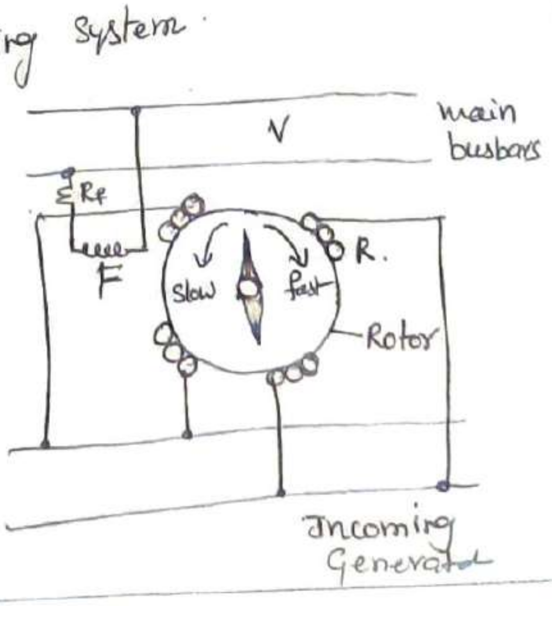
When two phase sequences are same.

under this condition, one lamp L_1 glows dark in period and L_2 and L_3 lamps glows with maximum brightness under two phase sequences are same of incoming and existing system Therefore at this instant the TPST switch can be closed so that incoming alternator is connected in palallel successfully with existing system in order to share the load.

iii) Synchro scope: It is two phase machine, is used for finding the difference in the frequency. It is connected only across a single phase. It will not measure phase sequence between incoming and existing system.



Speed of the m/c's (incoming and Existing)



A Synchroscope is an instrument having a rotating pointer, which indicates wether the incomming machine is slow or fast. one type of Synchroscope is shown in above figure. It consists of a field coil, F connected to the main busbars through a large resistance R_f to ensure that the field current is almost in phase with busbar voltage V. the rotor consists of two windings R and X, in space quadrature, connected in palallel to each other and the across the incoming generator. The windings R and X are so designed that their respective currents are approximately in phase and 90° behind the terminal voltage, V_i. of the incoming generator. The rotor will align itself so that axes of R and F are inclined at an angle equal to the phase displacement between V and V_i. if there is a difference between the frequencies of V and V_i, the pointer will rotate at a speed proportional to this difference. At Synchronism, the pointer will remain stationery at the index. In present day power stations, automatic synchronizers are used.

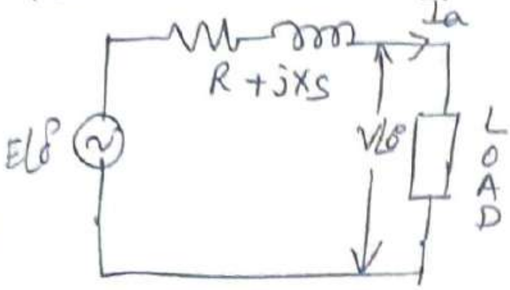
Synchronizing power

Syn. power, $P = \frac{EV}{X_s}\sin\delta$ for cylindrical m/c

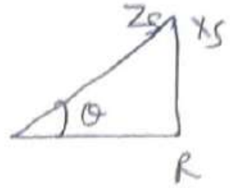
$$P = \frac{EV}{X_d}\sin\delta + \frac{V^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\delta \rightarrow \text{for salient pole m/c}$$

Synchronous power, P

power flow in alternator:



$V\angle 0$, $E\angle\delta$, $Z_s\angle\theta$.



$$I_a = \frac{\bar{E}-\bar{V}}{Z_s} = \frac{E\angle\delta - V\angle 0}{Z_s\angle\theta} = \frac{E}{Z_s}\angle\delta-\theta - \frac{V}{Z_s}\angle-\theta.$$

To calculate power, conjugate of I_a is I_a^*

$$I_a^* = \frac{E}{Z_s}\angle\theta-\delta - \frac{V}{Z_s}\angle\theta.$$

Complex power $P + jQ = V I_a^*$

$$= V\left[\frac{E}{Z_s}\angle\theta-\delta - \frac{V}{Z_s}\angle\theta\right]$$

$$= \frac{EV}{Z_s}\angle\theta-\delta - \frac{V^2}{Z_s}\angle\theta$$

$$P + jQ = \underbrace{\left[\frac{EV}{Z_s}\cos(\theta-\delta) - \frac{V^2}{Z_s}\cos\theta\right]}_{P} + j\underbrace{\left[\frac{EV}{Z_s}\sin(\theta-\delta) - \frac{V^2}{Z_s}\sin\theta\right]}_{Q}$$

$$P = \frac{EV}{Z_s}\cos(\theta-\delta) - \frac{V^2}{Z_s}\cos\theta.$$

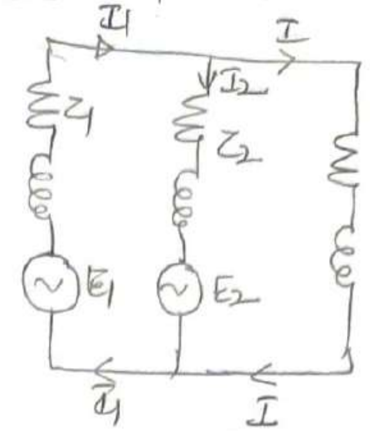
$$Q = \frac{EV}{Z_s}\sin(\theta-\delta) - \frac{V^2}{Z_s}\sin\theta.$$

$R_a \ll X_s$ $Z_s = X_s$
$\theta = 90^\circ.$

$$\boxed{P = \frac{EV}{X_s}\sin\delta}$$

palallel operation of Two Alternators : Sharing of load Currents by two alternators in palallel.

let consider two alternators with identical speed / load characteristics connected in parallel shown in fig



The common terminal voltage V is given by

$$V = E_1 - I_1 Z_1 = E_2 - I_2 Z_2$$

$$\therefore \; E_1 - E_2 = I_1 Z_1 - I_2 Z_2$$

Also $I = I_1 + I_2$ and $V = IZ$

$$\therefore \; E_1 = I_1 Z_1 + IZ = I_1 (Z + Z_1) + I_2 Z$$

$$E_2 = I_2 Z_2 + IZ = I_2 (Z + Z_2) + I_1 Z$$

$$\therefore \; I_1 = \frac{(E_1 - E_2) Z + E_1 Z_2}{Z(Z_1 + Z_2) + Z_1 Z_2}, \quad I_2 = \frac{(E_2 - E_1) Z + E_2 Z_1}{Z(Z_1 + Z_2) + Z_1 Z_2}$$

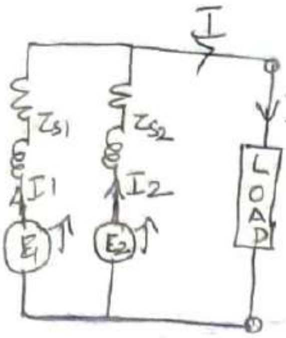
$$I = \frac{E_1 Z_2 + E_2 Z_1}{Z(Z_1 + Z_2) + Z_1 Z_2}$$

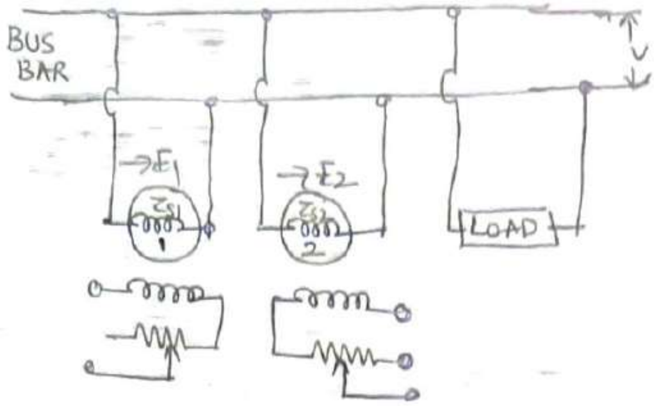
$$V = IZ = \frac{E_1 Z_2 + E_2 Z_1}{Z_1 + Z_2 + \left(\frac{Z_1 Z_2}{Z}\right)} \; ; \; I_1 = \frac{E_1 - V}{Z_1} \; ; \; I_2 = \frac{E_2 - V}{Z_2}$$

The Circulating Current under no-load conditions

$$I_C = \frac{E_1 - E_2}{Z_1 + Z_2}$$

LOAD SHARING BETWEEN TWO ALTERNATORS





Consider two machines with identical speed-load characteristics running in parallel with a common terminal voltage of "V" Volts and load impedance "Z".

let the generated emf's of the two machines 1 and 2 operating in palallel be E_1 and E_2 resply and synchronous impedance per phase be Z_{S1} and Z_{S2} resply.

Terminal voltage of machine 1. $V = E_1 - I_1 Z_{S1}$ — (1)

Similarly Terminal voltage of machine 2. $V = E_2 - I_2 Z_{S2}$ — (2)

Also $V = IZ = (I_1 + I_2) Z$ — (3)

From eqns (1) & (2)

$$I_1 = \frac{V - E_1}{Z_{S1}} \quad \text{— (4)}$$

$$I_2 = \frac{V - E_2}{Z_{S2}} \quad \text{— (5)}$$

Adding eqns (4) & (5)

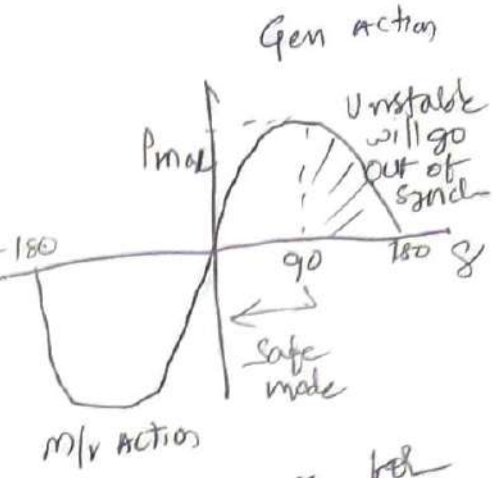
$$I_1 + I_2 = \frac{V - E_1}{Z_{S1}} + \frac{V - E_2}{Z_{S2}}$$

or $$\frac{V}{Z} = \frac{V - E_1}{Z_{S1}} + \frac{V - E_2}{Z_{S2}} \Rightarrow$$

from eqn (3). $I_1 + I_2 = \frac{V}{Z}$

$$-\frac{V}{Z} + \frac{V}{Z_{S1}} + \frac{V}{Z_{S2}} = \frac{E_1}{Z_{S1}} + \frac{E_2}{Z_{S2}}$$

Power Angle Characteristics

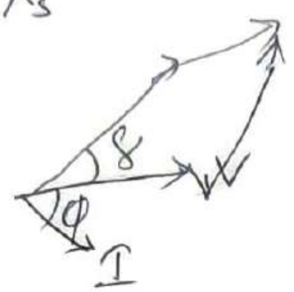


δ = phase angle b/w E_0 & V
Torque or power Angle

$$P = \frac{E_0 V}{X_s} \sin \delta$$

$$P_{max} = \frac{E_0 V}{X_s}$$

*15-20% power reserve for safe operation



* load ↑ → power ↓ → unstable

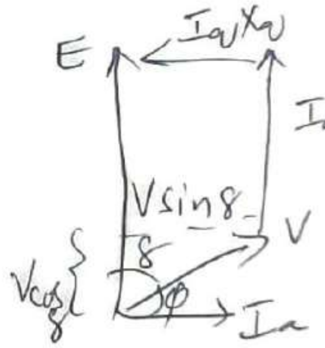
Sine rule

$$\frac{I_a X_s}{\sin \delta} = \frac{E}{\sin(90+\phi)} = \frac{E}{\cos\phi}$$

$$I_a \cos\phi = \frac{E}{X_s} \sin \delta$$

$$V I_a \cos\phi = \frac{VE}{X_s} \sin \delta$$

salient pole m/c



$$E = V\cos\delta + I_d X_d$$

$$I_d = \frac{E - V\cos\delta}{X_d} \quad (1)$$

$$V\sin\delta = I_q X_q$$

$$I_q = \frac{V\sin\delta}{X_q} \quad (2)$$

E.M.F Equation of an Alternator :

let Z = No. of conductors or coil sides in Series per phase

ϕ = Flux per pole in webers

P = No. of Rotor poles.

N = Rotor Speed in r.p.m

In one revolution (i.e $\frac{60}{N}$ second), each stator conductor is cut by $P\phi$ webers. i.e

$$d\phi = P\phi \quad , \quad dt = 60/N$$

As per Faraday's law,

∴ Average Induced emf in one stator conductor

$$= \frac{d\phi}{dt} = \frac{P\phi}{60/N} = \frac{P\phi N}{60} \text{ volts.}$$

Since there are "Z" conductors in Series per phase

∴ Average e.m.f/phase $= \frac{P\phi N}{60} * Z$ $\boxed{N_s = \frac{120f}{P}}$

$$= \frac{P\phi Z}{60} * \frac{120f}{P}$$

$$= 2f\phi Z \text{ volts}$$

Rms value of e.m.f/phase = Average emf/phase * form factor

$$= 2f\phi Z * 1.11$$

$$= 2.22 f\phi Z \text{ volts}$$

$$\boxed{\therefore E_{rms}/phase = 2.22 f\phi Z} \text{ volts} \quad \text{—— (1)}$$

If K_p and K_d are the pitch factors and distribution factors of the armature winding. then $E_{R.m.s}/phase = 2.22\, K_p K_d f \phi Z$ volts — (2)

Sometimes the turns (T) per phase rather than conductors per phase are specified, in that case eqn (2) becomes $\boxed{Z = 2T}$ T ⇒ no. of coils or Turns/phase

$$\boxed{E_{Rms}/phase = 4.44\, K_p K_d f \phi T_{ph} \text{ volts}} \quad (3)$$

The line voltage will depend upon wether the winding is star or Delta connected.

If the alternator is star-connected as is usually the case, then the line voltage is $\sqrt{3}$ times the phase voltage

$$\boxed{E_L = \sqrt{3}\, E_{Rms}/phase}$$

Effect of Harmonics on pitch and Distribution factor

(i) pitch factor (α).

If the short-pitch angle is α degrees for the fundamental flux wave, then its values for different harmonics are

for 3rd harmonic $= 3\alpha$,

for 5th harmonic $= 5\alpha$, and so on.

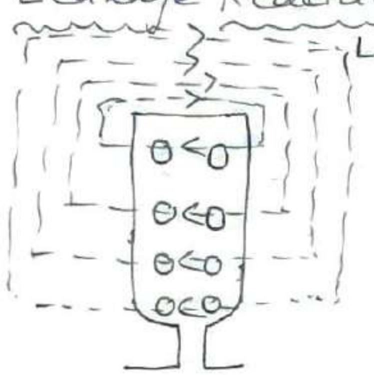
∴ pitch factor $K_c = \cos \alpha/2$ — for fundamental

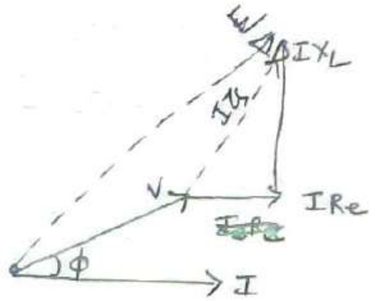
$= \cos 3\alpha/2$ — for 3rd harmonic

$= \cos 5\alpha/2$ — for 5th harmonic

without overheating and damaging to insulation. i.e rating of electric machine is governed by the temperature rise caused by the internal losses of the machine. The copper loss in the armature (I^2R) depends upon the strength of the armature current and core loss on voltage and thus these losses are independent of powerfactor. The alternators are rated in kVA or kW at specified power factor. The other name plate includes voltage, current, frequency, speed, number of phases, field ampere and voltage and maximum temperature rise.

Leakage Reactance:





When current flows through stator conductors, the flux is setup, a portion of this flux does not cross the airgap, but complets its path in the stator as shown in above fig. Such a flux is known as "Leakage flux". This leakage flux is proportional to stator (or armature) current. It also depends on the phase angle between the stator current and the voltage applied across the stator. The leakage flux sets up an emf of self inductance leading the load current I by $\pi/2$, and proportional to load current. Hence Armature winding is assumed to possess leakage reactance X_L such that voltage drop due to it, IX_L is equal to the emf setup by leakage flux. A part of the generated emf is used up to overcome this leakage reactance drop in addition to the armature resistance drop.

i.e Generated emf = phasor sum of terminal voltage, armature resistance drop, and leakage reactance drop.

i.e $E = V + IR_a + jX_L = V + I[R_e + jX_L]$

SYNCHRONOUS MOTOR

Construction wise the Synchronous motor and synchronous generator are same., For a S.M a 3-ϕ A.C. supply is given to the stator w/g which produces a rotating magnetic field around the stator whose speed is given by $\frac{120f}{P}$ where

f - frequency of the supply
P - no. of poles obtained by the w/g

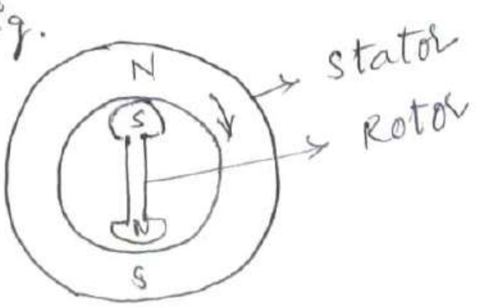
The flux that is produced in the stator will have a magnitudes of 1.5 times the max flux given by each phase $\phi_r = 1.5\,\phi_{max}$

The direction of the rotating magnetic field clockwise. construction wise 3-ϕ synchronous m/r is also same to that of the synchronous generator having stator & rotor.

A synchronous motor will perform its action by the magnetic locking ~~por~~ phenomena.

Magnetic Locking :

Consider the stator w/g is wounded to produce to magnetic poles rotating at synchronous speed. similarly consider a salient pole rotor with 2 poles N, S formed by DC excitation given to the rotor. It is shown in below fig.



From the above fig the stator rotating magnetic poles are similar with the rotor magnetic poles they will repel each other and attracts each other if the poles are different.

The rotor will continue to rotate with rotor flux direction & speed if opposite pole lock together. this is called magnetic locking.

But practically due to inertia of the rotor it is not possible for the rotor to get magnetic locking. Hence synchronous motor is not a self starting m/r.

STARTING METHODS OF SYNCHRONOUS MOTOR.

All the starting methods role is to get magnetic locking between stator and rotor poles. The methods are.

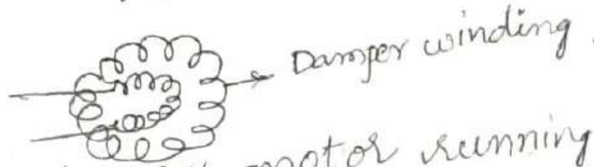
i) USING PONY MOTOR.

In this method by using small induction motors the rotor of synchronous motor is made to rotate nearer to synchronous speeds to get magnetic locking with stat magnetic poles, by supplying excitation to the rotor

(ii) Using damper winding

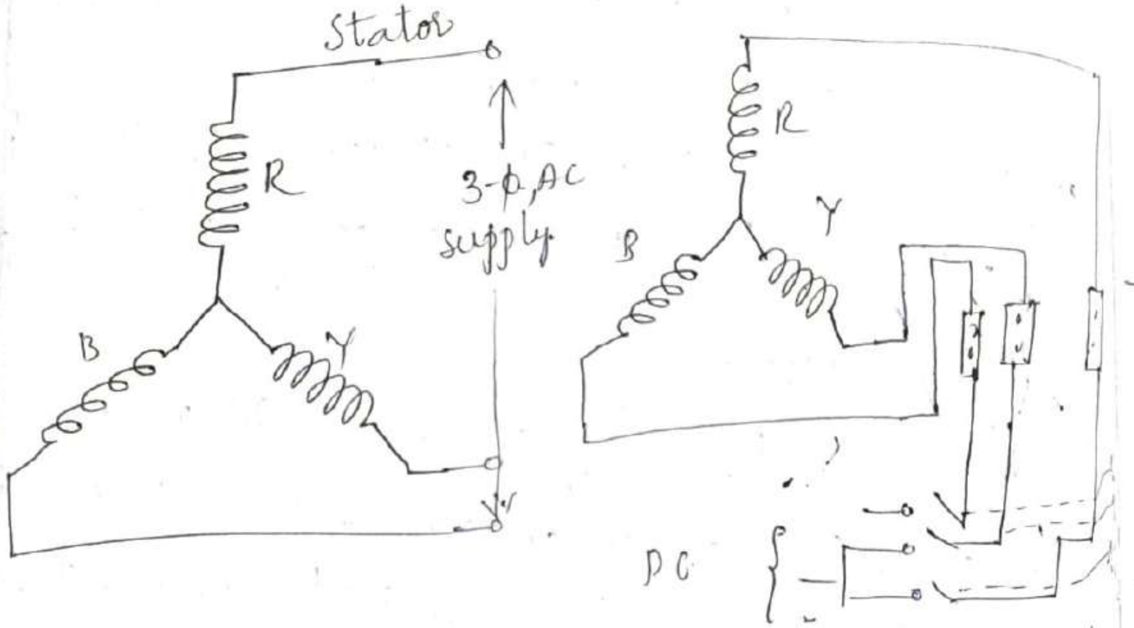
In order to overcome the inertia of the rotor an extra & special winding is to be placed on the rotor, this winding is short circuited by end rings. to ac as a squirrel cage rotor winding of a induction

: Once the rotor is rotating with synchronous b magnetic locking, there results no emf in the dam winding and makes the winding ideal hence it is us for starting purpose only.



(iii) Synchronous motor running as slipring I.M.

In this method we use starting resistor on series with the rotor starting winding which decreases the magnitude of the starting current which is the drawback in the previous method.

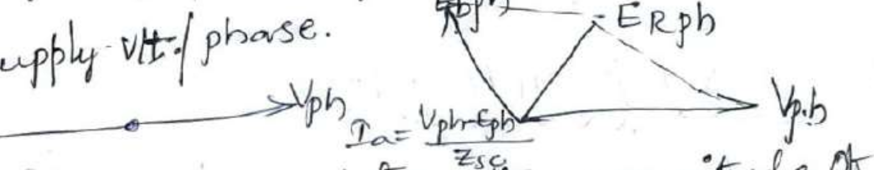


In this method first the synchronous motor be started as slip ring I.M. and when the rotor is made to rotated near to the synchronous speed as that of the stator flux 3-ϕ AC supply will to be given to the coil & a DC source is to be to the coil for producing magnetic field & magnetic locking. By the synchronous motor is started iv Using small D.c motors

In this method a small DC motor is used to rotate the rotor of the synchronous motor to its rated value, then the supply to the DC motor removed & the D.C. motor start working as a DC generator which is used for supplying the energy for the exciter or field w/g of S.M. synchronous motor.

Behaviour of synchronous motor ON load:

→ In synchronous m/r. an emf will be induced. produced in the rotor w/g. which is called back emf and having a direction opposite to that of the supply vlt/phase.



→ For an ideal condition the magnitude of E_{bph} is almost equal that of the Vph. we.k.T. in DC m/r the back emf is given as $E_b = \frac{\phi Z N P}{60A}$. Similarly E_{bph} in synchronous m/r is given as $E_b = 4.44 \times f \times \phi \times T_{ph}$

$\therefore E_{bph} \propto \phi$.

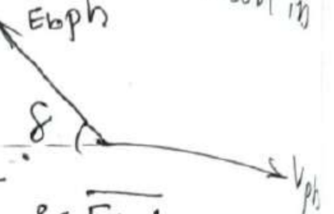
$\therefore Z_S = \sqrt{R_a^2 + X_S^2}$

Therefore the Iaph is given as $I_{aph} = \frac{V_{ph} - E_{bph}}{Z_S}$

where Z_S = Resultant impedance caused by the series resist (Ra) and synchronous reactance (X_S).

→ when synchronous m/r is no load cond. the magnet poles present in S/r & R/r will coincide exactly with each other. Hence there is no displacement b/w

2 vectors. But practically when a load is put on m/r. their must be some displacement in the m/g l... Hence the chang in the r/r position with the ref vect... given by δ. $\therefore$ The induced E_b will also change vector position from the reference line as shown in below fig.



- Then the resultant Emf will be the vector product of the both $\overline{V_{ph}}$ & $\overline{E_{bph}}$. This is shown in below fig.

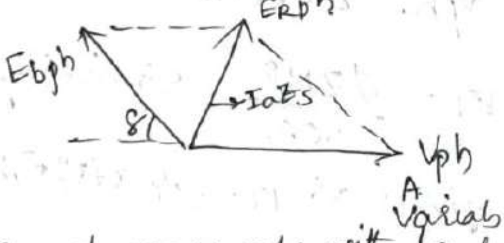
$V_{ph} - E_{bph} = \overline{I_a Z_s}$

For small changes in δ. The resultant E_{Rph} is also small.

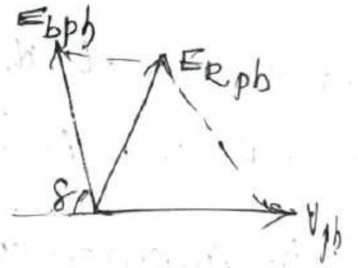
Synchronous m/r on no load with losses

Synchronous m/r on Load :-

Light Load

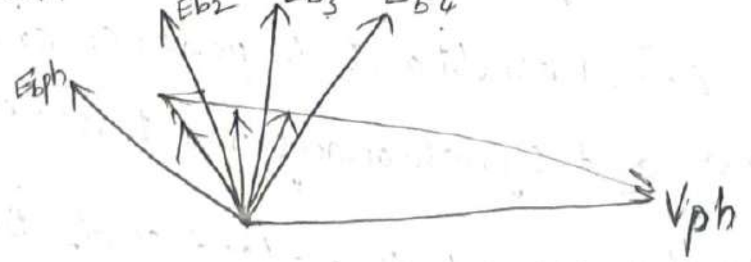


Heavy Load



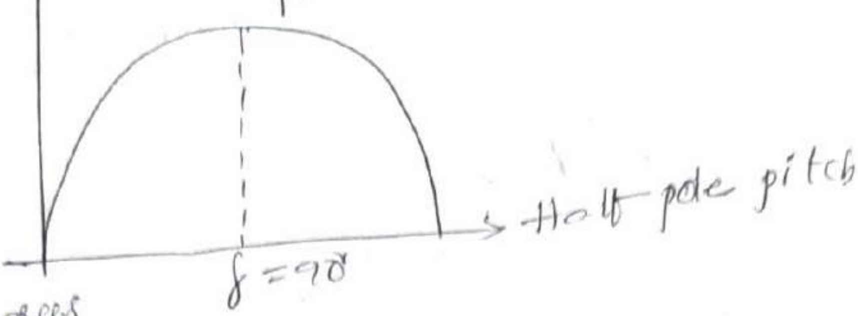
~~Synchronous m/r with Load~~ Variable

Synchronous m/r with Variable load and constant Excitation:



Torque - Angle characteristics

s δ is small
δ is measured
in sin δ



must be
in elec degrees

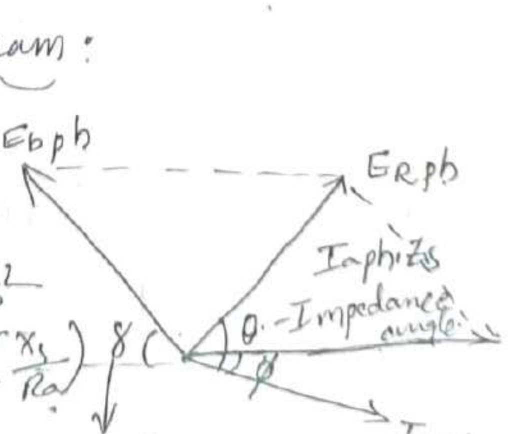
Different Torque in synchronous m/r.

1. starting torque:
   Torque obtained when rated V/t applied
2. Break away Torque - Necessary to overcome friction and inertia
3. pull in Torque :- The amount of torque developed by the motor at the time of pulling into synchronis
4. pull out Torque:
   whethern the synchronous m/r is load, the r/r when angle δ↑ and when it is just enough to cross above 90°, the torque, then obtained is called pullout torque. Since above that angle the m/r will loose its synchronism.

Analysis of phasor diagram:

$Z_S = \sqrt{Ra^2 + X_S^2}$

$\theta = \tan^{-1}\left(\frac{X_s}{Ra}\right)$



Operation of synchronous m/r at const. load with Variable Excitation

Normal Excitation

Excitation at which the Back EMF $(E_b) = V_{ph}$

$$P_{in} = \sqrt{3}\, V_{ph} \cdot I_{aph} \cos\phi$$

3-ϕ $$P_{in} = 3(V_{ph} I_{aph} \cdot \cos\phi)$$

Under this process of cosine component of I_a is constant. i.e., $I_a \cos\phi$ is const for const. power.

Under. Excitation

Excitation at which the $E_b < V_{ph}$. At this condition $I_a \uparrow$, p.f $\downarrow$ and hence it is more lagging in nature

Over excitation

In that Back Emf $E_b > V_{ph}$

- At this condition the p.f ~~$\downarrow$~~ increases with decrease in magnitude of I_a.. which results lead pf

Critical Excitation

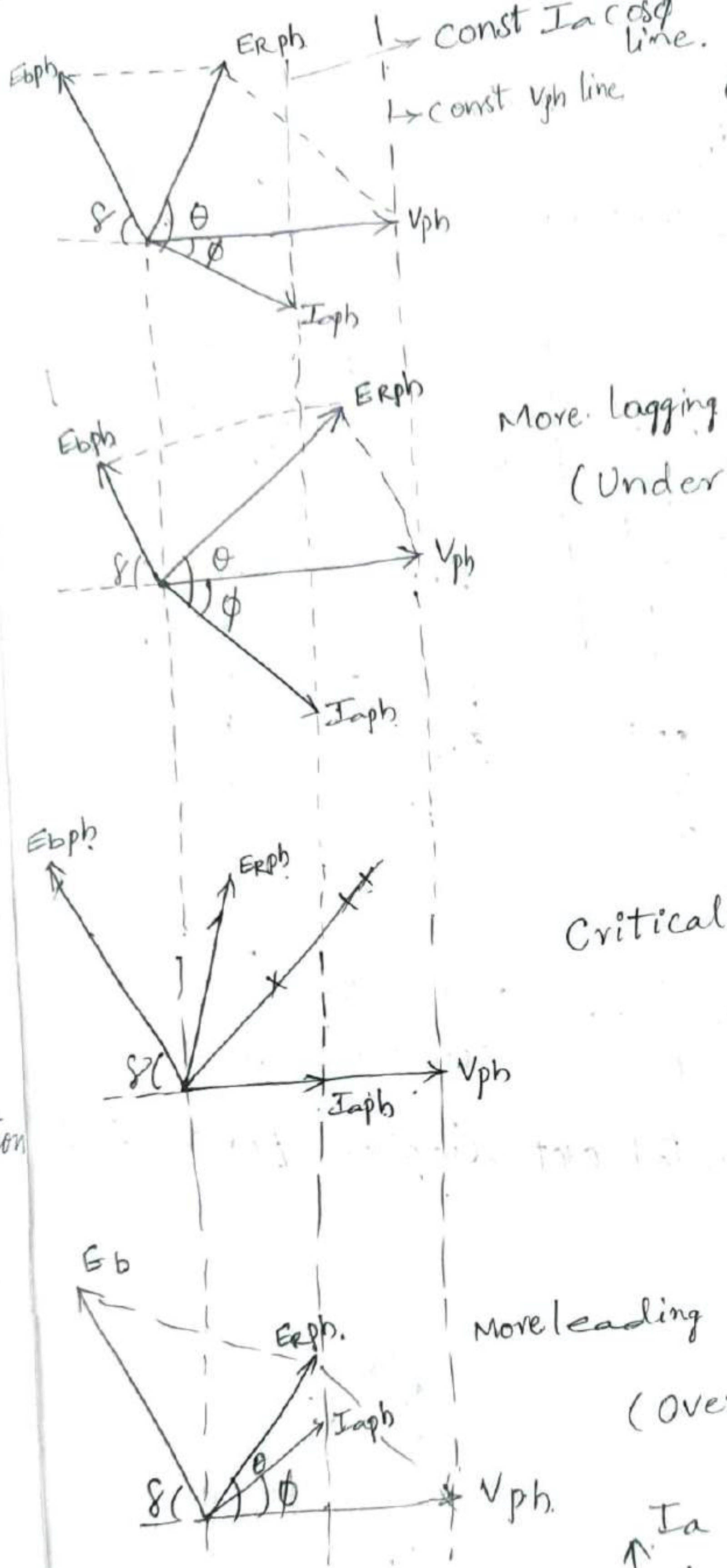
If p.f is unity for an excitation, that excitation is called critical excitation. At this condition the armature c/t per phase (I_{aph}) in phase with V_{ph} and the m/r draws minimum c/t.

- A s.m draws a lagging c/t when it is underexcit

it draws minimum c/t [illegible] c/t

Overexcit

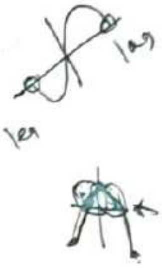
- draws a leading c/t



(Normal excitation

More lagging

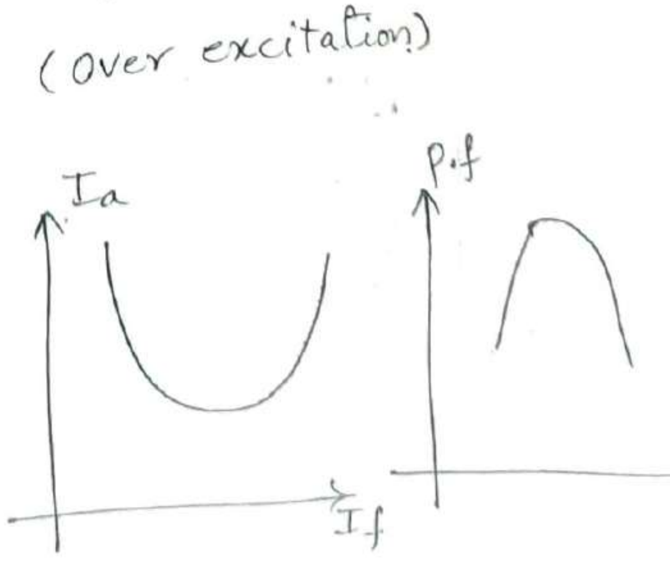
(Under Excitation



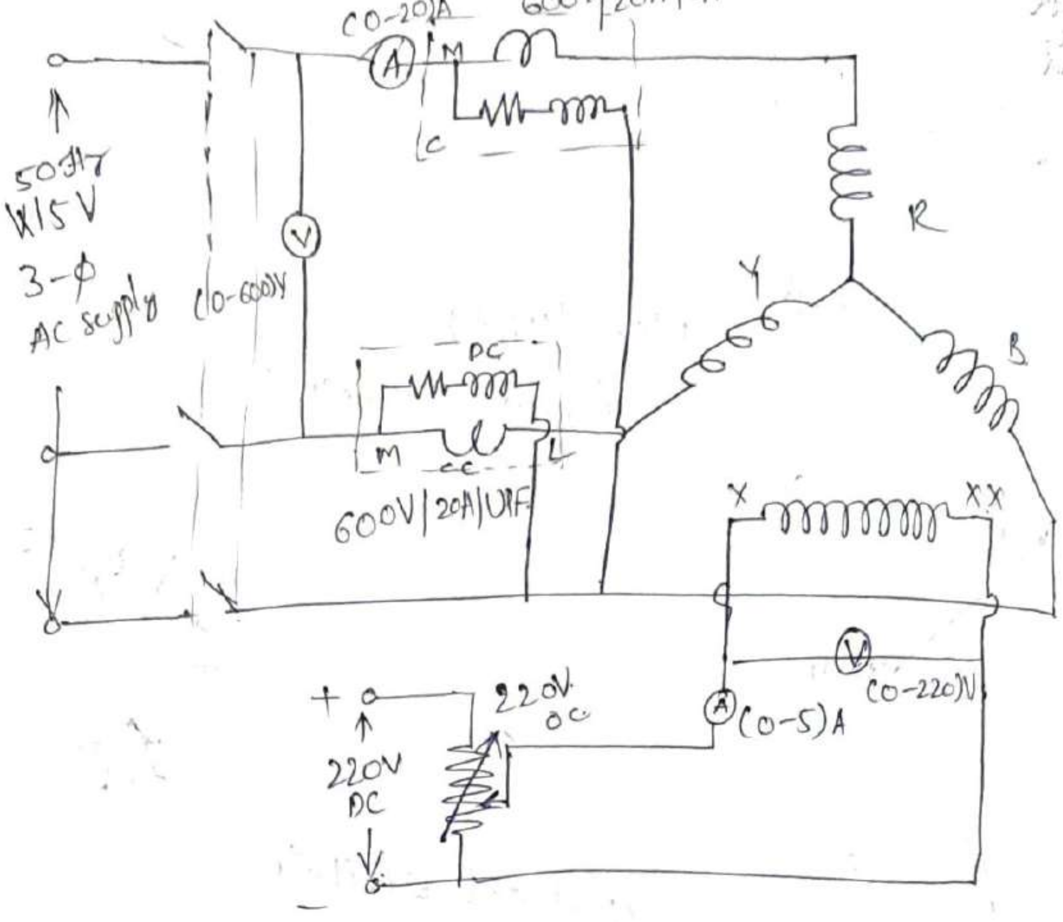
Critical Excitation

More leading

(Over excitation)

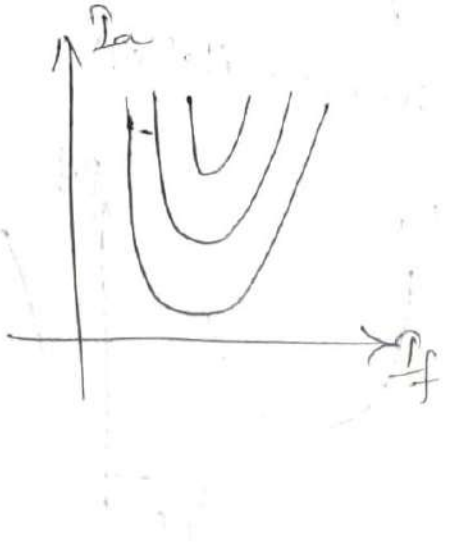


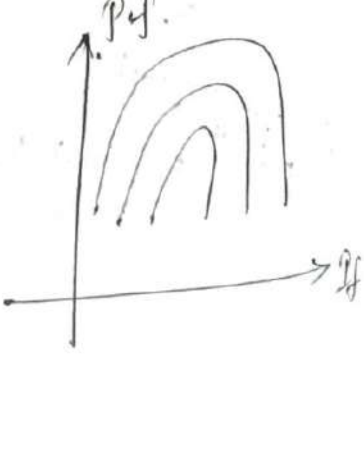
V and inverted V curves



$$\cos\phi = \cos\left\{ \tan^{-1} \frac{\sqrt{3}\,(\omega_1-\omega_2)}{(\omega_1+\omega_2)} \right\}$$

Laboratory experimental ckt diagram for V & inv V curves.





Expression for Back EMF

Under excitation :

$(E_{bph} < V_{ph})$

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \cos(\theta - \phi)$$

$$\sin\delta = \frac{E_{Rph}}{E_{bph}} \sin(\theta - \phi)$$

Over Excitation ($E_{bph} > V_{ph}$)

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{bph} \cos(\theta + \phi)$$

$$\sin\delta = \frac{E_{Rph}}{E_{bph}} \sin(\theta + \phi)$$

Critical Excitation

$$(E_{bph})^2 = (V_{ph})^2 + (E_{Rph})^2 - 2 V_{ph} E_{Rph} \cos\theta$$

$$\sin\delta = \frac{E_{Rph}}{E_{bph}} \sin\theta$$

power flows in synchronous m/r:

Input power $P_{in} = \sqrt{3} V_L I_L \cos\phi$ (or) $3 V_{ph} I_{ph} \cos\phi$

Total stator cu losses $= 3 I_{aph}^2 R_a$

P_m = P_{in} - stator cu loss

~~Tm~~ = Equivalent mech. power developed $P_m = T\omega$

$= T_g \times \frac{2\pi N_s}{60}$

Gross Torque $T_g = \frac{P_m \times 60}{2\pi N_s}$

$P_{out} = P_m - \text{mech. loss}$

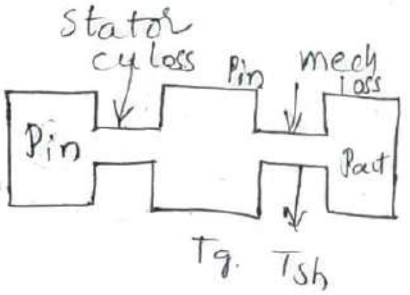
$P_{out} = T \times \omega$

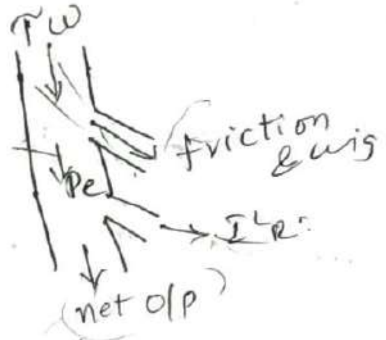
$$T_{shaft} = \frac{P_{out} \times 60}{2\pi N_s}$$

Electrical equation for Gross mechanical power Developed.

$P_m = 3 E_{ph} I_{aph} \cos(\text{angle b/w } E_{bph} \text{ \& } I_a)$

$\phi \pm \delta$





pblm

A 400V 3-ϕ Y connected. Syn m/r. has $R_a = \frac{0.2\Omega}{ph}$ $X_s = 2\Omega$/phase. while during a certain load it takes 25A from the supply. calculate the E_b induced. in the m/r if it is working with.

a) 0.8 lagging p.f b) 0.9 leading p.f c) UPF condition

Given data $V_L = 400V$, $R_a = \frac{0.2\Omega}{ph}$ $X_s = 2\Omega/ph$, $\cos\phi = 0.8$

$\phi = \cos^{-1}$

$= 36.8$

$E_b = ?$, $I_L = 25A$ $\quad V_{ph} = \frac{V_L}{\sqrt{3}}$

$= 230.9$

$Z_s = R_a + jX_s$ (or) $Z_s^2 = \sqrt{R_a^2 + X_s^2}$

$= 0.2 + j2 \Rightarrow 2.00 \angle 84.28$ $\quad \theta$

$E_{Rph} = I_L \times Z_s$ $\quad \theta = \tan^{-1}\left(\frac{X_s}{R_a}\right)$

$= 25 \times 2 \Rightarrow 50V$ $\quad \phi = \cos^{-1}(0.8)$

lag

$E_{bph} = \sqrt{(V_{ph}^2 + E_{Rph}^2 - 2V_{ph} E_{Rph} \cos(\theta - \phi)}$

i) p.f = 0.8 lag

$E_{bph} = \sqrt{(231)^2 + 50^2 - 2\times 231\times 50 \cos(84.3}$

$= 200.5\,V$

(ii) p.f = 0.9 lead.

$\phi = \cos^{-1}$

$E_{bph} = \sqrt{231^2 + 50^2 - 2\times 231\times 50 \cos(84.3 + \cancel{36.86})}$ 25.84 25.8

$= \cancel{218.84} \Rightarrow 252.64\,V$

(iii) Unity p.f

$(E_{bph})^2 = V_{ph}^2 + E_{Rph}^2 - 2V_{ph}E_{Rph}$

$E_{bph} = \cancel{241.120}$ 231.47 V

2. A 3-ϕ 500V syn m/r draws a c/t of from the supply the stator is Y connected with $R_a = 0.4\,\Omega/ph$, $X_s = 4\,\Omega/ph$ find p.f at which m/r would operate when the field c/t is adjusted to give the line values of generated EMF as i) 600V ii) 380V

Sol. $V_L = 500V$, $V_{ph} = \frac{500}{\sqrt{3}} = 288.67$

$R_a = 0.4\,\Omega\,ph$ $X_s = 4\,\Omega\,ph$

i) $E_b = 600V$, $E_{bph} = \frac{600}{\sqrt{3}} \Rightarrow 346.4V$

$E_b = \sqrt{}$ $\quad \bar{Z}_s = R_a + jX_s \quad Z_s = 4.01\angle$

$E_{Rph} = I_L \cdot Z_S$
$= .50 \times 4 \Rightarrow 200V.$

$E_b = \sqrt{V_{ph}^2 + E_{Rph}^2 - 2V_{ph}E_{Rph}\cos(\phi+\theta)}$ $\qquad \phi = 7.53$

$=$

$\frac{E_{bph}^2 - V_{ph}^2 - E_{Rph}^2}{-2V_{ph}E_{Rph}} = \cos(\theta+\phi) \Rightarrow \frac{(346.4)^2 - (288.6)^2 - 200^2}{-2 \times 288.6 \times 200}$

$\cancel{-2.04} = \cos(\theta+\phi)$

$= 0.02 \quad = \cos(.84.2+\phi)$
$1.55 \quad = 84.2 + \phi \Rightarrow \phi = -82.68$
$\phi = -82.64 \qquad \underline{\underline{\cos\phi = 0.547}}$

(ii) $E_b = 380V \Rightarrow \frac{380}{\sqrt{3}} = 219.39V$

$\frac{(219.39)^2 - (288.67)^2 - 200^2}{-2 \times 288.67 \times 200} = \cos(84.28+\phi)$

$\Rightarrow 0.687 = \cos(84.28+\phi) \Rightarrow 49.36 = 84.28 + \phi$
$0.861 - 84.28 = \phi \qquad \phi = -34.91$
$-83.41 = \phi \qquad \cos\phi = \cos(-34.91)$
$\underline{\cos\phi} = \underline{0.82}$

3. A 3-ϕ 6600V., Y. connected syn m/r delivers 500KW. power to the f.L. Its F.L efficiency is 83%., $R_a = 0.3\Omega/ph$, $X_s = 3.2\Omega/ph$. It is working with 0.8 lead p.f. on f.L then. Calculate
i) Generated Emf on f.L & the load angle

Sol. $V_L = 6600V$, $P = 500KW$ $\qquad \eta_{F.L} = 83\%$
$R_a = 0.3\Omega/ph$
$V_{ph} = \frac{6600}{\sqrt{3}} \Rightarrow 3810.51V$ $\qquad X_S = 3.2\Omega/ph$

$\eta = \frac{P_{out}}{P_{in}} \Rightarrow 0.83 = \frac{500 \times 10^3}{P_{in}}$

$P_{in} = 602409.63W$

$P_{in} = \sqrt{3}\, V_L I_L \cos\phi$

$\cos\phi = 0.$

$602409.63 = \sqrt{3} \times \overset{6600}{\cancel{3810.5}} \times I_L \times 0.8$

$\phi = 36.$

$I_L = \dfrac{602409.63}{\sqrt{3} \times 0.8 \times \cancel{3810.5}\ 6600}$

$I_a = I_L = 65.87\ A$

$E_{bph}^2 = E_{Rph}^2 +$

$E_{Rph} = I_a Z_S$

$-2E_{Rph}$

$Z_S = R_a + jX_s$

$= (0.3 + j\,3.2)\,\Omega \Rightarrow 3.21\,\underline{/84.64}$

$\theta = 84.$

$E_{Rph} = 65.87 \times 3.21\,\underline{/84.64}$

$= 211.44\,V$

Generated EMF

$(E_{bph})^2 = (E_{Rph})^2 + (V_{ph})^2 + 2\,E_{Rph} V_{ph} \cos(\theta+\phi)$

$= (211.44)^2 + (3810.5)^2 - 2\,(211.44)(3810.5)$

$\cos(84.64 +$

$E_{bph}^2 = 15406563.08$

$E_{bph} = 3925.31$

Load angle

$\dfrac{E_{bph}}{\sin(\theta+\phi)} = \dfrac{E_{Rph}}{\sin\delta}$

$\dfrac{3925.31}{\sin(84.64+36.86)} = \dfrac{211.44}{\sin\delta}$

$\sin\delta = 0.045$

$\boxed{\delta = 2.57^\circ}$