

**PKAIET BARGARH**

**5<sup>th</sup> SEMESTER ELECTRICAL ENGINEERING**

**TH-2 (ENERGY CONVERSION -II)**

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## SYNCHRONOUS MACHINE

$$f = \frac{PN}{120} \text{ Hz}$$

$$50 = \frac{PN}{120}$$

$$PN = 6000$$

Armature wdg → Stator (or) Rotor means both because of generation of AC  
 Armature wdg → Rotor (dc m/c) (or DAB)

↓  
Field (or) cond<sup>r</sup> both can rotate.

247 MVA, 0.85 PF lag, 3-φ Gen<sup>r</sup>, 50Hz, 8000 rpm

Armature wdg :- 3-φ AC, 15.75 KV, 9050A, double star. → on stator.  
 ↓  
 (Parallel line)

Insulation, High current, cooling are difficult in above.

Field wdg :- 2600A dc, 310V dc. → on rotor.

54Hz → Gives lamps flicker effect.

(freq. ↑ size ↓)

100Hz → Gives x<sup>n</sup> problem.

50Hz → Reliable. (std.)

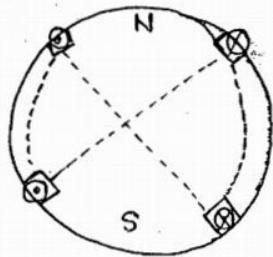
\* cylindrical rotor / Round Rotor / Non-salient

\* turbogenerator - Ni cd (3000 RPM) No lamination  
 Rotor

↓  
Relative velocity 0.

- 115cm diameter (Periphery) ↓ area for poles ↓.

Cylindrical Rotor/Non-salient.

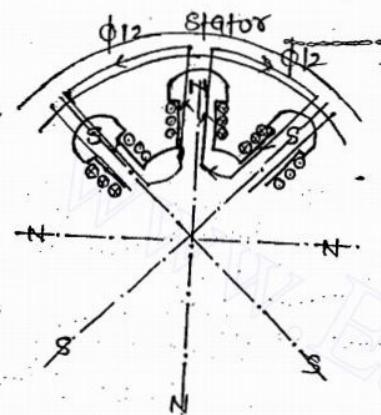


Poles:  $\frac{1}{3}$  rd

$$\text{field wdg} = \frac{2}{3} \text{ rd}$$

P ≠ 4

Salient pole rotor (salient - projected)



- \* leakage flux doesn't take place in the power transfer. like electric choke.
- \* mutual flux is responsible for power transfer.

Sinusoidal → This only producing the ~~REF~~ RMF waveform

\* This can be expressed in complex (phasors).

BLU

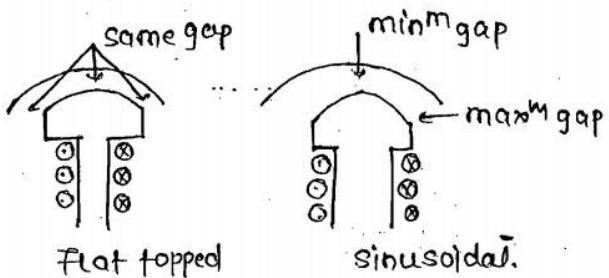
→ Not sinusoidal.

→ must be sinusoidal.

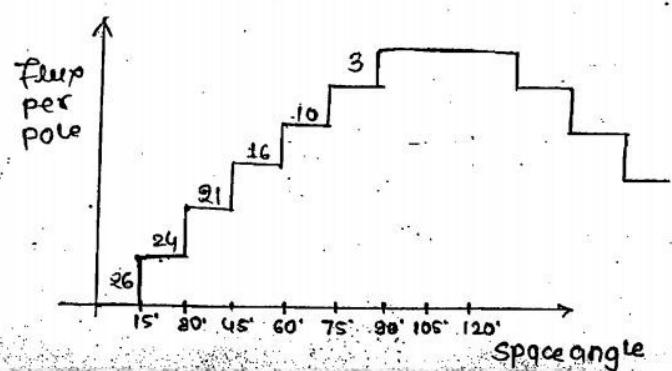
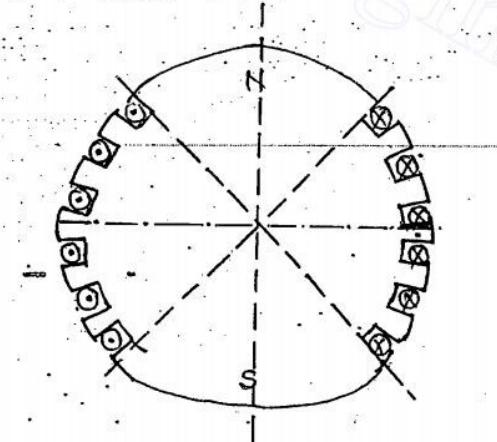
flux per pole - Total no. of ~~per-pole~~ flux line that an observer were find in total N-space. (1-pole pitch)

### Sinusoidal flux density distribution in the air gap:

- (1) The req. waveform of generated Vol. is sinusoidal.
- (2) A sinusoidal Vol. may only be generated if the radial flux density in the air gap is sinusoidal.



3) In a salient pole rotor the field wdg is concentric but concentrated & therefore the field mmf in the air gap of the pole arc is constant. Hence a sinusoidal flux density distribution may be obtained by shaping the pole such that the air gap at the center of pole kept min<sup>m</sup> & goes on increasing as one moves away from the center of the pole. Of course the variation in the airgap should be compatible with the desired sinusoid. (Ref above fig)



In a cylindrical rotor the field wdg is concentric but distributed in space in no. of slots. The air gap however is uniform & therefore the reluctance of airgap is constant.

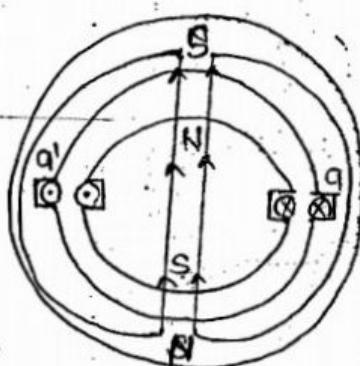
Therefore a sinusoidal flux density may only be obtain with a sinusoidal field mmf wave.

This may be obtained by providing max<sup>m</sup> no. of turns in the slots adjacent to the interpolar axis & the no. of turns in the subsequent slots goes on decreasing as one approaches the pole. Such that the min<sup>m</sup> no. of turns is provided in the slots adjacent to the pole.

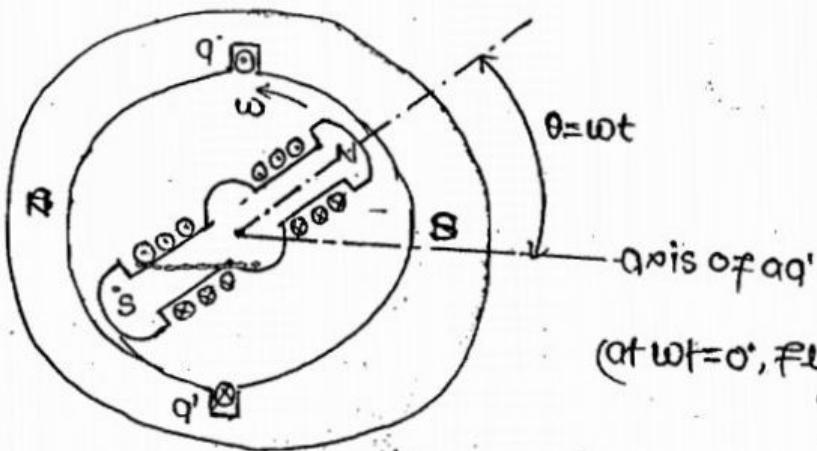
Of course the variation in the no. of turns the diff slots should be compatible with the desired flux-density distribution.

Such a provision results into a stepped field mmf wave that approximate a sinusoid.

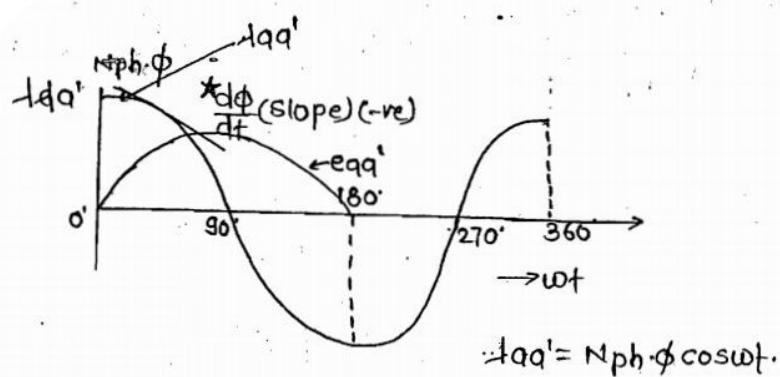
A perfect sinusoidal mmf may only be obtained if the no. of field slots is infinite.



Induced EMF →



(at  $\omega t = 0^\circ$ , flux will max<sup>m</sup> at q & q'')



$$eqq' = N_{ph} \cdot \phi \cos \omega t.$$

P = No. of pole, N = Speed in rpm.

$$f = \frac{PN}{1000} \text{ Hz}$$

$$\phi = f \mu_0 / \text{pole} = B_{avg} \times \text{Area/pole}$$

$$= \left( \frac{2}{\pi} B_m \right) \times \frac{\pi D L}{P} \text{ wb/pole}$$

$N_{ph}$  = No. of turns / phase.

$$eqq' = \pm \frac{d}{dt} (1qq')$$

$$eqq' = \pm \frac{d}{dt} (1qq')$$

$$eqq' = - \frac{d}{dt} (N_{ph} \cdot \phi \cdot \cos \omega t) = - \left[ N_{ph} \phi \frac{d}{dt} (\cos \omega t) + N_{ph} \cdot \cos \omega t \frac{d\phi}{dt} \right]$$

$$= -N_{ph} \phi (-\sin \omega t) \omega t = - \left[ N_{ph} \cdot \phi \omega (-\sin \omega t) + N_{ph} \cos \omega t \frac{d\phi}{dt} \right]$$

$$= \frac{N_{ph}}{\pi} \omega t \sin \omega t$$

$$= N_{ph} \cdot \phi \omega t \sin \omega t$$

$$= \left[ N_{ph} \cdot \phi \omega \sin \omega t - N_{ph} \cos \omega t \frac{d\phi}{dt} \right]$$

$eqq'$  = Speed voltage

$$eqq' = N_{ph} \cdot \phi \omega \sin \omega t - N_{ph} \cos \omega t \frac{d\phi}{dt}$$

Speed voltage

Xmer voltage

Since all synchronous m/c have there field excited by dc,  $\frac{d\phi}{dt} = 0$

$$eqq' = N_{ph} \cdot \phi \omega \sin \omega t = N_{ph} \cdot \phi \omega \cos(\omega t + 90^\circ)$$

$$\text{Therefore RMS } E_{ph} = \frac{N_{ph} \cdot \phi \cdot w}{\sqrt{2}}$$

$$= \frac{N_{ph} \cdot \phi \cdot (2\pi f)}{\sqrt{2}}$$

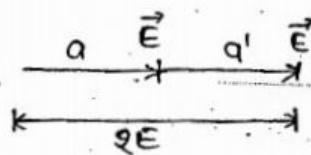
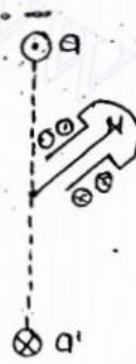
$$E_{ph} = \sqrt{2\pi f \phi \cdot N_{ph}}$$

$$E_{ph} = \sqrt{2\pi f \phi \cdot N_{ph}} \text{ Volts/ph.}$$

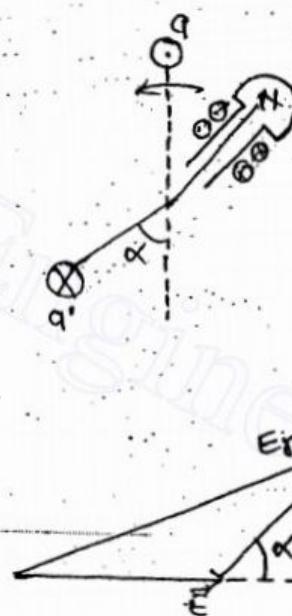
Valid for full pitched concentrated winding

DATE-12/11/14

Chorded winding →



Full pitched wdg



$$E_{res} = 2E \cos \frac{\alpha}{2} \quad \text{CHORDED wdg.}$$

chording factor/coil span factor/pitch factor

$$k_c = \cos \frac{\alpha}{2}$$

for fundamental

For  $n$ th harmonic voltage

replace ( $\alpha = n\alpha$ )

$$\text{Then } k_c(n) = \cos \frac{n\alpha}{2}$$

To eliminate  $n$ th harmonic

$$\frac{n\alpha}{2} = 90^\circ$$

$$\alpha = \frac{180^\circ}{n}$$

However practical value of  $\alpha$  is  $30^\circ$  elect. ( $\alpha = 30^\circ$ )

If  $m$ -phase sys. the  $2m \pm 1$  (Belt harmonics)

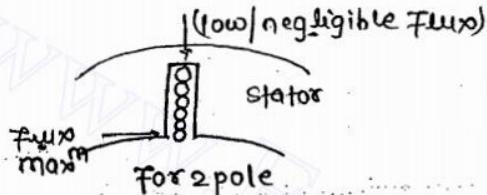
$m=3$  (3-ph sys) 5th & 7th harmonics are belt harmonics

\* chording reduces the harmonics

\* If  $\alpha \leq 60^\circ$ , more cu will be needed, so cost increases here.

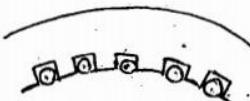
$$E_{ph} = k_c \sqrt{2\pi f} \cdot \phi N_{ph} \text{ Vol}/\phi$$

(Valid for chorded but concentrated wdg.)



\* Iron increases because of depth increasing.

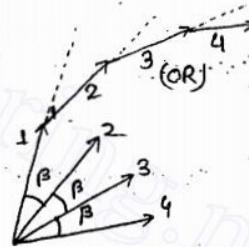
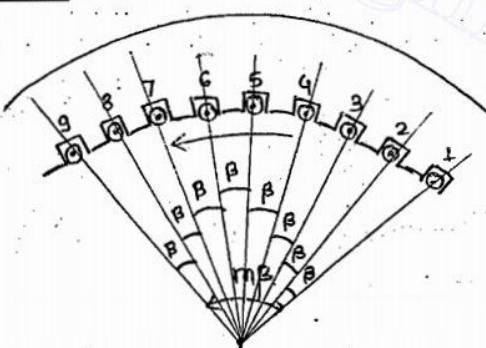
\* So we need more iron



\* Iron reduced & Flux is same for all the condts. (Good design)

\* Iron needed reduces.

\* Distributed winding →



$\beta$  = angle between adjacent slots.

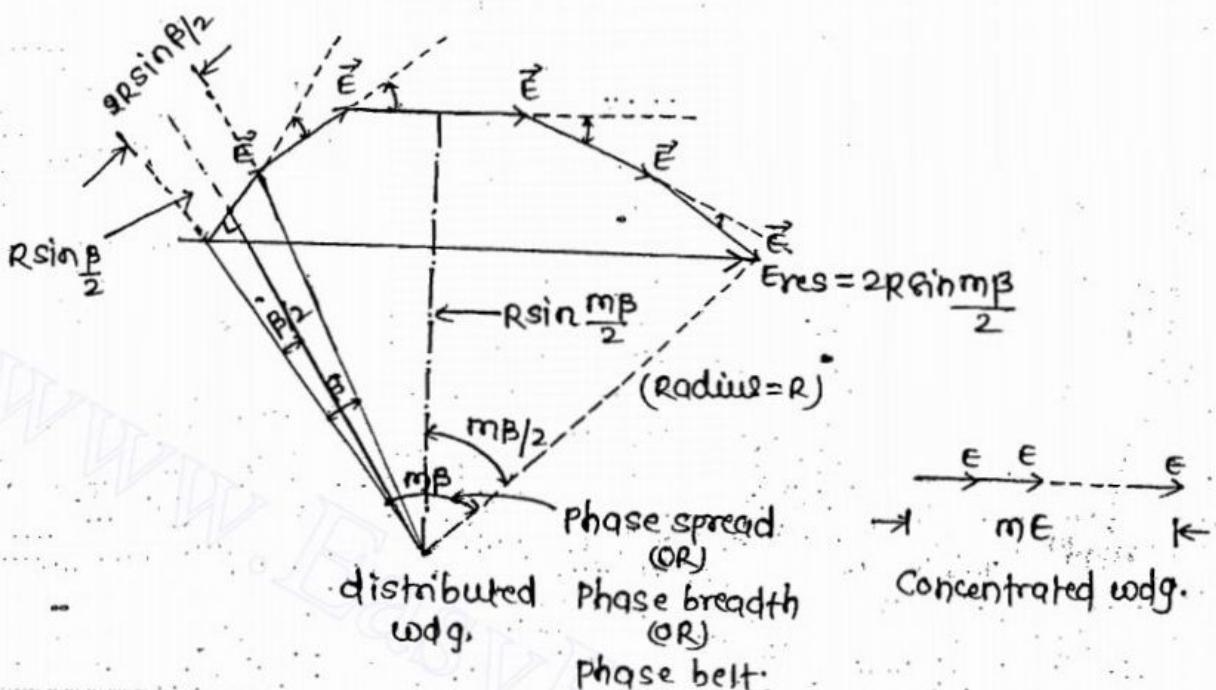
$$= \frac{360^\circ}{\text{No. of slots}} \text{ mech.}$$

$$= \frac{P}{2} \times \frac{360^\circ}{\text{No. of slots}} \text{ mech. elec.}$$

$$= \frac{180^\circ}{\text{No. of slots per pole}} \text{ elec.}$$

$$m = (\text{No. of slots per pole}) \text{ per phase} = \text{No. of slots per pole}/\text{phase}$$

$$= (\text{no. of slots/pole})/\text{phase}$$



$$\text{distribution factor; } k_d = \frac{2R\sin\frac{m\beta}{2}}{mE}$$

$$= \frac{2R\sin\frac{m\beta}{2}}{\frac{m \times 2R\sin\frac{\beta}{2}}{2}}$$

$$k_d = \frac{\sin\frac{m\beta}{2}}{m\sin\frac{\beta}{2}}$$

For fundamental..

\* For  $n$ th harmonics;

Replace  $\beta$  by  $n\beta$

$$k_d(n) = \frac{\sin\frac{m(n\beta)}{2}}{m\sin(\frac{n\beta}{2})}$$

\* distributed & chorded wdg is used mainly for reduction of harmonics.

approx  $k_d$  for fundamental vol.

since  $\frac{\beta}{2}$  is very small

$$\sin \frac{\beta}{2} \approx \frac{\beta}{2}$$

$$\text{then } k_d = \frac{\sin \frac{m\beta}{2}}{\frac{m\beta}{2}}$$

$$\text{approx } k_d = \frac{\sin \frac{\text{Phase spread}}{2}}{\frac{\text{Phase spread}}{2}}$$

$$\boxed{E_{ph} = k_c k_d \times \sqrt{2} \pi f \phi N_{ph} \text{ volts/}\phi}$$

$$= k_w \sqrt{2} \pi f \phi N_{ph} \text{ V/}\phi$$

Valid for chorded & distributed wdg.

where  $k_w = k_c k_d = \text{winding factor}$ .

Que → A 3φ 2P 3000 RPM 1-connected cylindrical rotor turbogenerator has the following data

No. of slots = 60, max flux density in air gap = 1.32 T

mean air gap dia = 1.12 m; effective axial length = 3 m,

No. of turns/φ = 10

i. Cal. the line-to-line vol. on NL if the coil span is 150°.

Soln →

$$\alpha = 180^\circ - 150^\circ$$

$$= 30^\circ \text{ ele.}$$

$$k_c = \cos \frac{30}{2} = 0.9659$$

$$\beta = \frac{180 - 360^\circ}{60} \text{ mech.}$$

$$= \frac{p}{2} \times 6 \text{ ele.} = \frac{2}{2} \times 6 \text{ ele.}$$

$$\beta = 6^\circ \text{ ele.}$$

$$m = \frac{60/2}{3} = 10$$

$$k_d = \frac{\sin \frac{10 \times 6}{2}}{10 \sin \frac{6}{2}}$$

$$= 0.9554$$

$$\phi = \left( \frac{2}{\pi} \times 1.32 \right) \times \left( \frac{\pi \times 1.12 \times 3}{2} \right)$$

$$\phi = 4.4352 \text{ wb/pole}$$

$$E_{ph} = k_c k_d \times \sqrt{2} \pi f \phi N_{ph}$$

$$= 0.965 \times 0.9554 \times \sqrt{2} \pi \times 50 \times$$

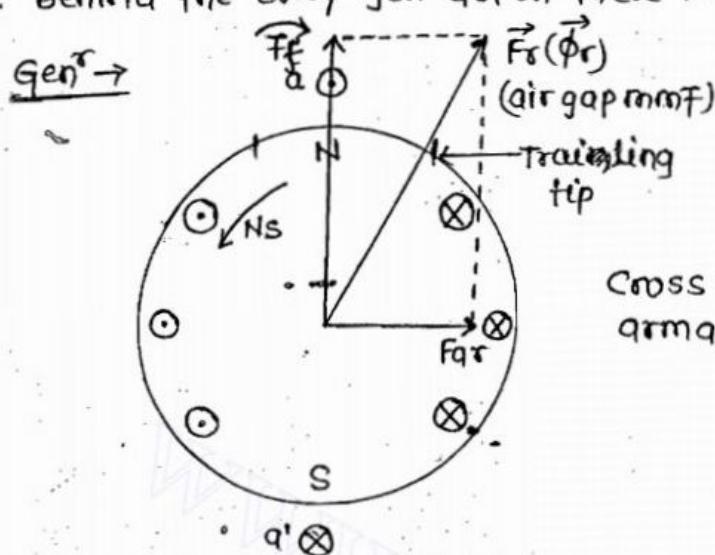
$$4.4352 \times 10$$

$$= 9092.13 \text{ Volts per star phase (line-to-neu.)}$$

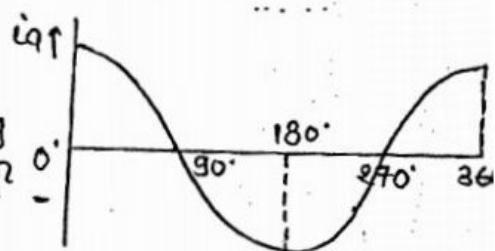
$$E_{(L-L)} = \sqrt{3} E_{ph} \approx 15.75 \text{ KV}$$

### Armature Reaction →

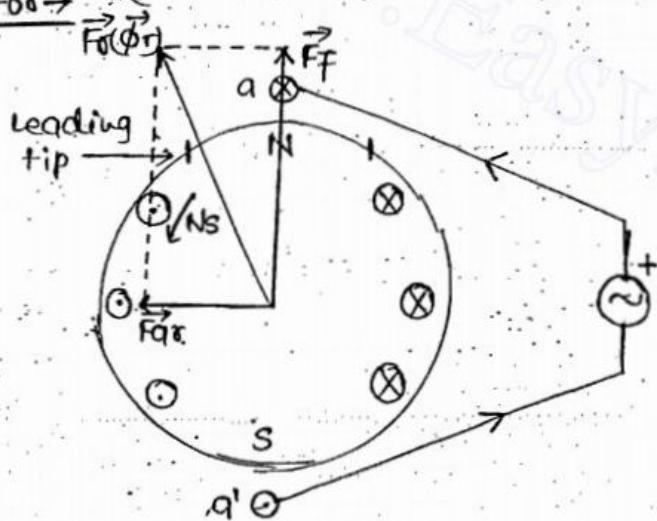
- \* The effect of arm. mmf on the main field is called arm. reaction.
- \* Behind every gen<sup>r</sup> action there is motoring action.



Cross magnetising armature Reaction



motor → (Internal) unity PF

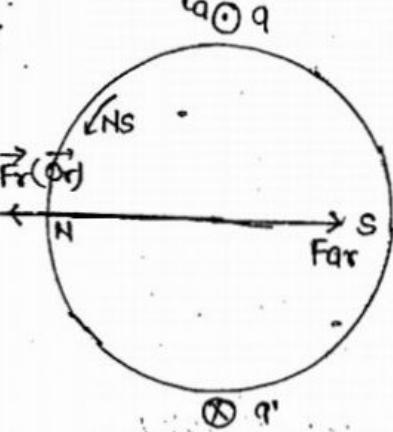


Cross magnetising armature Reaction

(Internal) unity PF

- \* Concentration of the flux is in the trailing tip at gen<sup>r</sup> action & in the motor the concentration is in the leading tip.

Gen<sup>r</sup> →

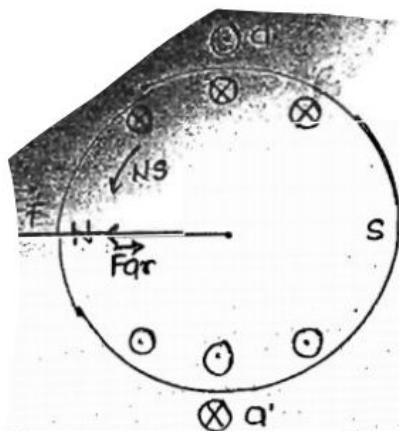


directly demagnetising armature Reaction

Since  $F_f > F_r$

Overexcited gen<sup>r</sup>

(Zero)PF lag

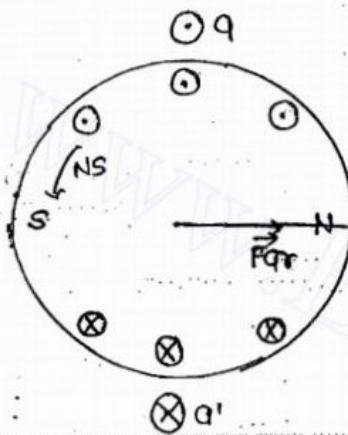


directly magnetising  
armature Reaction.

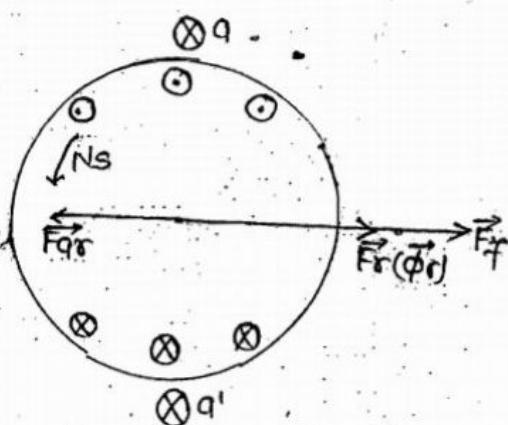
$$F_f < F_{ar}$$

$\therefore$  Under excited motor

(zero) PF lag.



(zero PF lead)



directly magnetising  
armature reaction

Since  $F_f < F_{ar}$

Under excited gen<sup>r</sup>

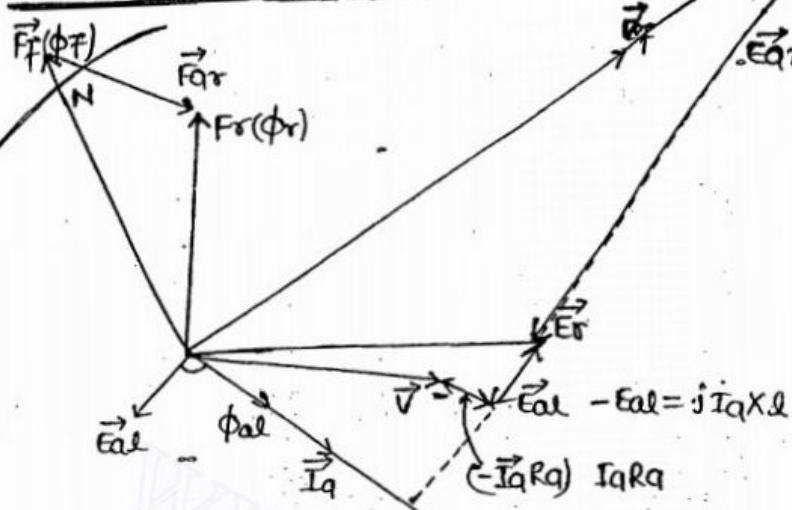
directly demagnetising  
armature reaction

Since  $F_f > F_{ar}$

Over excited motor

\* Cylindrical rotor Gen →

General phasor diagram & equivalent ckt



$$\vec{V} = \vec{E}_r + \vec{E}_{a1} - I_a R_a$$

$$\vec{V} = (\vec{E}_f + \vec{E}_{ar}) + \vec{E}_{a1} - I_a R_a$$

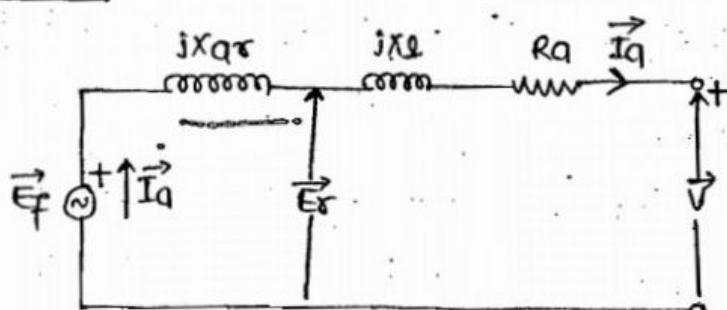
$$* \vec{E}_f = \vec{V} + I_a R_a - \vec{E}_{a1} - \vec{E}_{ar} \dots \text{(i)}$$

$$= \vec{V} + I_a R_a + j I_a X_L + j I_a X_{ar}$$

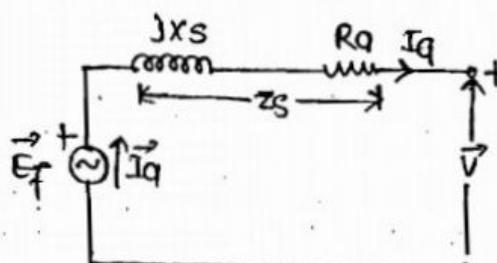
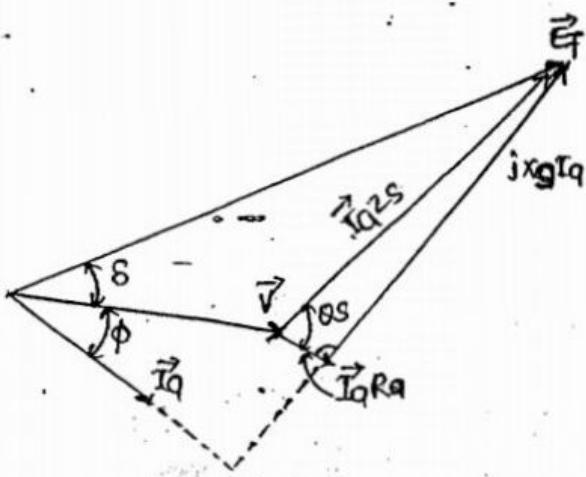
$$= V + I_a R_a + j I_a (X_L + X_{ar})$$

$$= \vec{V} + I_a R_a + j I_a X_s \dots \text{(ii)}$$

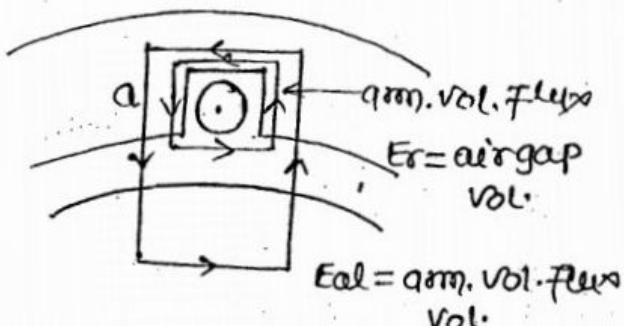
\* Equivalent ckt →



eq(i) ckt diagram



eq(ii) eq. ckt



$E_f$  = excitation vol.  
(OR)

Internal vol.  
(OR)

OC Voltage

$E_{ar}$  = armature reaction vol.

$X_L$  = Armature leakage reactance

$X_{ar}$  = armature Reaction reactance  
(OR)

magnetising Reactance of  
synchronous m/c

$X_s$  = synchronous Reactance  
( $X_L + X_{ar}$ )

Angle between  $E_f$  &  $\phi_r$  = torque angle

angle between  $E_f$  &  $V$  = power angle/ Rotor angle.

\* air gap is 200m $\mu$   
syn. m/c is 70mm  
500Mw - 130mm

Open circuit Test  
&  
Short circuit Test

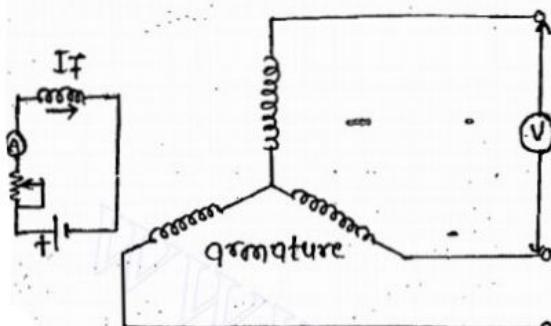


fig-oc test

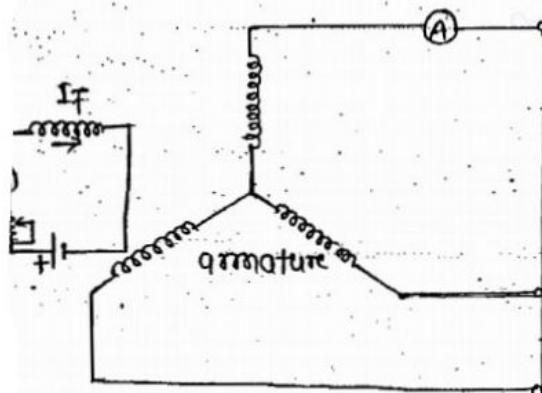
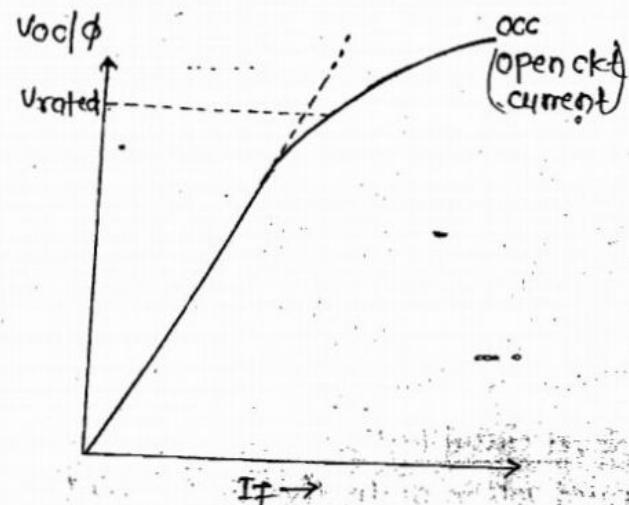
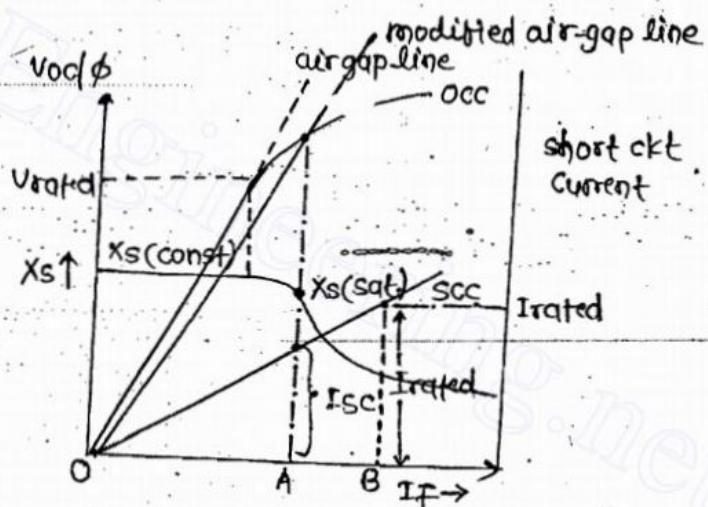


fig-sc test



allow 1.2-2 times of F.L current.

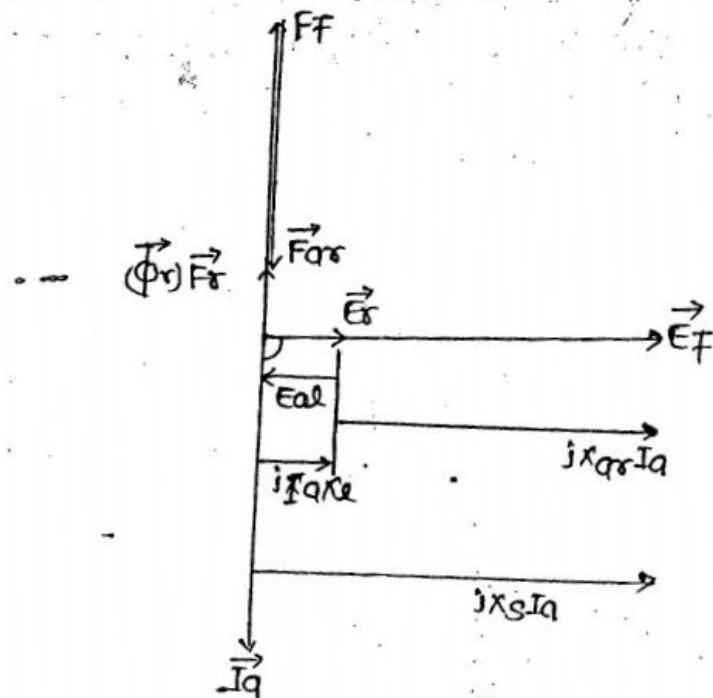
(X<sub>s</sub> constant at 1<sup>st</sup> then variable)

modified air gap line is the occ of an eq. unsaturated m/c that gives rated vol. at the same field current as the actual m/c.

sc by definition is that value of sc arm. current which is obtained at a field current that gives rated vol. on oc.

$$X_{s(\text{sat.})} \triangleq \frac{V_{\text{rated}}}{I_{\text{sc}}}$$

$X_{s(\text{sat.})}$  = Saturated synchronous Reactance (or) adjusted syn. reactance



\* Short circuit Ratio is defined as the ratio of the field current req. to give rated vol. on ac to the field current req. to give rated arm. current on sc.

Short circuit Ratio,  $SCR \triangleq \frac{OA}{OB}$

$$SCR = \frac{I_{sc}}{I_{rated}}$$

$I_{rated}$  = Base value,  $I_{sc}$  = actual value

$$\frac{I_{sc}}{I_{rated}} = \frac{I_{pu}}{1} = SCR$$

$$= \frac{V_{rated}/X_{s(sat)}}{I_{rated}}$$

$$\therefore X_{s(sat)} = \frac{V_{rated}}{I_{sc}}$$

$$= \frac{V_{rated}/I_{rated}}{X_{s(sat)}}$$

$$= \frac{Z_{base}}{X_{s(sat)}}$$

$$SCR = \frac{1}{X_{s(sat)}/Z_{base}}$$

$$SCR = \frac{1}{X_{s(sat)} \text{ pu}}$$

20% →

W.R. will be also increases because high value of vol. drop.  
Efficiency decreases.

\* For ten bogen<sup>r</sup> 0.58 but not less than 0.35 (By IEEE) <sup>For</sup> SCR

+ Sufficient pole gen<sup>r</sup> the efft needs (or) 0.8 not less than 0.8.

Zero Power Factor
ZPF C/S (OR) Potier c/s

\* ZPF c/s, also called Potier c/s shows the variation of terminal vol. against field current when arm. current is maintained at its rated value & ZPF lag.

- V/I/F  
when  $I_q = I_{\text{rated}}$  at ZPF lag.

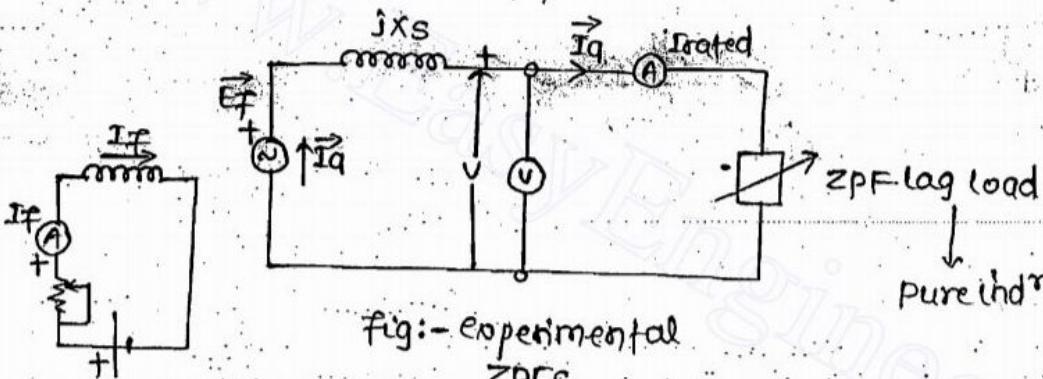


fig:- experimental  
ZPF C.

Pure ind. (or) Unloaded &  
underexcited syn.  
motor.

\* Since the variation in field current (or) the variation in load effects the arm. current as well as the terminal vol., it is recommended that the field current be increased for terminal vol. & subsequently the load may be adjusted for rated arm. current.

$I_f$	$V$	$I_a$
3.2A	225V	200A
3.5A	246V	218A
3.5A	257V	200A

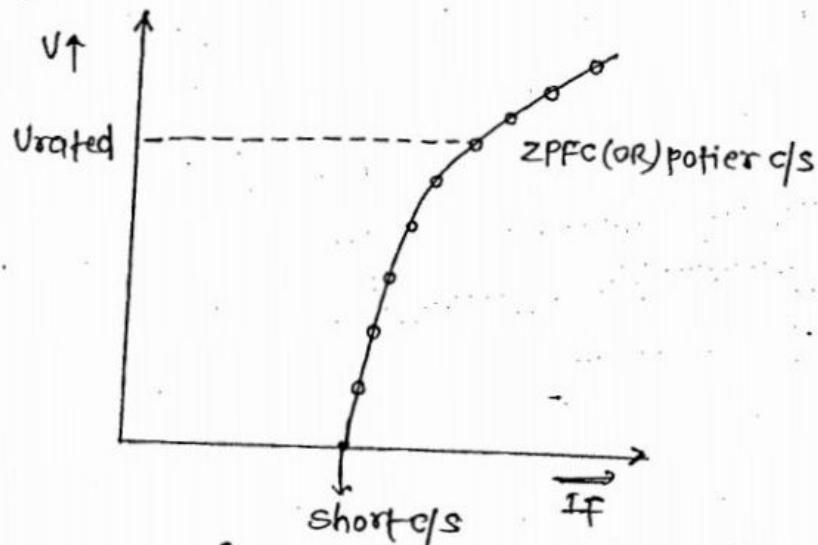
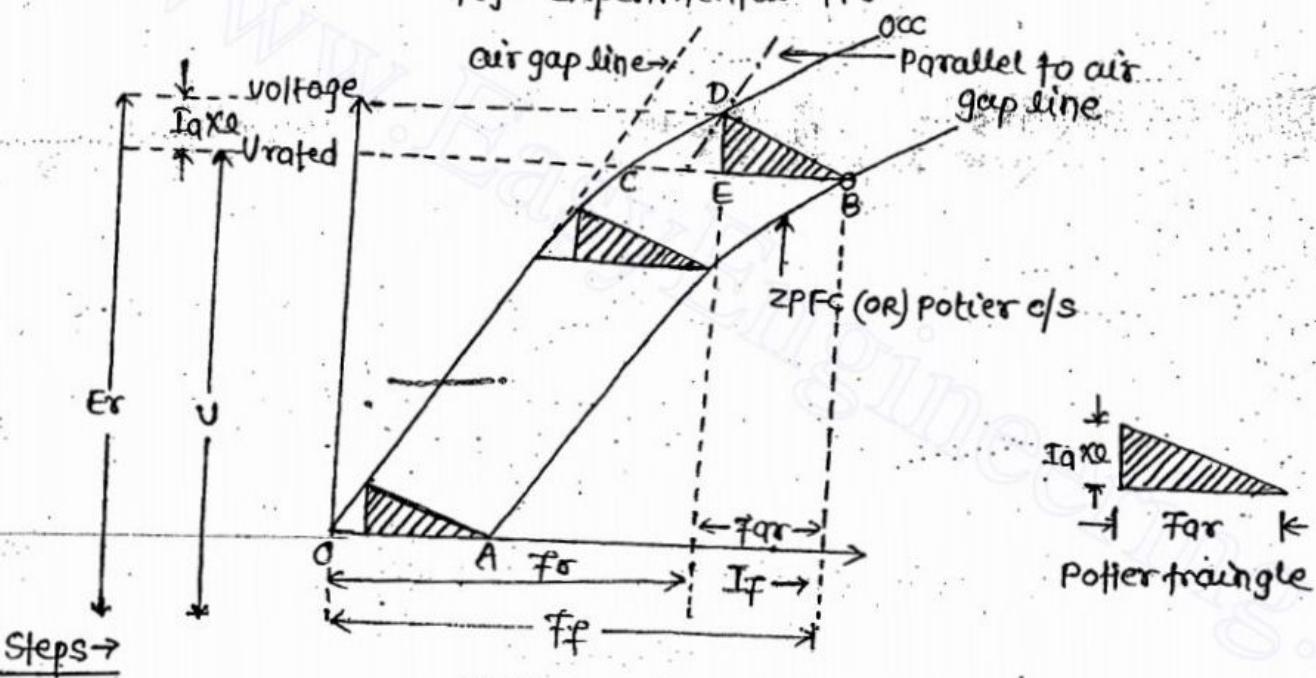


fig :- Experimental ZPFC

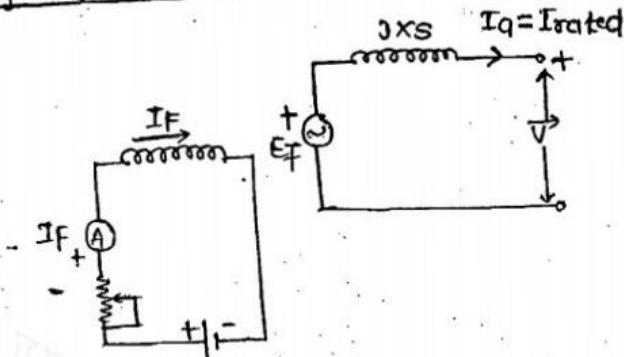


- \* Draw the OCC & locate the 2 experimental points A & B. point A represents the field current reqd to give rated arm. current on sc. point B represents point the field current reqd to give rated terminal vol. when the arm. current equals rated value at zpf lag.
- \* Take BC=OA as shown in fig.
- \* from point C, draw a line parallel to the air gap line intersecting the OCC at point D.
- \* from point D, draw a perpendicular DE on BC. the  $\Delta$  DEB is the potier  $\Delta$ . In the potier  $\Delta$  BE represents the effect of Far in the air gap. DE represents the arm. leakage reactance drop on FL. & its called potier drop.

move the polar A parallel to itself while always keeping its vertex D on the axis. The locus of point B is the ZPFC also called potier c/s.

DATE - 15/11/14

\* Voltage Regulation →



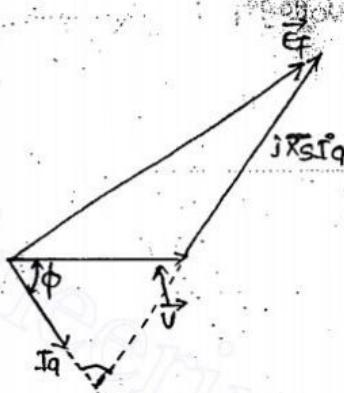
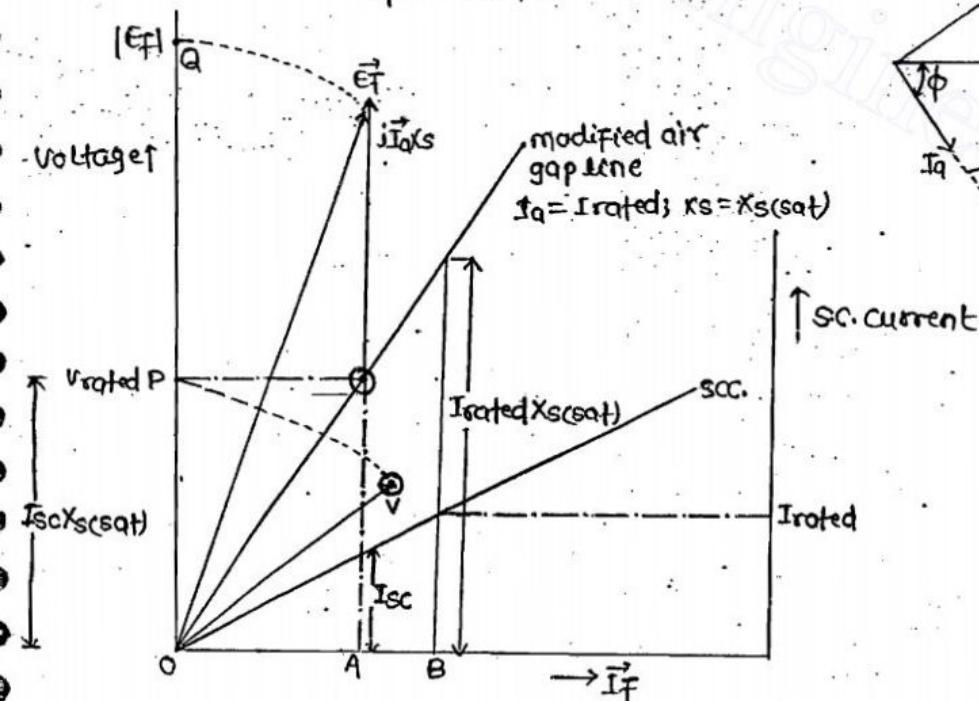
$$\text{Voltage Reg} \equiv \frac{E_f - V}{V} \text{ PU}$$

where  $V = V_{\text{rated}}$ .

\* VR% of an alternator is defined as the rise in o/p terminal vol. expressed as a fraction of FL rated vol. when FL at a specified PF is thrown off keeping the excitation constant.

VR% by EMF method →

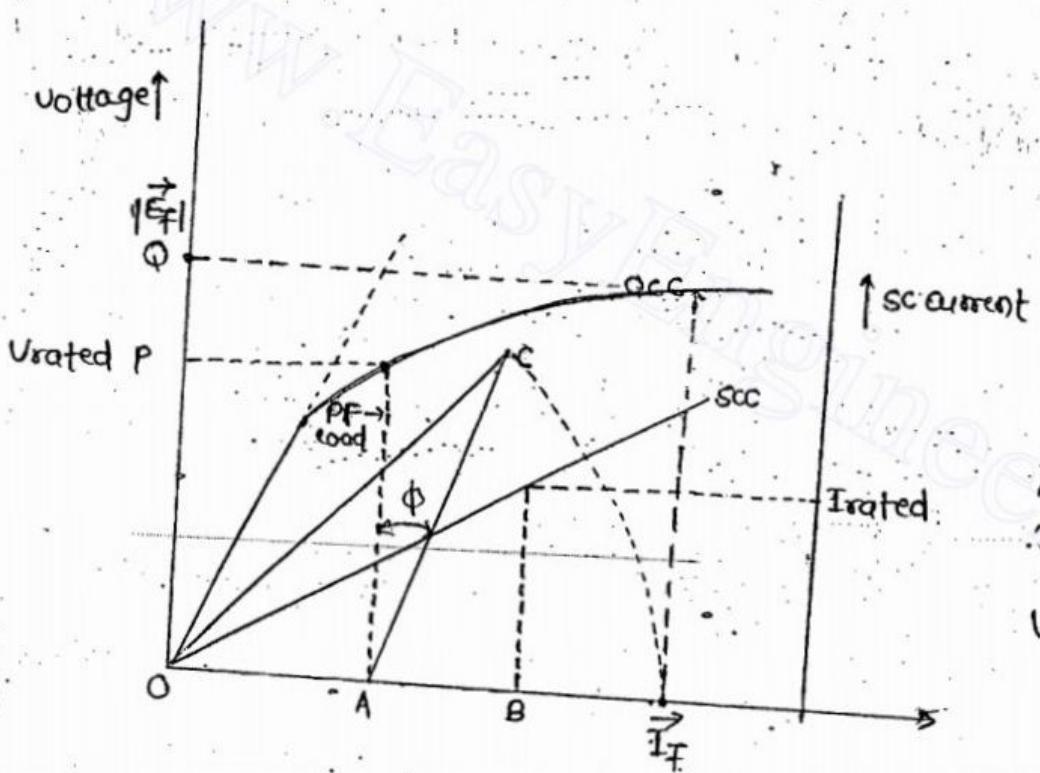
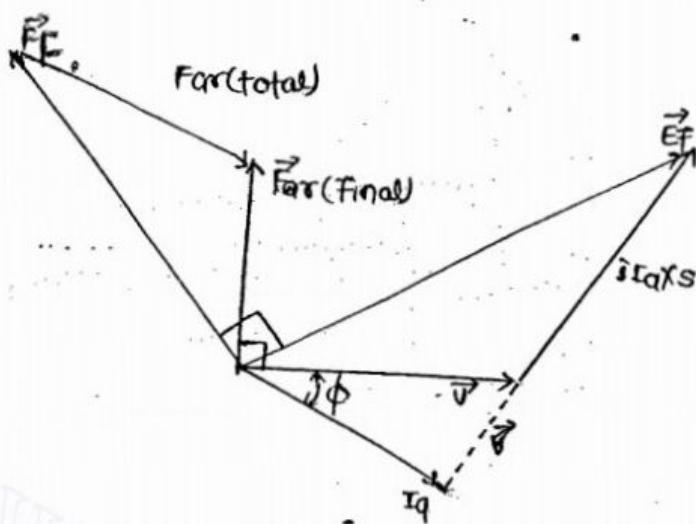
$$\vec{E}_f = \vec{V} + j \vec{I}_q x_s$$



$$VR\% = \frac{OQ - OP}{OP} \text{ PU}$$

\* The value of VR% obtained by EMF method is higher than actual & therefore this method is called pessimistic.

\*  $VR^n$  by mmf method  $\rightarrow$  (OR) amp.turn method.

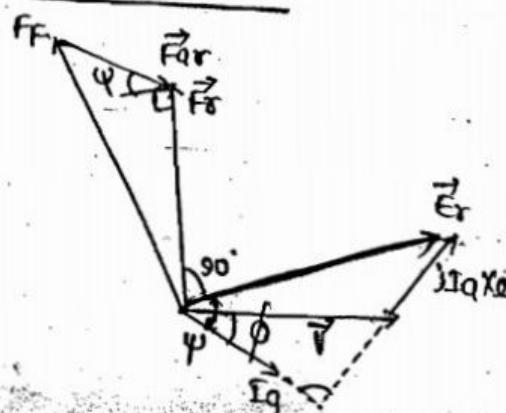


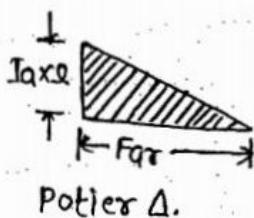
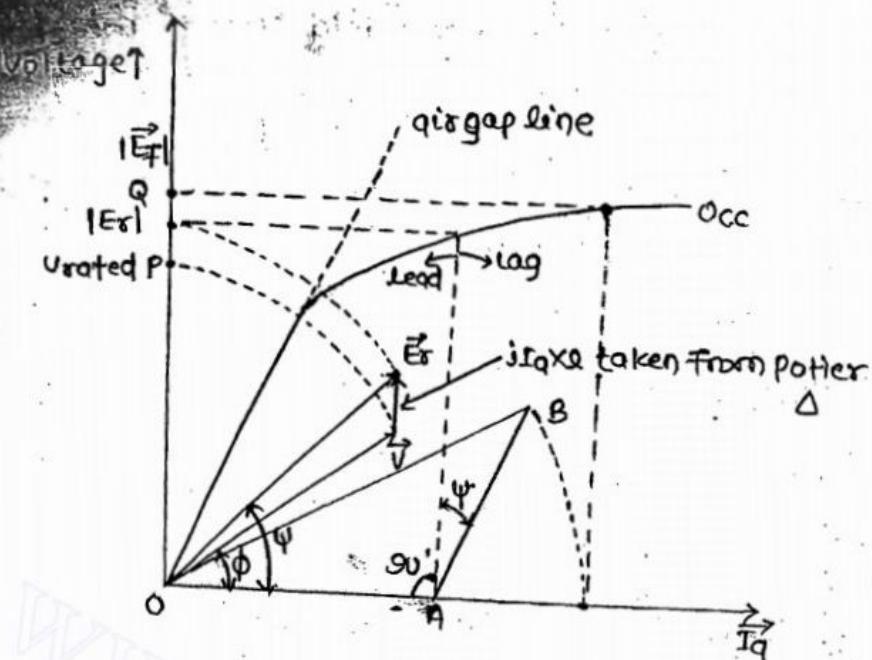
$$\begin{aligned} OA &\equiv F_r(\text{Final}) \\ OB &\equiv F_r(\text{total}) \\ AC &= OB \\ \therefore OC &\equiv F_F \end{aligned}$$

$$VR^n = \frac{OQ - OP}{OP}$$

\* The value of the  $VR^n$  obtain by mmf method is less than actual & therefore this method is called optimistic method.

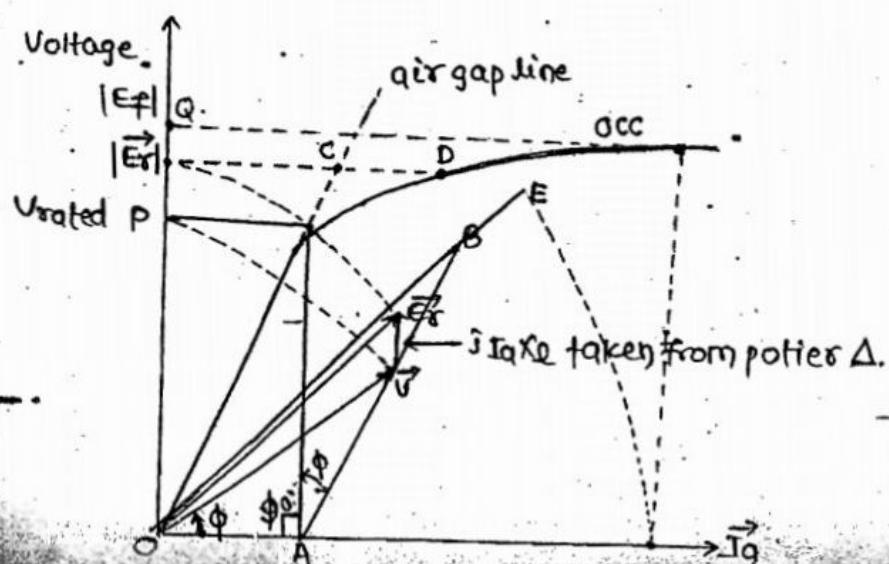
$VR^n$  by ZPF method (OR) potier method  $\rightarrow$





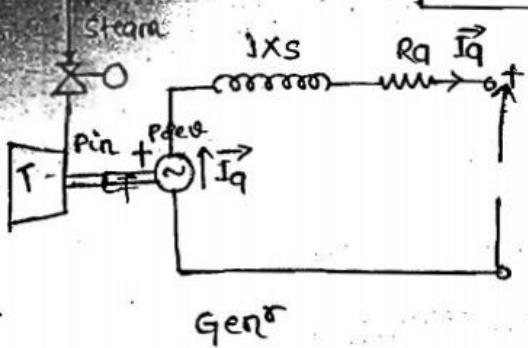
\* The  $VR^n$  obtained by EMF method was found to be pessimistic while the mmf method produced the optimistic. The Potier method also called ZPF method treats the quantity as they actually exist in a m/c on load. The  $VR^n$  obtained by ZPF method therefore more realistic than the earlier 2 methods. Thus the potier method was long used for the determination of  $VR^n$  of syn. gen. until American Rstd. Association (ASA) proposed the modification of mmf method. This method is now popularly known as ASA method.

#### \* $VR^n$ by ASA method →



- \* I<sub>pu</sub> field current in a syn. m/c is that value of field current which gives rated voltage on the air gap line.
- \* The ASA modified the mmf method by determining  $F_f$  final from the air gap line instead of from the occ. It was then combined with  $F_f$  total taken from SC data to determine the  $F_f$  of unsaturated m/c.
- \* Since the degree of saturation depends on the air gap mmf, the additional field mmf req. to overcome saturation was determined at a horizontal intersect b/w the air gap line and occ at  $E_g$  level.
- \* This additional field mmf was added to the  $F_f$  of unsaturated m/c to finally determine the  $F_f$  of actual m/c under actual operating condn.
- \* The ASA method has been found to give satisfactory method for cylindrical rotor & as well as the salient pole m/c & it is latest recommendation for determination of  $V_{RH}$  of syn. gen.

**POWER ANGLE  
RELATIONS**



$$\vec{E}_f = \vec{V} + \vec{I}_q Z_S$$

$$\vec{I}_q = \frac{\vec{E}_f - \vec{V}}{Z_S}$$

$$= \frac{E_f \angle \delta - V \angle 0}{Z_S \angle 0}$$

$$\vec{I}_q = \frac{E_f \angle \delta - \theta_S - V \angle 0}{Z_S \angle 0}$$

$$S_{out} = \vec{P}_{out} + \vec{Q}_{out} j$$

$$= V I_q^*$$

$$= V I_0 \cdot \left[ \frac{E_f \angle \delta - \theta_S}{Z_S} - \frac{V \angle 0}{Z_S} \right]$$

$$S_{out} = \frac{V E_f \angle \delta - \theta_S}{Z_f} - \frac{V^2 \angle 0}{Z_S} \quad (i)$$

$$\therefore P_{out} = \frac{V E_f}{Z_S} \cos(\theta_S - \delta) - \frac{V^2}{Z_S} \cos \theta_S$$

$P_{out}$  is max<sup>m</sup> when  $\delta = \theta_S$  (variable = constant)

then  $P_{out(max)} = \frac{V E_f}{Z_S} - \frac{V^2}{Z_S} \cos \theta_S$

$$\vec{S}_{dev} = P_{dev} + j Q_{dev} = \vec{E}_f \vec{I}_q^*$$

$$= E_f \angle \delta \left[ \frac{E_f \angle \delta - \theta_S}{Z_S} - \frac{V \angle 0}{Z_S} \right]$$

$$\vec{S}_{dev} = \frac{E_f^2}{Z_S} \angle \delta - \frac{V E_f}{Z_S} \angle \delta + \theta_S \quad (ii)$$

$$P_{dev} = \frac{E_f^2}{Z_S} \cos \theta_S - \frac{V E_f}{Z_S} \cos(\theta_S + \delta)$$

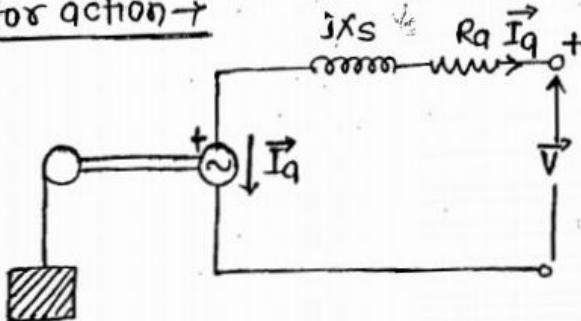
$P_{dev}$  is max<sup>m</sup> when -

$$\theta_S + \delta = 180^\circ$$

$$\delta = (180 - \theta_S)$$

And this decides steady state stability limit.

motor action →



$$E_f = V - I_q Z_s$$

$$\vec{I}_q = \frac{V - E_f}{Z_s}$$

$$\vec{I}_q = \frac{V L_0^\circ - E_f L - \delta}{Z_s L_0 s}$$

$$\vec{I}_q = \frac{V}{Z_s} L_0 s - \frac{E_f L}{Z_s} - \frac{(0s + \delta)}{Z_s}$$

$$S_{dev} = P_{dev} + jQ_{dev}$$

$$= E_f I_q^*$$

$$= E_f L - \delta \left[ \frac{V}{Z_s} L_0 s - \frac{E_f L_0 s + \delta}{Z_s} \right]$$

$$S_{dev} = \frac{V E_f}{Z_s} L_0 s - \delta - \frac{E_f^2}{Z_s} L_0 s \quad \text{--- (3.)}$$

$$\text{Now; } P_{dev} = \frac{V E_f}{Z_s} \cos(\theta_s - \delta) - \frac{E_f^2}{Z_s} \cos \theta_s$$

$P_{dev}$  is max<sup>M</sup> when  $\theta_s = \delta$  & this decides steady state stability limit of the motor.

$$P_{dev}(\max) = \frac{V E_f}{Z_s} - \frac{E_f^2}{Z_s} \cos \theta_s$$

$$S_{in} = P_{in} + jQ_{in}$$

$$= E \cdot \vec{V} \cdot \vec{I}_q^*$$

$$= V \left[ \frac{V}{Z_s} L_0 s - \frac{E_f L_0 s + \delta}{Z_s} \right]$$

$$S_{in} = \frac{V^2}{Z_s} L_0 s - \frac{V E_f}{Z_s} L_0 s + \delta \quad \text{--- (4.)}$$

$$P_{in} = \frac{V^2}{Z_s} \cos \theta_s - \frac{V \cdot E_f}{Z_s} \cos(\theta_s + \delta)$$

Neglecting  $R_q \rightarrow$

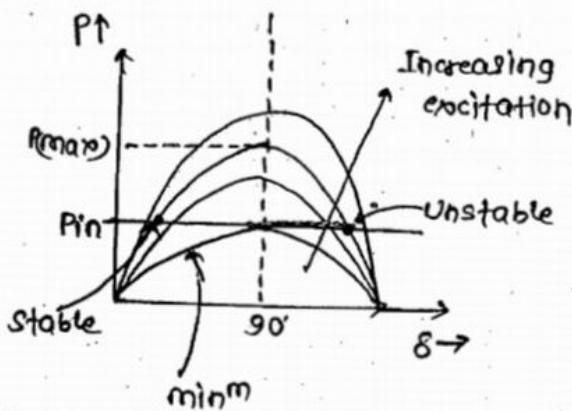
$R_q = 0$ ; then  $Z_s = X_s$ ,  $\theta_s = 90^\circ$

Gen<sup>r</sup> →  $P_{out} = P_{dev} = P = \frac{V \cdot E_f \cdot \sin \delta}{X_s}$

motor →  $P_{dev} = P_{in} = P = \frac{V \cdot E_f \cdot \sin \delta}{X_s}$

$\therefore P_{max} = \frac{E_f V}{X_s}$  at  $\delta = 90^\circ$

$$P = P_{max} \sin \delta$$



\* Reactive Power →

Gen<sup>r</sup> →

$$Q_{out} = \frac{V}{X_s} (E_f \cos \delta - V)$$

Gen<sup>r</sup> →

Case(i) →

when  $E_f \cos \delta = V$  i.e. normally excited gen<sup>r</sup> then  $Q_{out} = 0$ .

And therefore operating at UPF.

case(ii) →

when  $E_f \cos \delta$  is more than  $V$  i.e. over-excited gen<sup>r</sup> then  $Q_{out} = +ve$

i.e. supplying lagging VARs. And therefore operating at lagging PF.

case(iii) →

when  $E_f \cos \delta$  is less than  $V$  i.e. under-excited gen<sup>r</sup>, then  $Q_{out} = -ve$

i.e. supplying leading VARs & therefore operating at leading PF.

motor →

case(i) →

when  $E_f \cos \delta = V$ ; i.e. normally excited gen<sup>r</sup> then  $Q_{out} = 0$

& therefore operating at UPF.

Case(ii) →

when  $E_f \cos \delta > V$ ; i.e.  $Q_{out} = -ve$  i.e. taking leading VARs & ∴ operating at leading VARs.

Case(3) →

when  $E_f \cos \delta < V$ ; i.e. underexcited motor then  $Q_{in} = +ve$  i.e. absorbing lagging VAR & ∴ operating at lagging PF.

\* Effect of change in excitation at constant ( $k_w$ ) o/p →

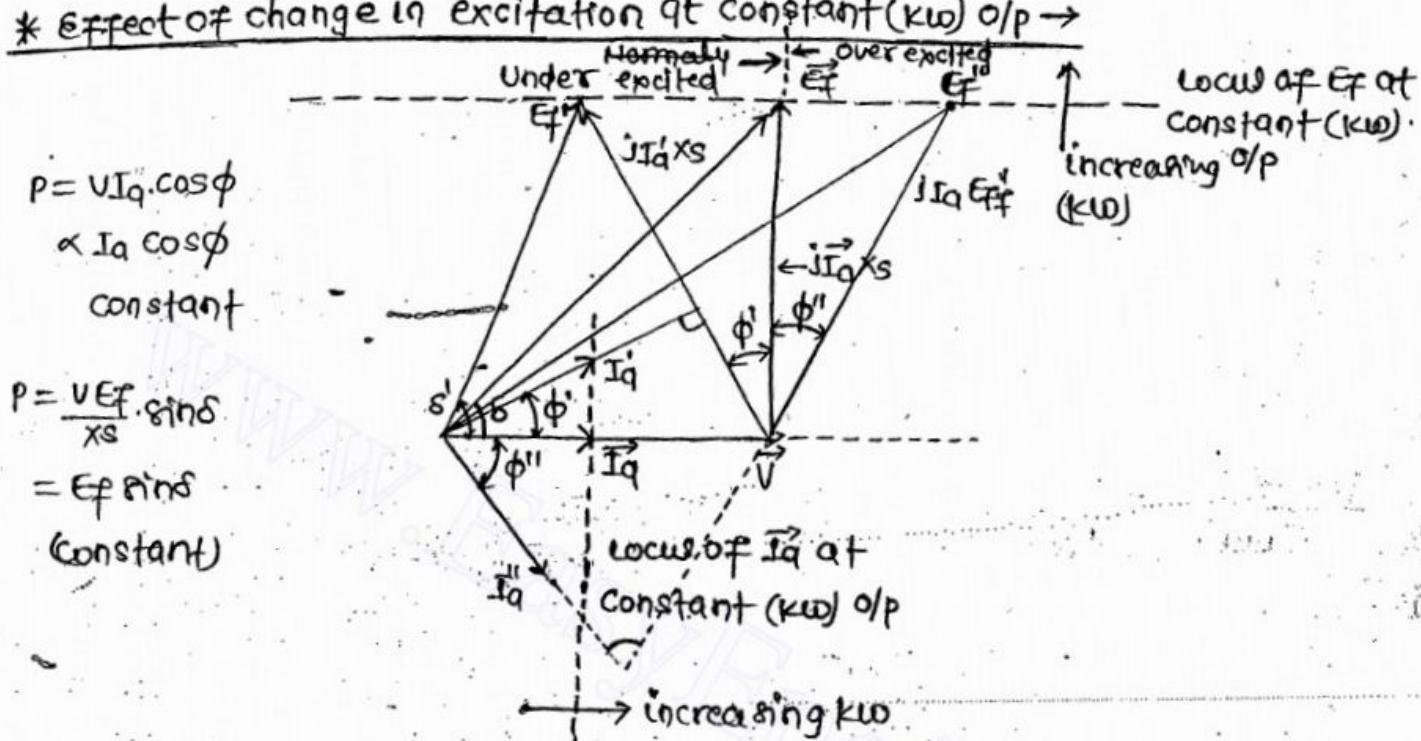


fig → Gen

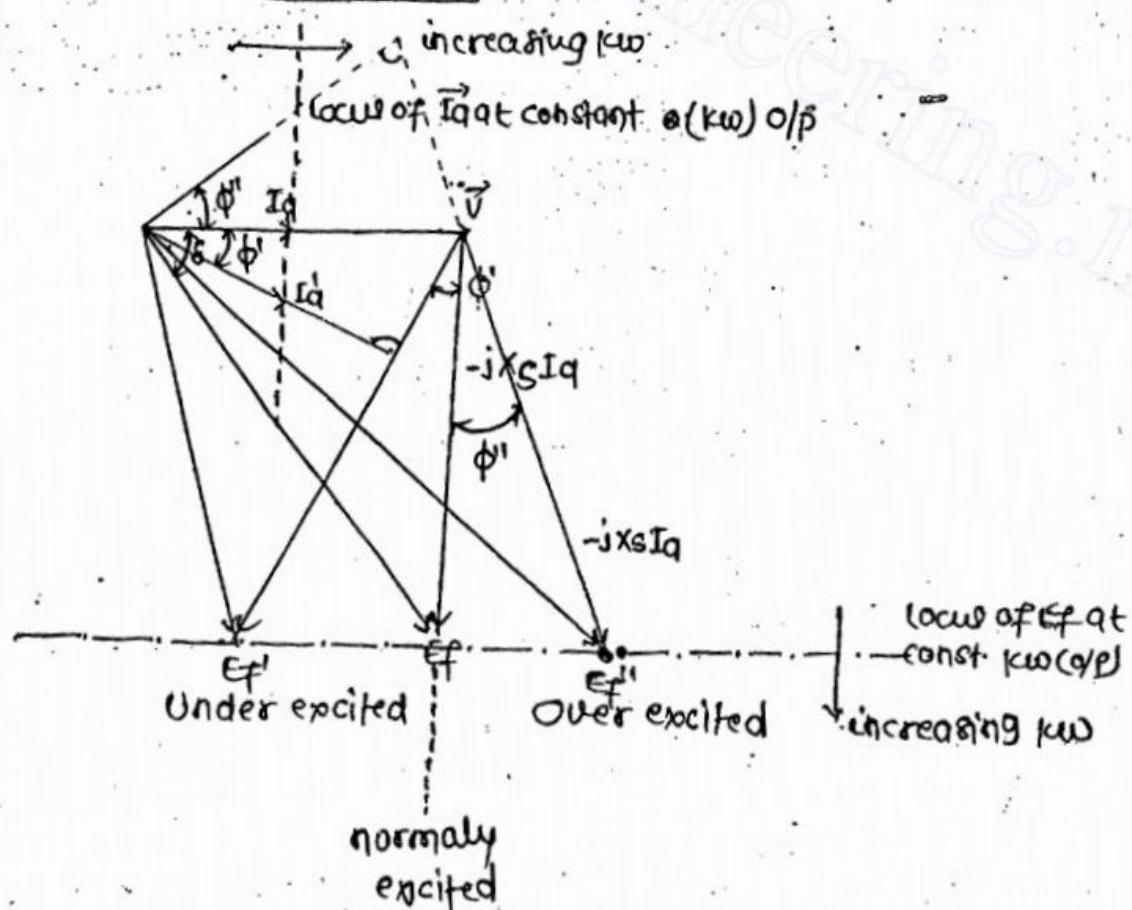


fig. → motor

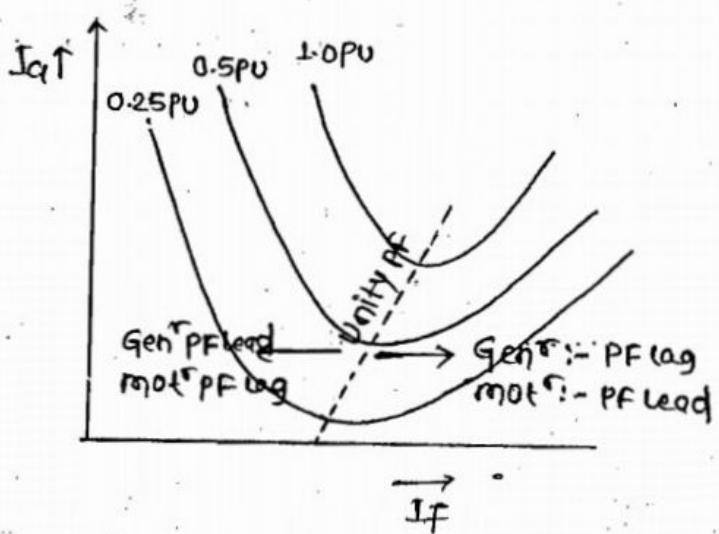


Fig:- Syn. m/c 'V' curves.

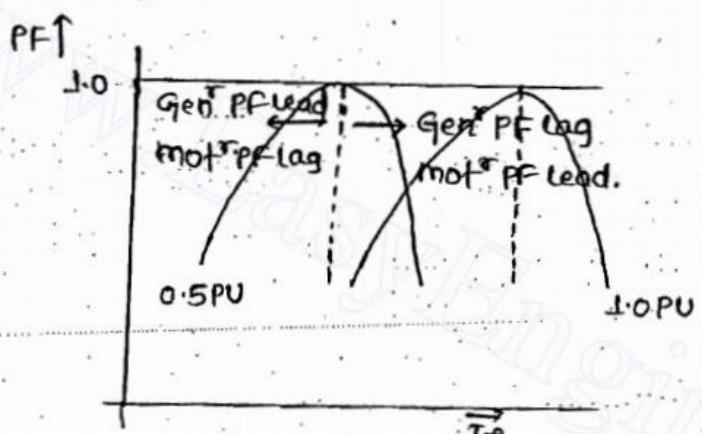
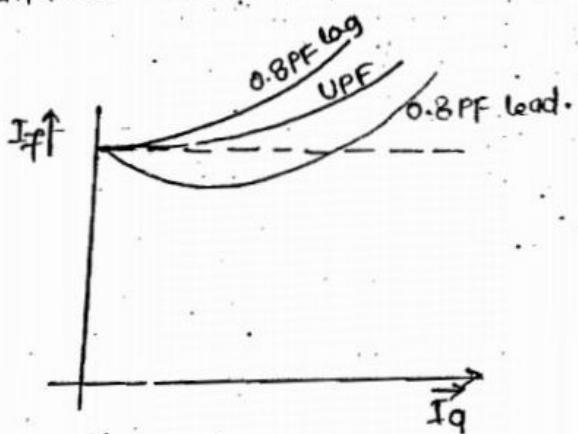


Fig:- syn. m/c inverted 'V' curves.

\* Compounding curve of a gen<sup>r</sup> shows the variation of the field current req. to maintain constant terminal vol. when a const. pf load is varied.



gen<sup>r</sup> compounding curves.

Que. → A cylindrical rotor syn. gen<sup>r</sup> with syn. reactance of 1.6 p.u. & negligible arm. reactance is connected to an  $\infty$  bus at rated vol. (a.) Determine the excitation emf & power angle when it delivers full load current at 0.8 PF lag.

Hence cal. VR<sup>n</sup> of the gen<sup>r</sup>.

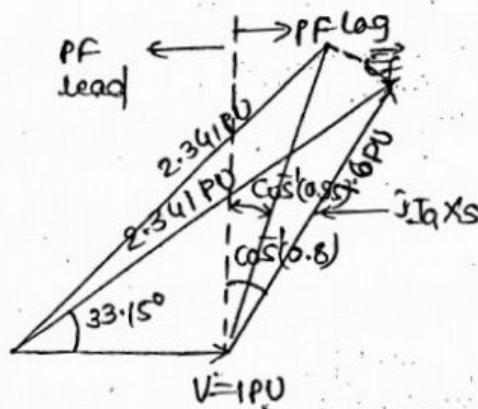
Sol<sup>n</sup>

$$X_S = 1.6 \text{ p.u}$$

$$E_f = V + j I_a X_S$$

$$= 1.0^\circ + j 1 / -\cos(0.8) \times 1.6$$

$$E_f = 2.341 \text{ p.u} \angle 33.15^\circ$$



$$\therefore VR^n = E_f (\text{p.u}) - 1$$

$$= 2.341 - 1$$

$$VR^n = 1.341 \text{ p.u} = 134.1 \times$$

(b.) With the excitation of pt(a) the gen<sup>r</sup> is made to operate at 0.95 PF lag. calculate the corresponding arm. current & power angle?

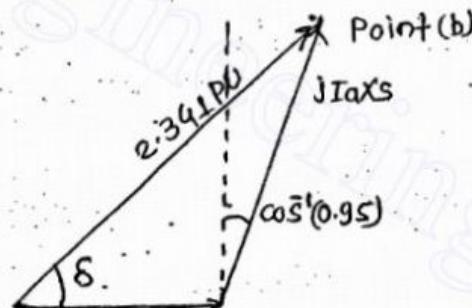
Sol<sup>n</sup>

$$E_f = V + j I_a X_S$$

$$2.341 \angle 33.15^\circ = 1.0^\circ + j 1.6 I_a (1.6) I_a / -\cos(0.95)$$

$$2.341 \angle 33.15^\circ = 1 + 1.6 I_a \angle 71.81^\circ$$

$$= [1 + 1.6 I_a \cos(71.81)] + j 1.6 I_a \sin(71.81)$$



Squaring & equating magnitudes

$$(2.341)^2 = 1^2 + 2 \times 1 \times 1.6 I_a \cos(71.81) + (1.6 I_a)^2$$

$$(1.6)^2 I_a^2 + 2 \times 1.6 I_a \cos 71.81 + (1 - 2.341)^2 = 0$$

By solving eqn

$$I_a = 1.142 \text{ p.u}$$

$$\text{from (1)} \quad \delta = \angle [1 + 1.6 \times 1.142 \angle 71.81]$$

$$\therefore \delta = 47.87^\circ$$

With the excitation as part (a), determine the max<sup>m</sup> power o/p & the corresponding arm. current & PF.

$$\text{Soln} \rightarrow P_{\max} = \frac{V \cdot E_F}{X_S} \quad (\text{at } \delta = 90^\circ)$$

$$= \frac{1.0 \times 2.341}{1.6} \text{ PU}$$

$$= 1.4631 \text{ PU}$$

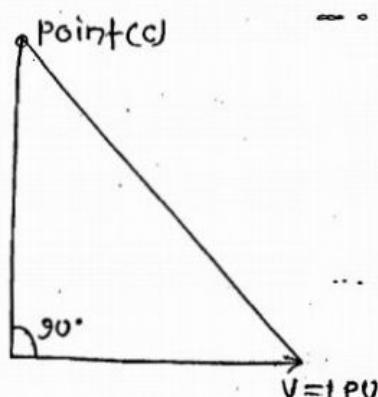
$$I_q = \frac{E_F - V}{J X_S}$$

$$= \frac{2.341 / 90^\circ - 1}{1.6j}$$

$$I_q = 1.591 / 23.130$$

$$\text{PF} = \cos(23.130) \text{ leading}$$

$$\boxed{\text{PF} = 0.9196}$$



calc'n check

$$V I \cos \phi = P_{\max}$$

$$1.0 \cdot I_q \times 0.9196 = 1.4631$$

(b) If the steam i/p of part (a) remains unchanged calc. the excitation emf & power angle at which PF becomes 0.95 lagging.

$$\text{Soln} \rightarrow P = V I_q \cos \phi$$

$$\propto I_q \cos \phi$$

constant

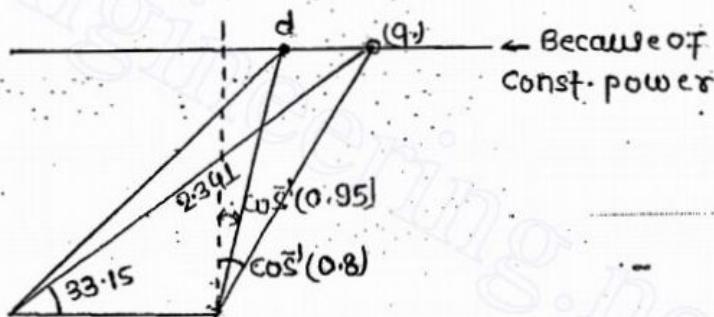
$$I_{q2} \cos \phi_2 = I_{q1} \cos \phi_1$$

$$I_{q2} \cdot (0.95) = (1.0) \times 0.8$$

$$I_{q2} = 0.8421 \text{ PU}$$

$$\vec{E}_{F2} = 1.0 + j 0.8421 \angle -\cos^{-1}(0.95) \times 1.6$$

$$\boxed{\vec{E}_{F2} = 1.9123 / 42.02^\circ \text{ PU}}$$



(c) If the steam i/p of part (a) remains unchanged calc. the excitation emf & PF at which PF becomes 0.85 leading.

$$\text{Soln} \rightarrow I_{q2} \cos \phi_2 = I_{q1} \cos \phi_1$$

$$I_{q2}(0.85) = 1.0 \times 0.8$$

$$I_{q2} = 0.9411$$

$$\vec{E}_{F2} = 1.0 + j 0.9411 \angle \cos^{-1}(0.85) \times 1.6$$

$$\boxed{\vec{E}_{F2} = 1.297 / 80.822 \text{ PU}}$$

(f) Cal. the min<sup>m</sup> excitation emf for the same steam i/p as in part (a) & determine corresponding arm. current & PF?

Sol<sup>n</sup>  $P = VI \cos \phi$   
 $\propto I \cos \phi$

Alternative (1)  $\rightarrow$  when  $P_{in}$  is given

$$P = 1 \times 1 \times 0.8$$

$$P = 0.8 \text{ PU}$$

$$0.8 = \frac{V \times E_f(\min)}{X_S}$$

$$E_f(\min) = \frac{1.6 \times 0.8}{1}$$

$$E_f(\min) = 1.28 \text{ PU}$$

Alternative (2)  $\rightarrow$  when  $P_{in}$  is not given

$$P = \frac{V \cdot E_f \cdot \sin \delta}{X_S}$$

$$\propto E_f \sin \delta = \text{constant}$$

$$E_f_2 \sin \delta_2 = E_f_1 \sin \delta_1$$

$$E_f(\min) \sin 90^\circ = 2.341 \times \sin(33.15^\circ)$$

$$E_f(\min) \approx 1.28 \text{ PU}$$

$$Iq_2 = \frac{1.28 / 90^\circ - 1 / 0^\circ}{1.6j} = 1.0152 / 38^\circ \text{ PU}$$

$$PF = \cos 38^\circ (\text{leading})$$

$$PF = 0.788 (\text{leading})$$

(g) If the steam i/p of (a) unchanged but the excitation is increased by 30% cal. the new arm. current & PF

Sol<sup>n</sup> Alternative (1)  $\rightarrow$  when  $P_{in}$  is given

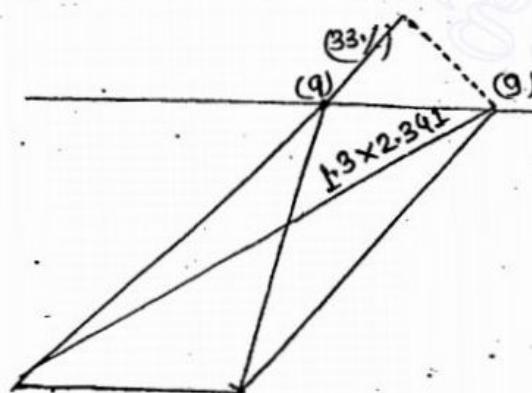
$$P = VI \cos \phi = 1 \times 1 \times 0.8$$

$$P = 0.8 \text{ PU}$$

$$P_{\max} = \frac{V \cdot E_f \cdot \sin \delta}{X_S}$$

$$0.8 = \frac{1 / 0^\circ \times 1.3 \times 2.341 \sin \delta_2}{1.6}$$

$$\delta_2 = 24.87^\circ$$



Alternative(2) → when p is not given

$$P = \frac{E_f \cdot V}{X_s} \sin \delta$$

$$\propto E_f \sin \delta$$

constant

$$E_{f2} \sin \delta_2 = E_{f1} \sin \delta_1$$

$$(1.3 E_{f1}) \sin \delta_2 = E_{f1} \sin(33.15^\circ)$$

$$\delta_2 = 24.87^\circ$$

$$I_{q2} = \frac{1.3 \times 2.341 / 24.87^\circ - 1.10}{1.6j}$$

$$= 1.3607 L - 53.99^\circ \text{ PU}$$

$$\therefore PF = \cos(53.99^\circ) (\text{lagging})$$

$$= 0.5839 (\text{lagging})$$

(H) For a power angle of  $20^\circ$  cal. the 2 possible values of excitation emf, if the gen' delivers 30% of FL current.

Determine corresponding PF & power o/p.

Soln → ( $\delta = 20^\circ$ )

$$I_q = \frac{E_{f1} / 0}{X_s}$$

$$0.3 I_q = \frac{E_{f2} - 1}{1.6}$$

$$P = \frac{V \cdot E_{f1} \sin \delta}{X_s}$$

$$I_q = \frac{E_{f1} - 1}{1.6}$$

$$0.3 \times 1.6 I_q = E_{f2} - 1$$

$$P = \frac{1 \times E_{f1} \sin(20^\circ)}{1.6}$$

$$1.6 I_q = E_{f1} - 1$$

$$E_{f2} = 0.48 I_q + 1$$

$$P = 0.213 E_{f1}$$

$$- 1.6 I_q + E_{f1} = 1$$

$$E_f / 20^\circ = 1.0^\circ + j 0.3 / \phi + 1.6$$

( $\phi$  is +ve for leading PF)

$$E_f / 20^\circ = 1 + 0.48 / (90 + \phi)$$

$$0.48 / (90 + \phi) = E_f / 20^\circ - 1$$

$$= E_f \cos 20^\circ + j E_f \sin 20^\circ - 1$$

$$0.48 / (90 + \phi) = (E_f \cos 20^\circ - 1) + j E_f \sin 20^\circ \quad \text{--- (1)}$$

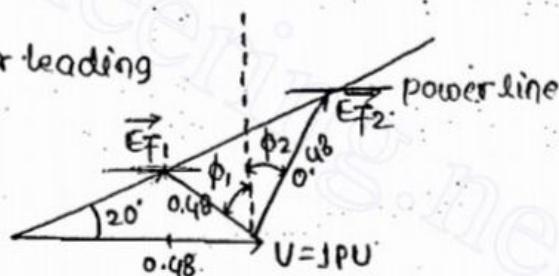
squaring & equating.

$$(0.48)^2 = E_f^2 - 2 E_f \cos 20^\circ + 1$$

$$E_f^2 - 2 E_f \cos 20^\circ + (1 - 0.48^2) = 0$$

$$E_f = 1.278, 0.6029$$

$$E_f = 0.6029, 1.28 \text{ PU}$$



Low excitation →

$$90^\circ + \phi = \sqrt{[0.6029 / 20 - 1]} \\ = 154.26^\circ$$

$$\phi = 64.56^\circ$$

$$PF = 0.4296 \text{ (leading)}$$

$$P = 1 \times 0.30 \times 0.4296$$

$$P = 0.1289 \text{ PU}$$

High excitation →

$$90^\circ + \phi = \sqrt{[1.2765 / 20 - 1]} \\ = 65.44^\circ$$

$$\phi = -24.56^\circ \text{ leading}$$

$$= 24.56^\circ \text{ lagging}$$

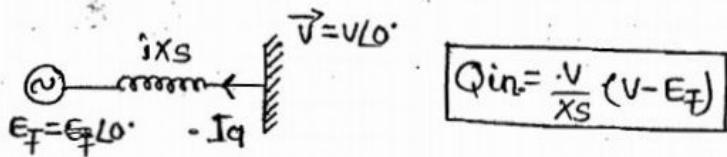
$$PF = \cos 24.56^\circ \text{ lagging}$$

$$= 0.9095 \text{ (lag)}$$

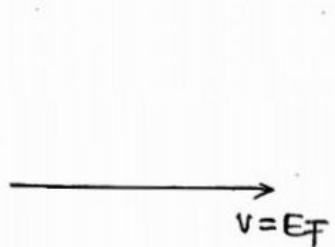
$$P = 1 \times 0.30 \times 0.9095$$

$$P = 0.2729 \text{ PU}$$

Synchronous Condenser  $\rightarrow$  (Synchronous phase advancing, syn. capacitor)

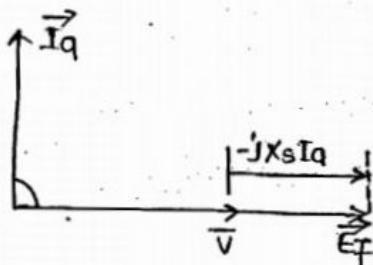


$$Q_{in} = \frac{V}{X_s} (V - E_f)$$

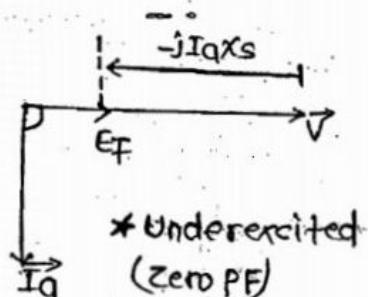


(Indetermined PF  
Because  $I_q = 0$ )

\* Normally excited -



\* Overexcited  
(zero PF lead)



\* Underexcited  
(zero PF)

\* Underexcited - absorbing lagging VARs.

✓ syn. compensator (actual name)

\* syn. phase modifier

- Note:-
- (1) If big m/c is operating without prime mover & shaft  $\rightarrow$  syn. com.
  - (2) The dia. of shaft is kept small because of operating on NL.
  - (3) It is wed 200 MUARS (upto)
  - (4) It gives clean Reactive powers (like w/o harmonics)

$$\text{Gen} \rightarrow Q_{out} = \frac{V}{X_s} (E_f \cos \delta - V)$$

If  $E_f = 0$ ,  $\cos \delta = 90^\circ$

$$Q_{out} = -\frac{V^2}{X_s}$$

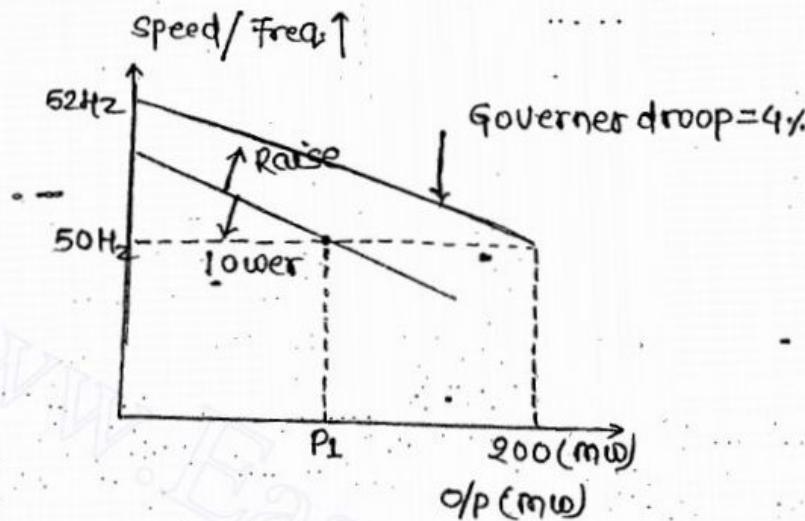
$$Q_{out} = -V^2 \times SCR$$

$\downarrow$   
(line charging capacity)

- \* Turbogen<sup>r</sup> are situated at load center so req. less  $X^2$  line & the SCR is low but hydrogen<sup>r</sup> is situated at different area so req. more  $X^2$  line & SCR is high for those.

\* Parallel Operation of gen<sup>r</sup> →

\* The ele. aspects of parallel operation of syn. gen<sup>r</sup> would be handled by Millmens theorem exactly similar as in parallel operation of TF with unequal voltage Ratio.



$$\star \text{ Governor Regn} = \frac{52\text{Hz} - 50\text{Hz}}{52\text{Hz} - 50\text{Hz}} = \frac{2\text{Hz}}{50\text{Hz}} = 0.04 \text{ pu} / 4\%$$

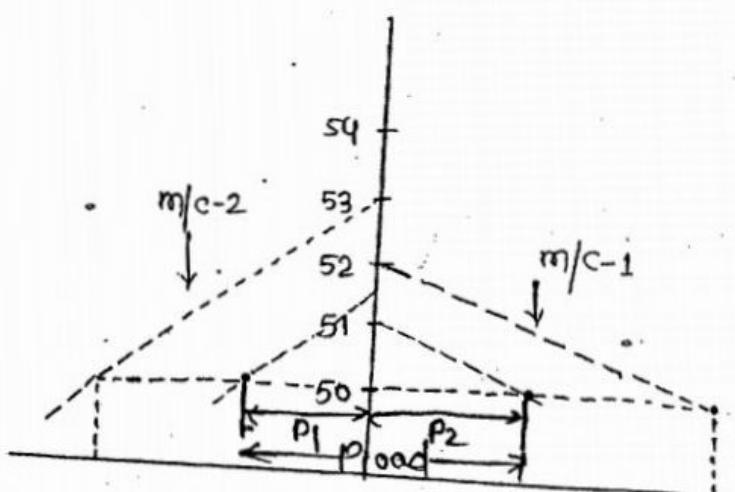
(OR)

$$\text{Droop} = \frac{52\text{Hz} - 50\text{Hz}}{200\text{MW}} = 0.01 \text{ Hz/MW}$$

when once droop is decided then it is not changed.

\* Control gear also known as speeder gear / speed changer is a device that simply shifts the governor c/s <sup>parallel</sup> to itself on being given a raise or lower command. (above dia.)

$$\text{In pu (droop)} = \frac{1.04 - 1.00}{1.00} = 4\%$$



Que. → 2 identical 2000kW, 50Hz alternator operate in parallel. The governor of the 1st m/c is such that the freq. rises uniformly from 50Hz on NL to 52.5Hz on FL. The corresponding uniform freq. rise of 2nd m/c is 50Hz to 52.5Hz.

(a) If each m/c is fully loaded at rated freq. what would be load in each m/c when total load is reduced 2560kW.

(b) Calc. the max<sup>m</sup> load at which one of the m/c would become unloaded?

Sol<sup>n</sup> → (a) →

m/c A

$$\frac{P_A}{2000} = \frac{52-F}{52-50} \quad \text{--- (A)}$$

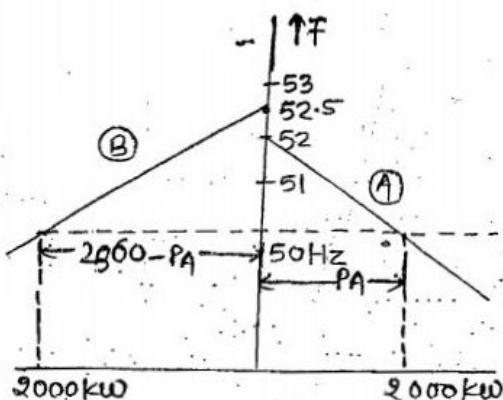
m/c B

$$\frac{2560-P_A}{2000} = \frac{52.5-F}{52.5-50} \quad \text{--- (B)}$$

Solving eqn (A) & (B).

$$P_A = 1200 \text{ kW}, P_B = 2560 - 1200 \\ = 1360 \text{ kW}$$

$$F = 50.8 \text{ Hz}$$



(b) →

$$\frac{P_L}{2000} = \frac{52.5-50}{52.5-50}$$

$$P_L = 4000 \text{ kW}$$

Que. → 2 identical 2000kW alternators operate in parallel. The governor of the 1st m/c is such that the freq. drop uniformly from 50Hz on NL to 49.5Hz on FL. The corresponding uniform freq. drop of 2nd m/c is 50Hz to 47.5Hz.

(a) How will the 2-m/c share the load of 2880kWs.

(b) What is the max<sup>m</sup> load that can be delivered w/o overloading either m/c.

Sol<sup>n</sup> →

Q) →

$$\frac{P_A}{2000} = \frac{50-F}{50-48} \quad \text{--- (A)}$$

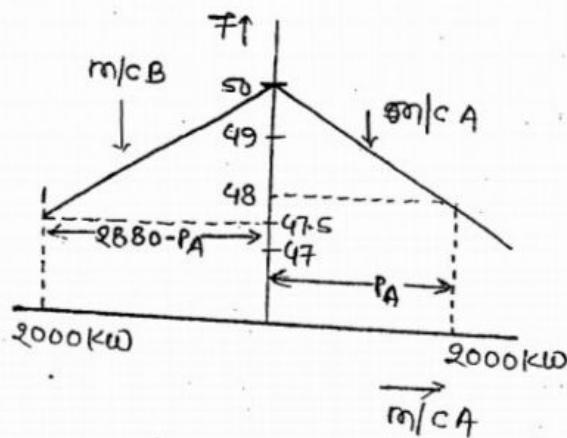
$$\frac{2880-P_A}{2000} = \frac{50-F}{50-47.5} \quad \text{--- (B)}$$

Solving eqn A & B

$$P_A = 1600 \text{ kW}, F = 48.4 \text{ Hz}$$

$$\text{Then, } P_B = 2880 - 1600$$

$$= 1280 \text{ kW}$$



(b.) →

$$\frac{P_B}{2000} = \frac{50-48}{50-47.5}$$

$$P_B = \frac{2000 \times 2}{2.5} = 1600 \text{ kW}$$

$$P_{\text{load}}(\text{max}) = 2000 + 1600 \\ = 3600 \text{ kW}$$

$$\boxed{P_{\text{load}}(\text{max}) = 3600 \text{ kW}}$$

## \* Synchronization →

Condition to be satisfied →

- (1) Equal freq.
- (2) Equal voltage
- (3) Same polarity in 1-φ gen & same phase seq. in 3-φ gen
- (4) Zero phase difference at instant of synchronization.
- (5) Same waveforms.

## Synchronization by synchroscope →

- (1) Match the freq. of the incoming m/c with that of the running m/c. It is recommended that the incoming freq. be kept slightly higher.

\*(2) match the incoming vol. with the running vol. It is again recommended that the incoming vol. be kept slightly higher

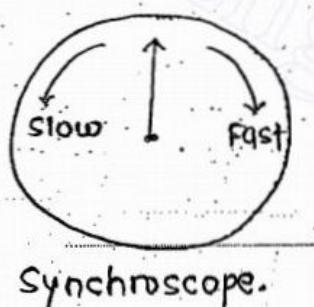
\*(3) switch ON the synchroscope & also the check synchronization relay if such relay is available. Switch off antimotoring protection if provided.  
(4)

\*(4) Fine control the incoming freq. such that the synchroscope pointer moves very slowly in the fast dirn. when the pointer reaches 11 o'clock position, give a command to the CB switch to close the breaker.

It is expected that the breaker contacts would actually close at 12 o'clock position, a position that represents zero phase diff.

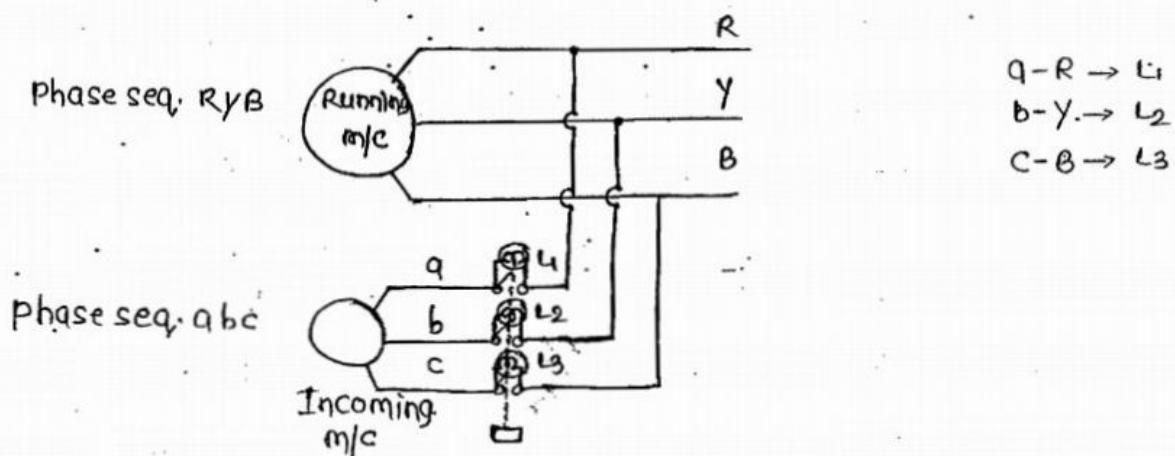
\*(5) Switch-off the synchroscope & also check synchronization relay. Take min<sup>m</sup> recommended load on the unit & adjust excitation for desired PF of operation.

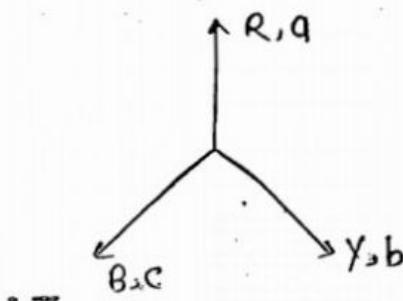
\*(6) After taking sufficient load on the unit switch on the antimotoring protection switch.



Synchroscope.

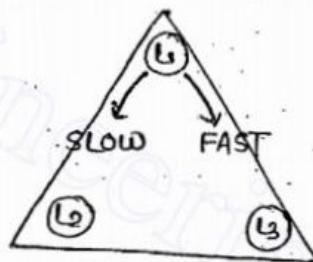
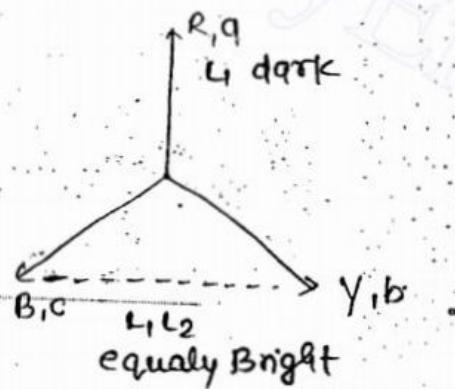
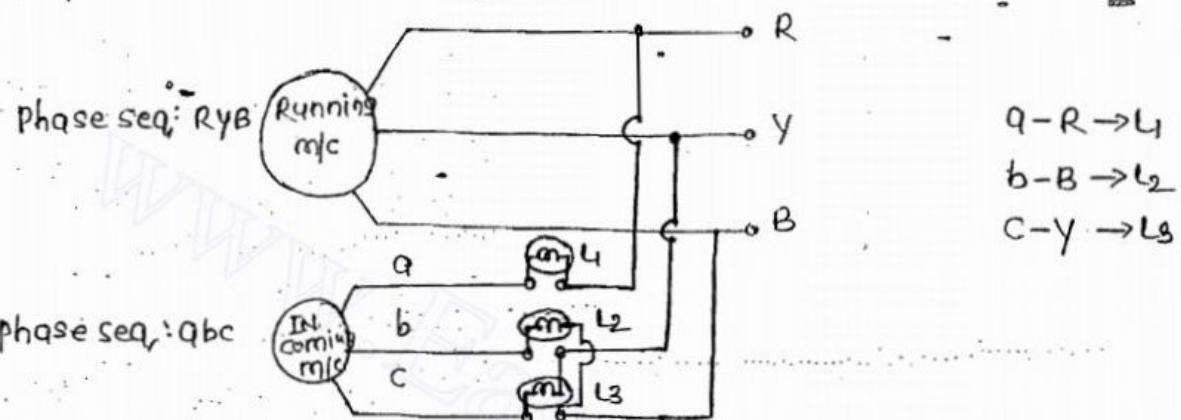
\* Dark Lamp Method → (Kothari/Ashphaa)





$L_1, L_2, L_3$  dark then synchronise.

\* Rotating Lamp method  $\rightarrow$  (Dark & bright method) (siemens & HALSKE method)



Sequence  $\rightarrow$

$L_1 - L_3 - L_2$ ; Incoming m/c is Fast.

$L_1 - L_2 - L_3$ ; Incoming m/c is slow.

5.10/600

Que.  $\rightarrow$  A syn. m/c is synchronised with an  $\infty$  bus at rated vol. Now the steam i/p to prime mover is increased. If the syn. m/c starts operating at rated kVA. The m/c has syn. imp.  $z_s = 0.02 + j0.8$  pu. Determine the operating pf of alternator & its load angle.

### Analytical approach →

Soln.  $Z_s = 0.02 + 0.8j \text{ PU}$ ,  $\text{PF} = ?$ ,  $\delta = ?$   
 $= 0.80025 / 88.57^\circ$   $\cos\phi = ?$ ,  $\delta = ?$

$$E_f = V + I_a R_a ; \quad \cos\phi = \frac{kVA}{VI}$$

$$E_f = 1/\delta, V = 1/0^\circ, I_a = 1/\phi$$

$\therefore$

$$1/\delta = 1/0^\circ + 1/\phi (0.80025 / 88.57^\circ)$$

$$1/\delta = 1 + 0.80025 / (25.57 + \phi)$$

$$0.80025 / 88.57^\circ + \phi = 1/\delta - 1 \quad \text{(i)}$$

$$0.80025 / (88.57^\circ + \phi) = (\cos\delta - 1) + j \sin\delta$$

squaring & equate eqn

$$(0.80025)^2 = 1 - 2\cos\delta + 1$$

$$\delta = 44.17^\circ$$

Putting in eqn (i)

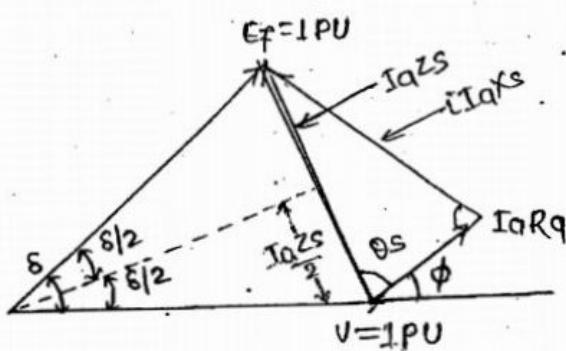
$$(88.57^\circ + \phi) = \frac{[1/44.17^\circ - 1]}{1/88.57^\circ} = 113.59^\circ$$

$$\phi = 25.02^\circ$$

$$\text{PF} = \cos(25.02^\circ) \text{ leading}$$

$$\boxed{\text{PF} = 0.9062 \text{ leading}}$$

### Graphical Approach →



$$\theta_s + \phi = 90^\circ + \frac{\delta}{2}$$

$$\phi = (90 - \theta_s) + \frac{\delta}{2} \text{ (leading)}$$

$$\sin \frac{\delta}{2} = \frac{I_a Z_s / 2}{V}$$

$$\frac{\delta}{2} = \sin^{-1} \left[ \frac{1.0 \times 0.80025}{1.0 \times 1.0} \right]$$

$$= 23.586^\circ$$

$$\delta = 47.17^\circ$$

$$\phi = (90^\circ - 88.57) + 23.586^\circ$$

$$\boxed{\phi = 25.02^\circ}$$

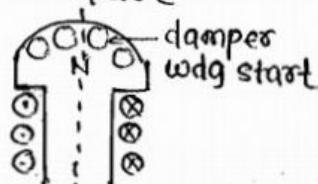
## Synchronous motor starting

**ON-LOAD START**

miable freq.  
start

$$\frac{V}{f} = \text{constant}$$

Damper wdg  
start



- \* Syn induction motor
- \* Hunting phenomenon

No Load start

Auxillary (PONY) moto start

Inductionmotor

dc motor

$$P = \text{No. of SM Poles}$$

If SM poles  
are large in no.  
then  $P = SM - 2$

Speed control available  
(synchronise as gen later  
remove pony motor)

Speed control not available  
Do as with Im.

Ques. → A 3-φ-Δ connected load takes 50A current at 0.707 lagging PF with 220V b/w the lines. A 3φ Δ connected round rotor syn. motor having a syn. reactance of  $1.27\Omega/\phi$  is connected in parallel with the load. The power developed by motor is 33kW at a power angle of  $30^\circ$ . Calculate the overall PF of the motor & the load.

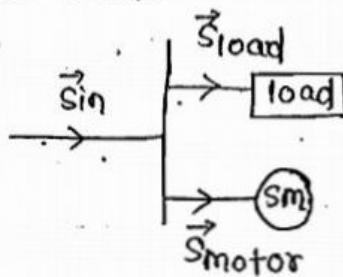
Soln →

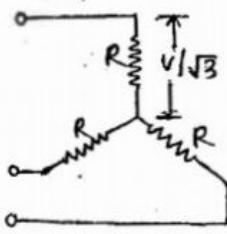
$$\begin{aligned}\vec{S}_{\text{load}} &= \sqrt{3} \times 220 \times 50 / \cos(0.707) \text{ VA} \\ &= 19.053 \angle 45^\circ \text{ kVA}\end{aligned}$$

$$P = V \times E_f \sin \theta$$

$$33 \times 10^3 = \frac{220 \times E_f \sin 30^\circ}{1.27}$$

$$E_f = 381 \text{ Volts (L-L)}$$





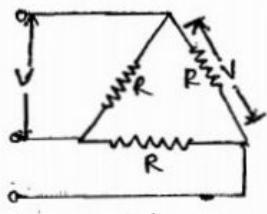
$$P_{1-\phi} = \frac{(V/\sqrt{3})^2}{R} = \frac{V^2}{3R}$$

$$P_{3-\phi} = 3 \times P_{1-\phi} = 3 \times \frac{V^2}{3R}$$

$$P_{3-\phi} = \frac{V^2}{R}$$

$$\boxed{P_{1-\phi} = \frac{V^2}{3R}}$$

$$\boxed{P_{3-\phi} = \frac{V^2}{R}}$$



$$P_{1-\phi} = \frac{V^2}{R}$$

$$P_{3-\phi} = 3 \times P_{1-\phi}$$

$$P_{3-\phi} = \frac{3V^2}{R}$$

$$\boxed{P_{1-\phi} = \frac{V^2}{R}}$$

$$\boxed{P_{3-\phi} = \frac{3V^2}{R}}$$

$$Q_{\text{motor}} = \frac{V}{X_S} (V - E_f \cos \phi)$$

$$= \frac{220}{1.27} (220 - 381 \cos 30^\circ)$$

$$= -19.047 \text{ kVAR (leading VARS)}$$

$$\vec{s}_{\text{motor}} = (33 - j19.047)$$

$$\vec{s}_{\text{in}} = \vec{s}_{\text{load}} + \vec{s}_{\text{motor}}$$

$$= 46.806 L - 6.84^\circ \text{ kVA}$$

$$\text{Overall PF} = \cos(6.84) \text{ (leading)}$$

$$= 0.9929 \text{ (leading)}$$

$$\boxed{\text{PF} = 0.9929}$$

5.5  
590

A 230V, 4P 50Hz L connected syn. motor has  $R_q + jX_S = (0.6 + j3) \Omega/\phi$ . Its field current is so adjusted that the motor draws 10A at UPF from rated vol. cond. Now with field current unchanged load on the motor increase till it draws 40A from supply. Find the torque dev. & new PF.

SOL At UPF  $E_f = \frac{230 L 0^\circ}{\sqrt{3}} - 10 L 0^\circ \times (0.6 + j3)$

$$= 130.29 L - 13.81^\circ \text{ volt (L-N)}$$

When load is increased →

$$130 \cdot 29 L - \delta_2 = \frac{230}{\sqrt{3}} 60^\circ - 40 L - \phi_2 \times 3 \cdot 06 / 78 \cdot 89^\circ$$

$$130 \cdot 29 L - \delta_2 = 132 \cdot 79 - 122 \cdot 4 [78 \cdot 69^\circ - \phi_2]$$

$$= [132 \cdot 79 - 122 \cdot 4 \cos(78 \cdot 69^\circ - \phi_2)] - j [122 \cdot 4 \sin(78 \cdot 69^\circ - \phi_2)]$$

Squaring & equating magnitudes

$$\cos(78 \cdot 69^\circ - \phi_2) = 0.4811$$

$$\phi_2 = 17.45^\circ \text{ lagging}$$

$$\text{New PF} = \cos(17.45^\circ) \text{ lagging}$$

$$\boxed{\text{New PF} = 0.954 \text{ lagging}}$$

$$P_{dev} = P_{in} - \text{Total arm. cu loss}$$

$$= \sqrt{3} \times 230 \times 40 \times 0.954 - 3 \times 40^2 \times (R_q = 0.6)$$

$$\boxed{P_{dev} = 12321.86 \text{ Watts.}}$$

$$T_{dev} = \frac{P_{dev}}{\omega_{SM}}$$

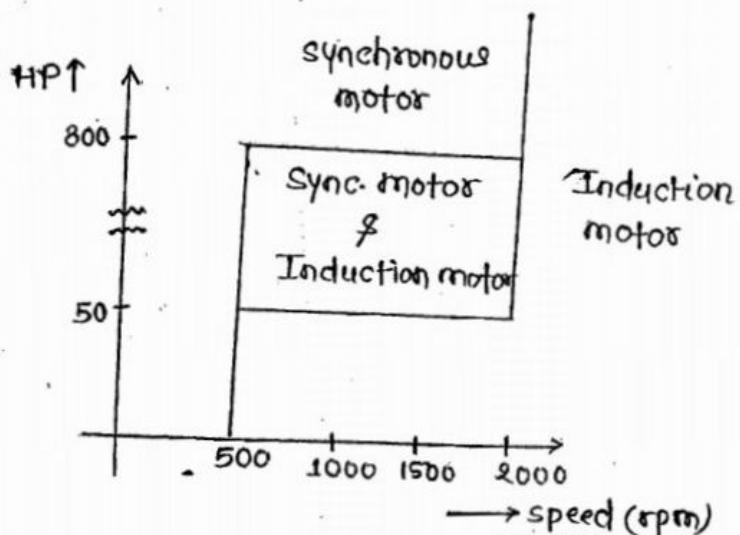
$$= \frac{12321.86}{\frac{2}{(P=4)} \times 2\pi f}$$

$$= \frac{12321.86}{(1/2) \times 2\pi \times 50}$$

$$\boxed{T_{dev} = 78.44 \text{ N-m}}$$

$$\left\{ \begin{array}{l} \therefore \omega_{SM} = \frac{2\pi f N_S}{60} = \frac{2\pi}{60} \times \frac{1200}{P} \\ \omega_{SM} = \frac{D}{P} \times 2\pi f \end{array} \right.$$

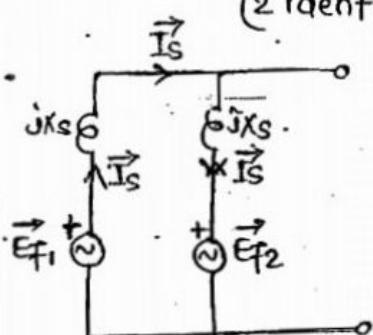
**MOTOR APPLICATION  
GUIDE**



- \* Below 500 rpm ind<sup>n</sup> motor not is use (12P) & above 2000 rpm. syn. motor is not in use.
- \* Below 50 HP use Ind<sup>n</sup> motor & above HP 800 only syn. motor.
- \* (50HP-800HP) & (500-2000) RPM both is available.
- \* squirrel cage SM is popular because of
- \* SM speed is not effected by voltage whereas IM highly affected by vol. variation.

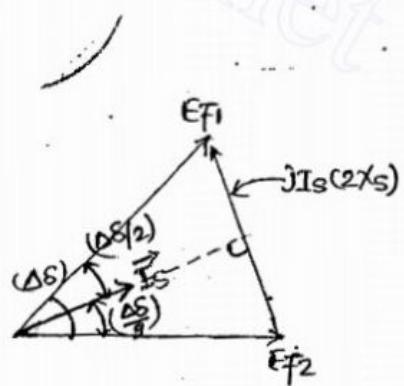
**SYNCHRONISING  
POWER**

(2 identical m/e on No-load)



$$E_{F1} = E_{F2} = E_F$$

Before disturbance



$$\sin \frac{\Delta\delta}{2} = \frac{I_S X_S}{E_F}$$

$$I_S = \frac{E_F}{X_S} \sin \frac{\Delta\delta}{2}$$

- \* Due to incoming disturbance in the m/c there will be an excitation occurs & then  $E_f_2$  will be excited by  $(\Delta\delta)$  with  $E_f_1$ .
- \* m/c-1 (work as gen & source) will decelerate this increase in the excitation & the m/c-2 (work as motor & sink) will accelerate.
- \* The amount of power which is going away from gen & coming into motor is equal in amount is known as synchronising power. i.e. the power used for synchronising the excitation is.

$$\text{Synchronising power } P_s = \Delta P = E_f \cdot I_s \cdot \cos \frac{\Delta\delta}{2}$$

$$= E_f \left[ \frac{E_f}{X_s} \sin \frac{\Delta\delta}{2} \right] \cos \frac{\Delta\delta}{2}$$

$$P_s = \Delta P = \frac{E_f^2}{2X_s} \sin(\Delta\delta) \text{ watts}$$

Since;  $\Delta\delta$  is very small,

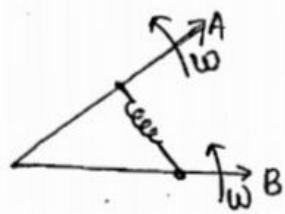
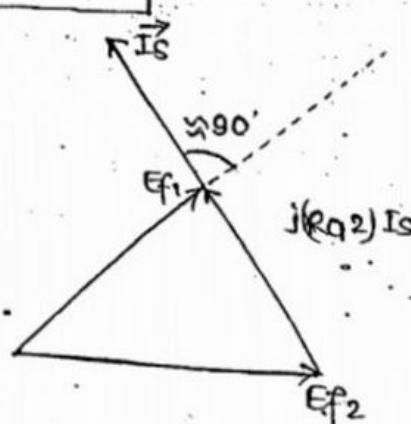
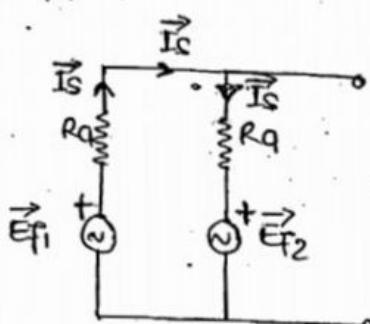
$$\sin(\Delta\delta) = \Delta\delta \text{ elect rad}$$

$$P_s = \Delta P = \frac{E_f^2}{2X_s} \times (\Delta\delta) \text{ watts}$$

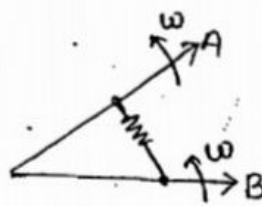
Synchronising power coeff.  $S_p \triangleq \frac{P_s}{\Delta\delta} = \frac{\Delta P}{\Delta\delta} = \frac{1}{X_s} \text{ watts/elect rad.}$

OR  
Stiffness coeff

$$S_p = \frac{E_f^2}{2X_s} \text{ watts/elect rad.}$$

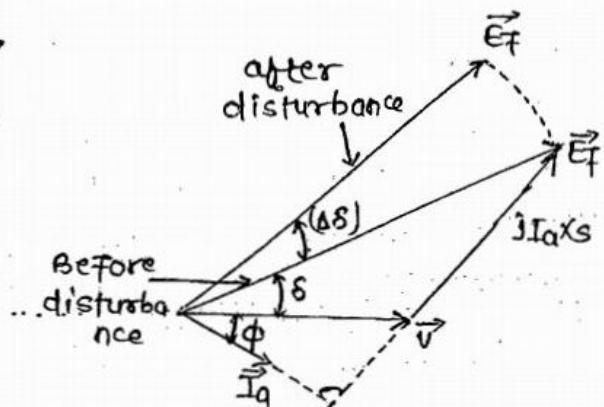
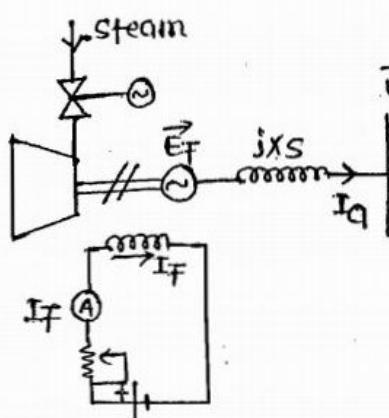


Restoring capability



No restoring capability.

## Synchronising Power $\rightarrow$ (Large m/c connected to $\infty$ bus)



$$\text{Before disturbance; } P = \frac{VE_f \sin \delta}{xs}$$

$$\text{After disturbance; } P + \Delta P = \frac{VE_f \sin(\delta + \Delta\delta)}{xs}$$

$$\therefore \text{synchronising power; } P_s = \Delta P = \frac{VE_f}{xs} [\sin(\delta + \Delta\delta) - \sin \delta] \text{ watts}$$

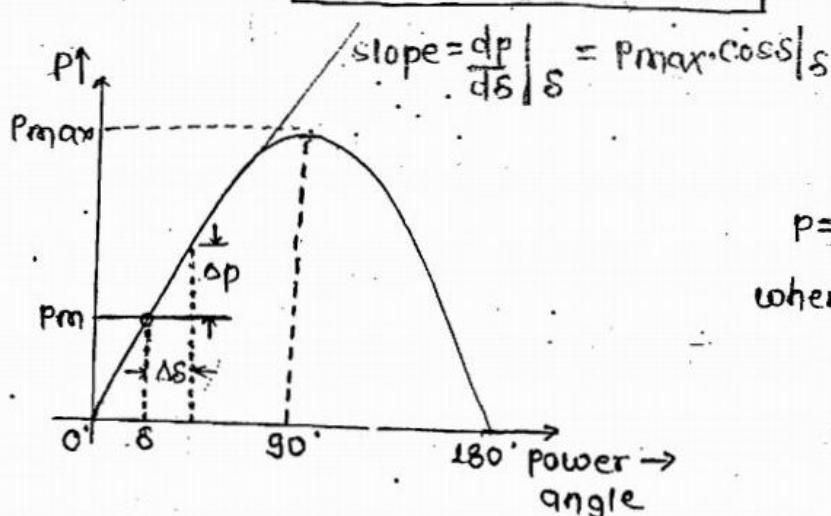
$$= \frac{VE_f}{xs} [\sin \delta \cos \Delta\delta + \cos \delta \sin \Delta\delta - \sin \delta]$$

$$= \frac{VE_f}{xs} [\cos \delta \sin \Delta\delta - \sin \delta (1 - \cos \Delta\delta)]$$

$$= \frac{VE_f}{xs} [\cos \delta \sin \Delta\delta - \sin \delta \times 2 \sin^2 \left( \frac{\Delta\delta}{2} \right)]$$

since  $\frac{\Delta\delta}{2}$  is very small;  $\sin^2 \frac{\Delta\delta}{2} \approx 0$

$$P_s = \Delta P = \frac{VE_f \cdot \cos \delta \times \sin(\Delta\delta)}{xs} \text{ watts}$$



$$P = P_{max} \sin \delta$$

$$\text{where } P_{max} = \frac{VE_f}{xs} \text{ at } \delta = 90^\circ$$

Since  $\Delta\delta$  is small;  $\sin(\Delta\delta) = (\Delta\delta)$  elect. rad

$$P_s = \Delta P = \frac{V_E F}{X_S} \cdot \cos \delta \times (\Delta\delta) \text{ watts}$$

$$\text{Hence } S_p = \frac{P_s}{\Delta\delta} = \frac{\Delta P}{\Delta\delta} \text{ watts/elect. Rad.}$$

$$S_p = \frac{V_E F}{X_S} \cdot \sin \delta$$

$$= P_{max} \sin \delta$$

$$= \frac{dP}{d\delta} \quad | \quad \delta = \text{initial operating angle}$$

$$S_p = P_{max} \text{ at } \delta = 0 \text{ (i.e. on NL)}$$

\* This is the reason that it is recommended that the gen<sup>r</sup> is synchronise on No Load.

\* Captive power plant is a prisoner for own industries. i.e. generation of power for only own industries.

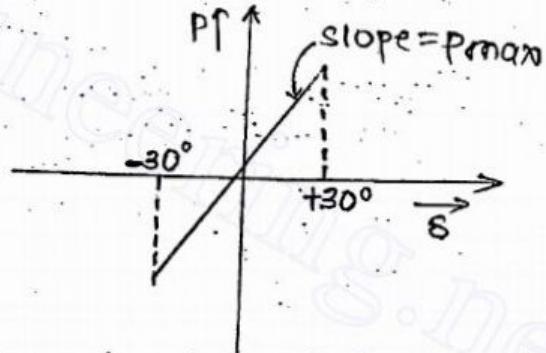
\* Linearised Analysis →

$$P = P_{max} \cdot \sin \delta$$

In the range  $-30^\circ \leq \delta \leq +30^\circ$

$\sin \delta \approx \delta$  elect. rad.

$$\text{Thus; } P = P_{max} \delta \text{ watts}$$



\* This is the reason that it is recommended that the syn. m/c be operated with power angle limited to  $30^\circ$ .

Que. → Cal. the synchronizing coefficient in kW & N-m/mech° at FL for a 50 Hz 1000 KVA 0.8 PF lag, 6.6 KV 8P & connected syn. gen<sup>r</sup> of negligible resistance & syn. reactance of 0.8 PU.

Sol. →

$$\vec{E}_f = 110 + j(1.0) \angle -\cos(0.8) \times 0.8$$

$$= 1.60 / 23.38^\circ \text{ PU} \approx 1.6125 / 23.39^\circ \text{ PU}$$

$$- S_p = \frac{E_f U}{X_S} \cdot \cos \delta \quad | \quad \delta = 23.38^\circ = \frac{1.60 \times 1}{0.8} \cos(23.38)$$

$$= 1.836 \text{ PU}$$

$\approx 1.85 \text{ PU per elect. rad.}$

$$Sp = 1.85 \times 1000 \text{ kW/elect rad.}$$

$$= 1850 \text{ kW/elect rad.}$$

$$= 1850 \times \frac{\pi}{180} \text{ kW/elect}^{\circ}$$

$$= 32.289 \text{ kW/elect}^{\circ}$$

$$= 129.156 \text{ kW/mech}^{\circ}$$

$$\text{Rad} - \frac{\pi}{180} \text{ degree}$$

$$\text{Synchronising torque coeff.} = \frac{129.156 \times 10^3}{\frac{2}{3} \times 2\pi \times 50}$$

$$= 1644.465 \text{ Nm/mech}^{\circ}$$

$$Far = Far(d) + Far(q)$$

$$N_{ph} Iq = Far(d) + Far(q)$$

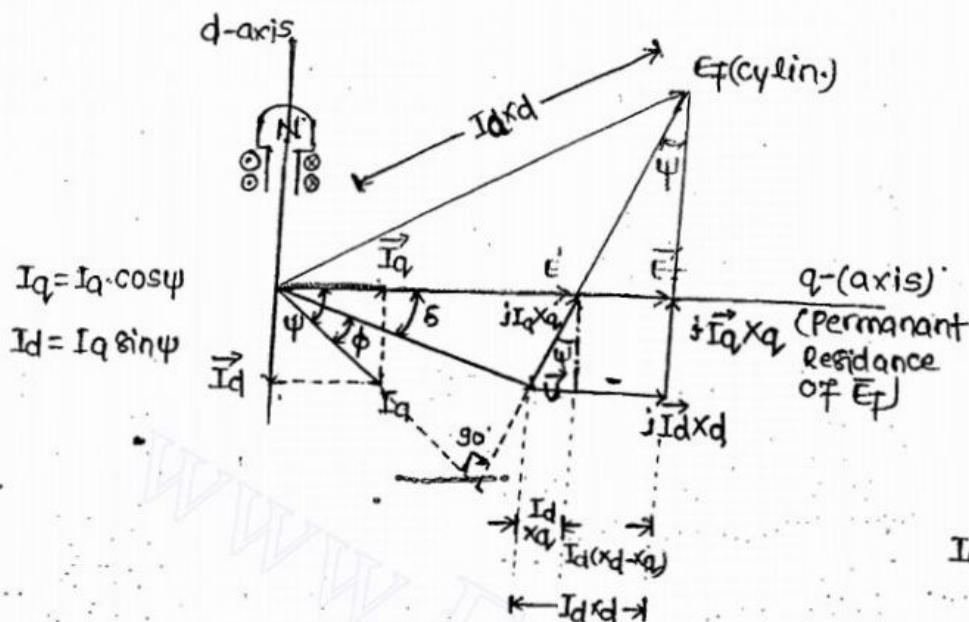
$$Iq = \frac{Far(d)}{N_{ph}} + \frac{Far(q)}{N_{ph}}$$

$$\vec{I}_q = \vec{I}_d + \vec{I}_q$$

$$Xq = 0.6 \times d \text{ to } 0.7 \times d$$

## Salient Pole m/c

\* Blondel's 2 reaction theory →



Over excited gen<sup>r</sup> (PF lag)

$$P = VI_q \cdot \cos\phi$$

$$= VI_q \cos(\psi - \phi)$$

$$= V I_q [\cos\psi \cdot \cos\delta + \sin\psi \cdot \sin\delta]$$

$$= V \cos\delta (I_q \cos\psi) + V \sin\delta (I_q \sin\psi)$$

$$= V \cos\delta \cdot I_q + V \sin\delta \cdot I_d$$

$$= \frac{V \cos\delta \cdot I_q}{x_q} + \frac{V \sin\delta \cdot I_d}{x_d}$$

$$= \frac{V \cos\delta}{x_q} V \sin\delta + \frac{V \sin\delta}{x_d} (E_f - V \cos\delta)$$

$$= \frac{V E_f}{x_d} \sin\delta + V^2 \sin\delta \cos\delta \left( \frac{1}{x_q} - \frac{1}{x_d} \right)$$

$$= \frac{V \cdot E_f}{x_d} \sin\delta + \frac{V^2}{2} \sin 2\delta \left( \frac{1}{x_q} - \frac{1}{x_d} \right)$$

$$P = \frac{V \cdot E_f}{x_d} \sin\delta + \frac{V^2}{2} \sin 2\delta \left( \frac{1}{x_q} - \frac{1}{x_d} \right)$$

↓  
Excitation  
Power

↓ Power due to  
Saliency  
(OR)  
Reluctance power

The initial challenge

Locating the  $q$ -axis

$$E' = V + j I_q x_q$$

$$\therefore E_f = E' + I_d (x_d - x_q) \quad (\text{OR})$$

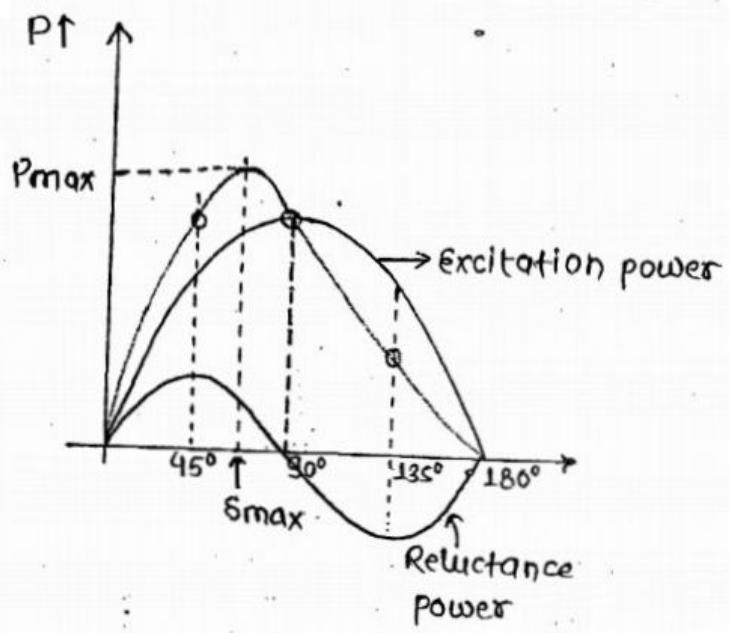
$$E_f = V \cos\delta + I_d x_d$$

$$I_q x_q = (I_q \times ?) \cos\psi$$

$$= (I_q \cos\psi) \cdot ?$$

$$? = x_q$$

$$? = x_q$$



## Induction m/c

\* These are the most commonly used motors because of their basic ad. like simple design, less cost, mech. strong, excellent running c/s, good speed regn no arm. reactions, commutation, sparkings & operates on Ac (No need of any dc supply).

\* RMF → It also operates as gen<sup>r</sup> but not preferred conventional pwr generation these are more popular in motor segment.

\* They operate on the basis of Rotating magnetic field.

\* RMF → \* When a 3φ supply is applied to a 3φ wdg which is distributed with the space displacement 120° a net flux is produced which rotates at a constant speed ( $N_S = 120f/p$ ) with a const. magnitude ( $1.5\phi_m$ ) and with a perpct. dirn depending on φ seq.

$$\phi_A = \phi_m \sin \omega t$$

$$\phi_B = \phi_m \sin(\omega t - 120^\circ)$$

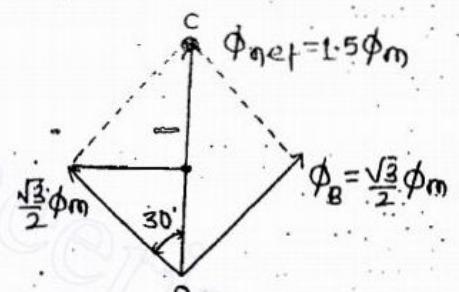
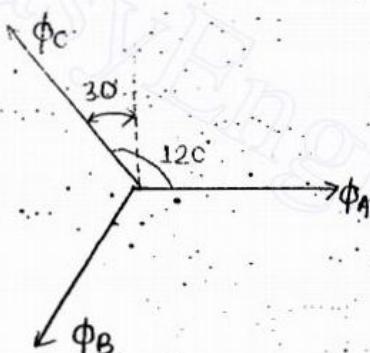
$$\phi_C = \phi_m \sin(\omega t - 240^\circ)$$

at  $\omega t = 0$

$$\phi_A = 0$$

$$\phi_B = -\frac{\sqrt{3}}{2} \phi_m$$

$$\phi_C = \frac{\sqrt{3}}{2} \phi_m$$



From ΔOAB

$$\cos 30^\circ = \frac{OA}{OB}$$

$$OA = OB \cos 30^\circ = \frac{\sqrt{3}}{2} \phi_m \cdot \frac{\sqrt{3}}{2} = \frac{3}{4} \phi_m$$

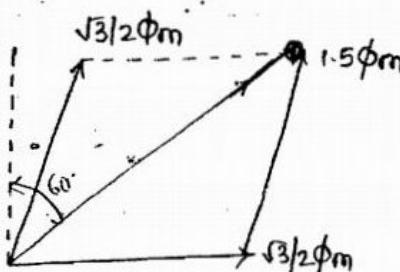
$$OC = \frac{3}{2} \phi_m = 1.5 \phi_m$$

at  $\omega t = 60^\circ$

$$\phi_A = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_B = -\frac{\sqrt{3}}{2} \phi_m$$

$$\phi_C = 0$$

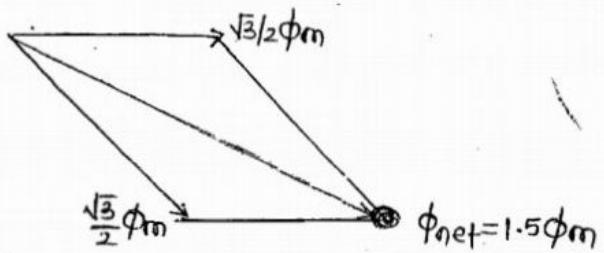


at  $\omega t = 120^\circ$

$$\phi_A = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_B = 0$$

$$\phi_C = -\frac{\sqrt{3}}{2} \phi_m$$

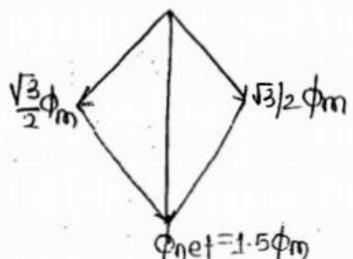


at  $\omega t = 180^\circ$

$$\phi_A = 0$$

$$\phi_B = \frac{\sqrt{3}}{2} \phi_m$$

$$\phi_C = -\frac{\sqrt{3}}{2} \phi_m$$



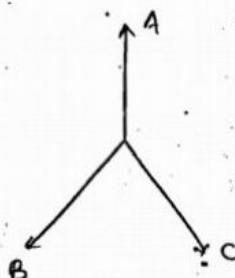
N/60 RPS

$$\text{cycles/rotation} = P/2$$

$$\text{rot/sec} \times \text{cycles/rot} = \frac{PN}{120}$$

$$\text{cycles/sec} \Rightarrow f = \frac{PN}{120}$$

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



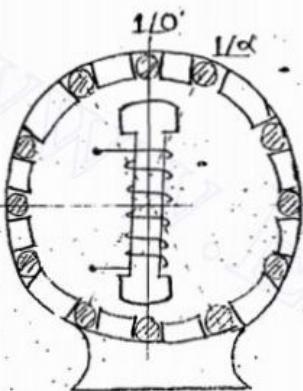
## \* Construction →

- \* Like all rotating ele. m/c it also consists of stationary part stator & the rotating part rotor mounted on the shaft & supported by suitable bearings.
- \* There will be least possible air gap b/w stator & rotor.

## \* Stator →

- \* It contains slots at the inner peripheral made up of Si-steel laminations.
- \* 3φ wdg either  $\lambda$  (or)  $\Delta$  (depending on starting method) will be placed in the slots which offers good mech. security for the wdg.

## \* Design of 3φ wdg →



slots angle  $\alpha^{\circ}$   
phase displacement contributed by 1 slot in ele<sup>o</sup>

$$\alpha = \frac{180^{\circ}}{\text{No. of slots/pole}}$$

$$\text{Slots} = 12, \alpha = 30^{\circ}$$

$$\text{Slots} = 120, \alpha = 3^{\circ}$$

Phase Group / Band / Belt :  $n$ . (adjacent)  
Phase spread :  $n\alpha$

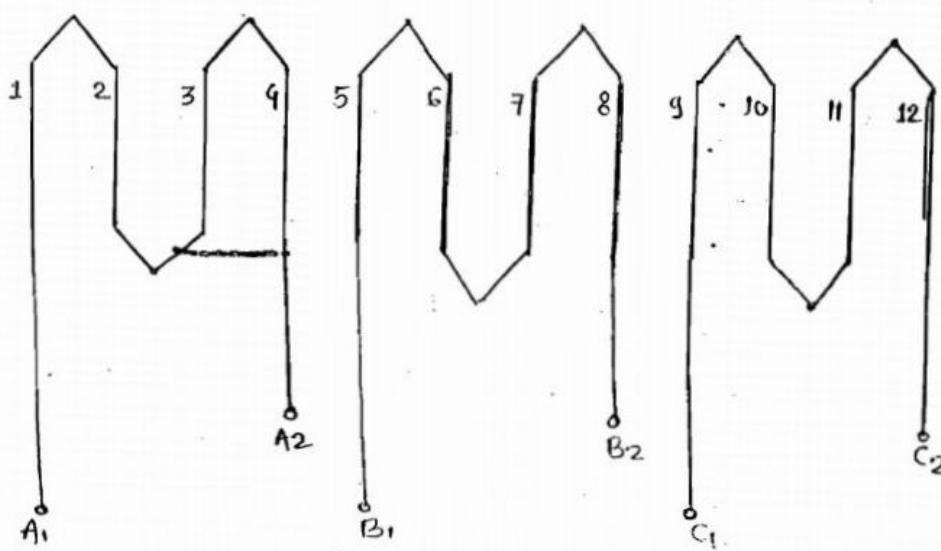
Phase group → The no. of adjacent slots (or) cond<sup>r</sup> belonging to a same phase.

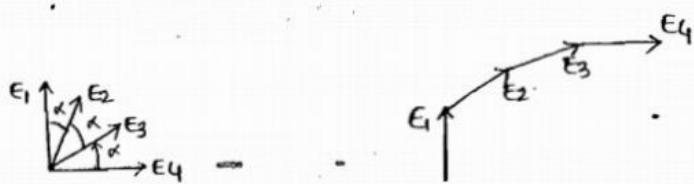
Phase spread → The angle subtended by one phase group is phase spread.

3φ wdgs can be designed for 120° ph. spread (or) co-phase spread.

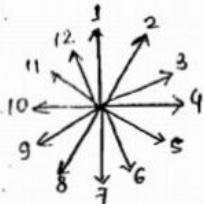
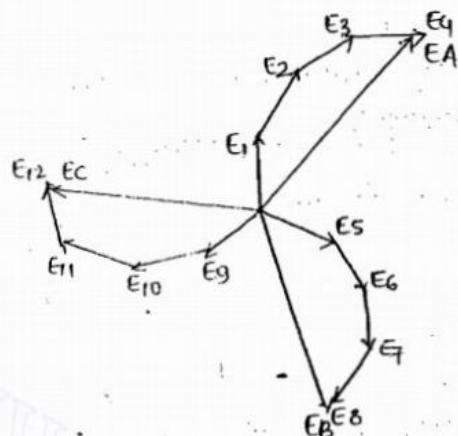
120° phase spread →  $n\alpha = 120^{\circ}, \alpha = 30^{\circ}, n = 4$

$n \rightarrow \text{slots/pole/phase (SPP)}$



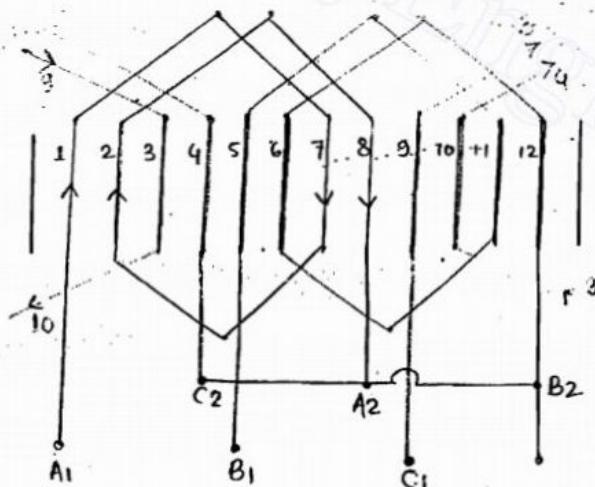


\* Distribution of wdg is done only for getting improving the shape of waveforms.



\* 60° phase spread  $\rightarrow n\alpha = 60^\circ$ ;  $\alpha = 30^\circ$ ;  $n = 2 \rightarrow 6$  phases

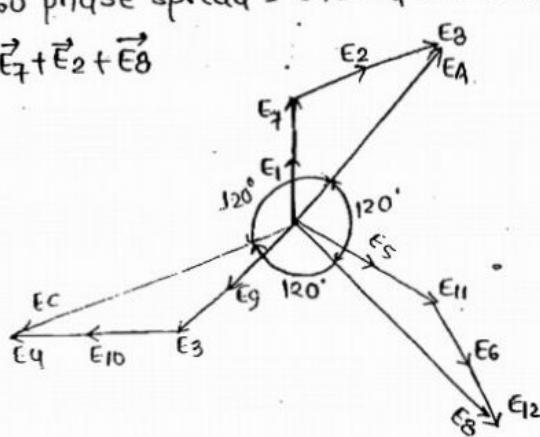
↓  
Combined to be 3 phase  
Bunch of 2 phases.



Note:-

To maintain 60° phase spread 1 should be connected to 7.

$$E_A = \vec{E}_1 + \vec{E}_7 + \vec{E}_2 + \vec{E}_8$$



$E_{120^\circ} < E_{60^\circ}$   
Phase spreads

$$\text{distribution factor } k_d = \frac{\text{emf D.W}}{\text{emf C.W}}$$

$$k_d = \frac{\sin \frac{n\alpha}{2}}{\frac{n \sin \alpha}{2}}$$

$$\text{since; } \sin \frac{\alpha}{2} \approx \frac{\alpha}{2}$$

$$k_d = \frac{\sin \frac{n\alpha}{2}}{\frac{n\alpha}{2}}$$

$$k_{d60} = \frac{\sin \frac{60}{2}}{60/2}; \quad k_{d120} = \frac{\sin \frac{120}{2}}{120/2}$$

$$\frac{k_{d60}}{k_{d120}} = 1.15$$

$$k_{d60} = 1.15 k_{d120}$$

### \* Pitch Factor →

$$k_p = \cos \beta / 2$$

$$3^{\text{rd}} \rightarrow k_p = 0.866$$

$$5^{\text{th}} \rightarrow k_p = 0.95$$

$$7^{\text{th}} \rightarrow k_p = 0.97$$

$$k_{p3} = \cos 3\beta / 2$$

$$k_{p\tau} = \cos \tau \beta / 2$$

\* \* \*

$$\frac{\tau \beta}{2} = 90^\circ$$

$$\beta = \frac{180}{\tau}$$

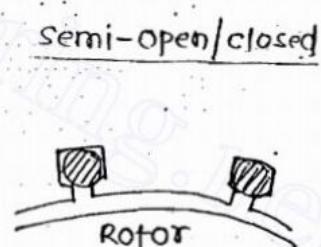
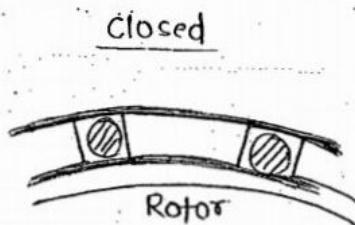
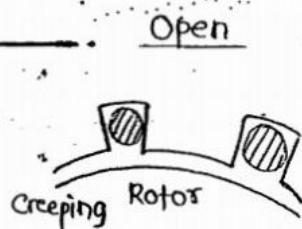
$$k_{d\tau} = \frac{\sin \frac{n\tau\alpha}{2}}{n \sin \frac{\tau\alpha}{2}}$$

$$\sin \frac{n\tau\alpha}{2} = 180^\circ$$

$$n\alpha = \frac{360}{\tau}$$

- \* Practically  $60^\circ$  phase spread is preferred as it gives better vol. & power ratings.  
 $120^\circ$  ph. spread will eliminate 3rd harmonic content in line.  
 However the wdg's are preferred to be 1. Therefore the 3rd harmonic content in line is 0 even though it exists in each phase.
  - \* Harmonics can be eliminated by short pitching the coils by introducing pitch factor eliminating higher order harmonics like 5th & 7th is more advantageous.
  - \* For high vol. 1 connected stator wdg is preferred as it reduces insulation requirements as well as no. of turns in each phase.
  - \* The 3ph wdg is also classified acc. to 2 types :-
    - (1) Integral slot wdg (2) Fractional slot wdg
- $\downarrow$                                      $\downarrow$   
 $n = SPP \text{ (integer)}$                      $n = \text{non integer (fraction)}$   
 Eg:-  $12/2/3, 18/2/3$                     Eg:-  $18/4/3$
- \* Fractional slot wdg's practically offer short pitched wdg specially more suitable in double layer wdg cases.  
 Fractionally  $\rightarrow$  Automatically short pitched.

#### Type of slots $\rightarrow$



\* Wdg design, routine maintenance, repairs is easy  
 less expensive.

Difficult

quite difficult

\* Offer high reluctance to leakage flux, less leakage reactance.

High leakage flux; high leakage reactance

Moderate

\* Net air gap is more which requires more magnetising current to maintain flux & the operating PF will be low wrt ft.

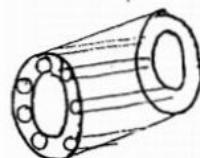
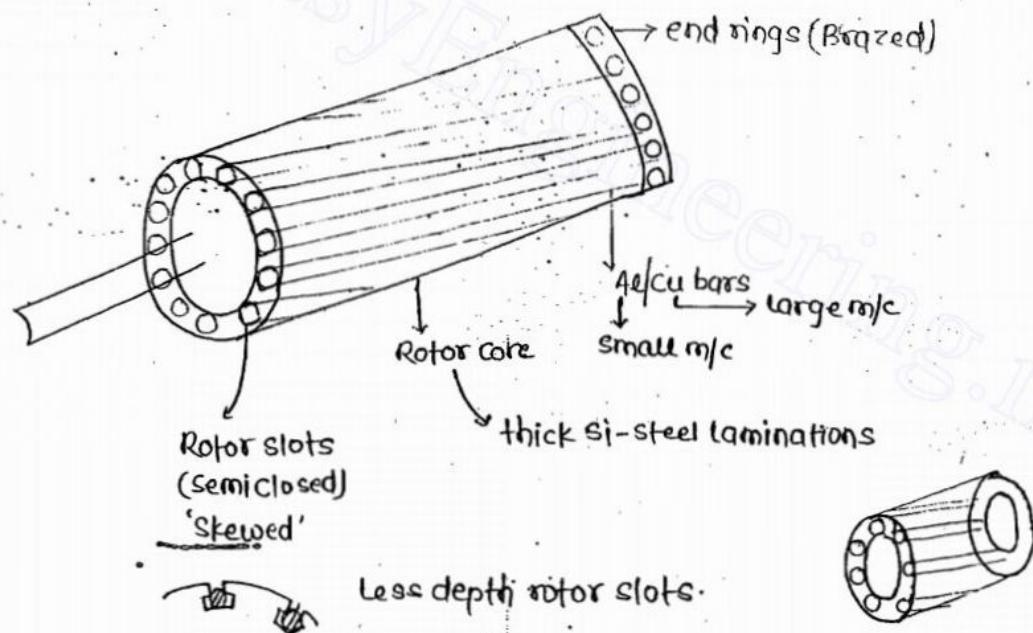
Net air gap is less, so magnetising current less & PF more.

Moderate

- \* W.Rt. leakage reactance its Operating pf is better Comparitively.
- \* Non uniform air gap will produce space harmonics by distorting flux waveform. also called as slot/tooth harmonics.
- \* Generally preferred slots in IM in stator (OR) rotor are semi closed type.
- \* Large rating m/c eq power plant gen. OR large rating im preferred open type because they produce less leakage reactance & also offers easy maintenance repair works.

#### \* Rotor →

- (1) Squirrel cage (OR) Cage rotors
- (2) Wound / slip ring rotors.

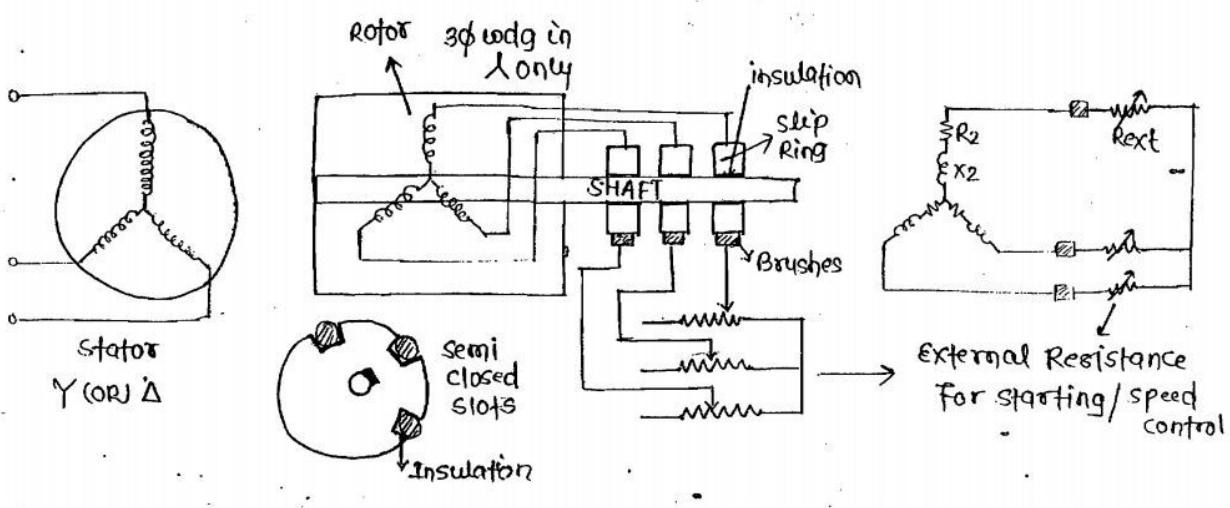


- \* It has most simple construction doesn't contain any wedg.
- \* Rotor is made up of thick si-steel laminations punched into slots of less depth Preferably semiclosed.
- \* Al(Cu) Cu bars are directly placed in this slots w/o any insulation (as the current flows only through least resistance)

- \* This bars are solidly closed (or) sc with 2 end rings (Brazed)
- \* Rotor slots are skewed (twisted or inclined) wrt shaft axis or stator slots to avoid locking tendency during starting.
- \* <sup>Under</sup> the running cond<sup>n</sup> rotor freq. is negligible & the rotor core losses are very low.
- \* Therefore no need of thin laminations.
- \* It requires least maintenance repairs, mech. strong, simple design, less cost & excellent running c/s.
- \* The drawback is due to its low starting torque.
- \* As the rotor is permanently closed its resistance can't be varied for starting (or) controlling purpose.
- "Poles are automatically formed on the rotor equal to the no. of poles on stator."
- \* Due to mutual ind<sup>n</sup> the poles are induced in the rotor. Therefore it reacts to any no. of poles on the stator.

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- (2.) Slip Ring/Wound → \* The rotor is a cylindrical drum shaped st. punched into slots (semiclosed) on the outer peripheral which contain a 3φ wdg similar to stator wdg but essentially star connected.
- \* Rotor is designed for the same no. of poles as on the stator. but preferably the no. of slots should not be same & should not have a common factor to avoid any chance of magnetic locking during starting.
- \* The 3 terminals of L connected wdg will be brought out & connected to 3 slip rings mounted on the same shaft with suitable insulation.



- \* The starting torque is proportional to rotor resistance but the rotors are naturally designed for least possible resistance. In order to have high starting torque an external resistance is inserted in each phase equally through slip ring & brushes.
- \* Under running cond<sup>n</sup> the resistance is disconnected using a METAL COLLAR arrangement the brushes are slight down & 2 slip rings are sc to form a closed rotor.
- \* This is only used for high starting torque app<sup>n</sup>. Around 90% of motors are squirrel cage type only.
- \* Slip motors are expensive, complicated design, high maintenance repairs, running c/s are not good comparatively.

#### \* Principle:- (How motor run)?

- \* When a 3φ supply is given to stator RMF is produced at  $N_s$ . As the flux sweeps past the rotor cuts it & cuts it & induces EMF due to relative speed  $N_s$ . & the rotor freq. at stand still is supply freq.
- \* As the rotor is essentially closed it produces current & the current carrying cond<sup>r</sup> placed in the magnetic field will experienced a force which is torque & the rotor rotates.
- \* According to Lenz law it rotates in the dir<sup>n</sup> of magnetic field to oppose the cause i.e. relative speed.
- \* Actually the rotor want to catch the rotating magnetic field but it could not catch it due to losses in the rotor. and rotates at a speed  $N$  slightly less than  $N_s$ .
- \* The rotor slips back RMF by a speed  $N_s - N$  known as steep slip speed.
- \* The principle of operation is mutual ind<sup>n</sup> acc. to Faraday & it is equivalent to a rotating Xmer with sc 2°.
- \* It is a singly excited m/c.
- \* Vol. is applied only to stator & the Vol. are induced in the rotor through electromagnetic ind<sup>n</sup>.  
Therefore called as ind<sup>n</sup> motor.
- \* As it can't run at synchronous speed it is also called as asynchronous motor.

\* slip →

\* It is the diff of syn. speed & actual speed of the rotor expressed in % of syn. speed.

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

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

$$N_s - N = S N_s$$

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

\* During starting at  $N=0, S=1.0$

\* A well designed ind<sup>n</sup> motor runs near to syn. speed with low value of slip on NL & slip is near to 0 (but not 0)

\* If the rotor runs at  $N_s$ , then no relative speed, no  $E_2, I_2=0, T=0$ .

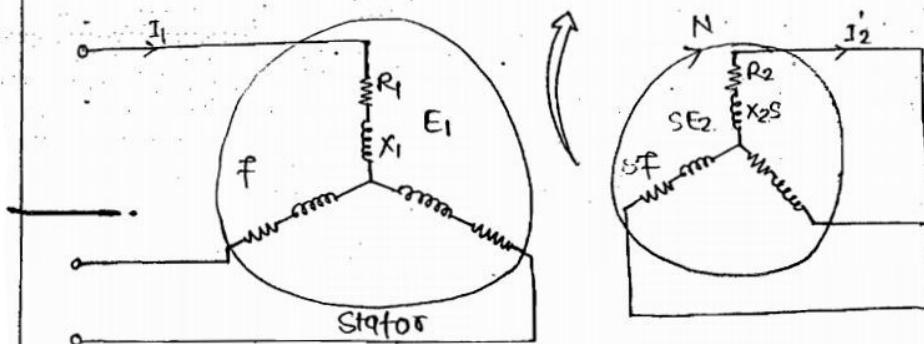
\* The operating region of ind<sup>n</sup> motors will be around 1-5% slips from NL to rated load.

\* For small motor it may be around 8% at rated load.

\* Slip plays major role in the operation & performance & behaviour of IM.

\* Affect of slip →

Representation →



$$E_2 \propto N_s - 0$$

$$E_2' \propto N_s - N$$

$$\frac{E_2'}{E_2} = \frac{N_s - N}{N_s}$$

$$E_2' = S E_2$$

Relative Speed  
 $N_s - N$

\* If the rotor resistance is adjusted to a suitable value i.e. exactly equal to rotor leakage reactance at standstill then the motor starts with its max<sup>m</sup> torque.

\* Under such cond<sup>n</sup> the rotor PF will be 0.707 lagging

\* Running torque → Consider a motor running at rated load with slips & speed NS

$$T_f \propto E_2' I_2' \cos\phi_2'$$

$$T_f \propto [K_1 \phi] I_2' \cos\phi_2' \quad (E_2 \propto \phi)$$

$$T_f \propto (K_1 \phi) \times \frac{SE_2}{\sqrt{R_2^2 + (Sx_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (Sx_2)^2}}$$

$$T \propto \frac{(K_1 \phi) SE_2 R_2}{\sqrt{R_2^2 + (Sx_2)^2}}$$

$$T = K \boxed{\frac{SE_2^2 R_2}{R_2^2 + (Sx_2)^2}}$$

$$\left( K = \frac{3 \times 60}{2\pi NS} \right)$$

\* For a given (or) const. supply vol:  $T_f \propto \frac{SR_2}{R_2^2 + (Sx_2)^2}$

\* Under normal running cond<sup>n</sup> at low values of slip;

$$S \downarrow; (Sx_2)^2 \ll R_2$$

$$T_f \propto \frac{SR_2}{R_2^2}$$

$$\boxed{T_f \propto \frac{S}{R_2}}$$

% at the high values of slip

$$S \uparrow; (Sx_2)^2 \gg R_2$$

$$T_f \propto \frac{SR_2}{(Sx_2)^2} \propto \frac{R_2}{Sx_2^2}$$

$$\boxed{T_f \propto \frac{R_2}{Sx_2^2}}$$

\* For a given  $R_2, x_2$  values of rotor the torque developed is directly proportional to slip in the low slip region & torque is inversely proportional to slip in the high slip region.

\* The running torques are also sensitive to supply vol. variations.

\* Cond'n for max<sup>m</sup> running torque →

$$T_F = \frac{SR_2}{R_2^2 + (sx_2)^2}$$

$$\text{let } y = \frac{1}{T_F} \uparrow$$

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

$$y = \frac{1}{T_F} = \frac{R_2^2 + (sx_2)^2}{SR_2}$$

$$\frac{dy}{ds} = \frac{-R_2}{S^2} + \frac{x_2^2}{R_2} = 0$$

$$\frac{R_2}{S^2} = \frac{x_2^2}{R_2}$$

$$R_2^2 = x_2^2 S^2$$

$$\boxed{R_2 = sx_2}$$

\* If the rotor resistance = slip times the rotor reactance at stand still, then the rotor develops max<sup>m</sup> running torque.

max<sup>m</sup> starting torque  $\boxed{R_2 = x_2}$

max<sup>m</sup> running torque  $\boxed{R_2 = sx_2}$

$T_{st\max} \propto \frac{R_2}{R_2^2 + x_2^2}$ $T_{st\max} \propto \frac{1}{2x_2}$	$T_F(\text{running}) \propto \frac{SR_2}{R_2^2 + (sx_2)^2}$ $T_F(\max) \propto \frac{1}{2x_2}$
---	---

Running torque

$$T_F(\text{running}) \propto \frac{SR_2}{R_2^2 + (sx_2)^2}$$

$$T_F(\max) \propto \frac{1}{2x_2}$$

$$\boxed{T_{\max} \propto \frac{1}{2x_2}}$$

$$K_1 = \frac{3 \times 60 E^2}{2 \pi N_s}$$

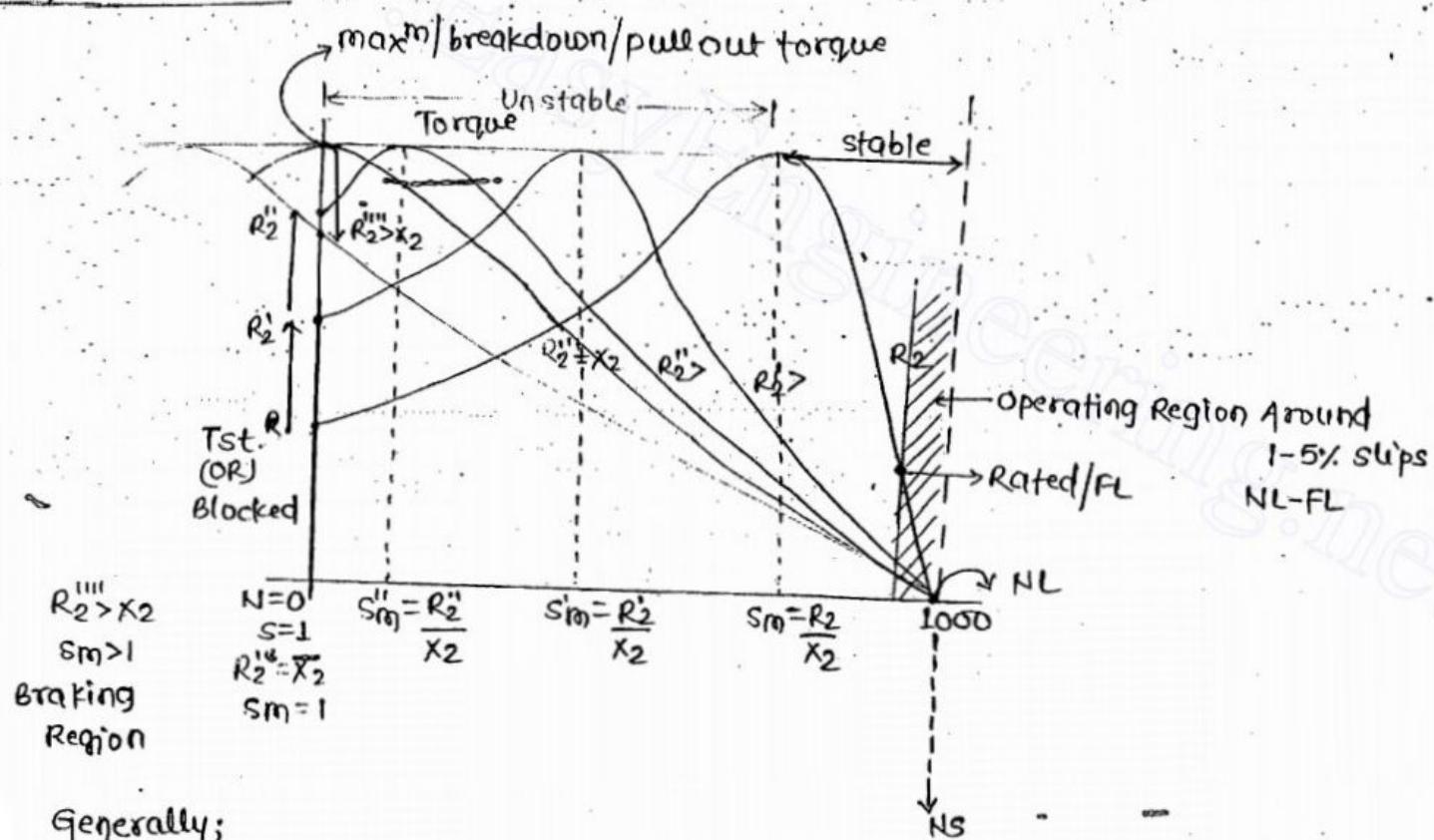
(Refer  $\frac{V}{f}$  speed control)

$$\boxed{s = \frac{R_2}{m x_2}}$$

(Also a cond'n for max<sup>m</sup> value)

- \* The motor rotates at any slip b/n 0 & 1 but it delivers its max<sup>m</sup> torque only at a particular slip  $s_m = R_2/X_2$ .
  - \* Generally rotor resistance is a least possible value compared to its leakage reactance at standstill.
  - \* If an external resistance is added into the rotor to make  $R_2 + R_{ext} = X_2$  then  $s_m = 1$  which means the motor starts with its max<sup>m</sup> torque because slip at which max<sup>m</sup> torque occurs  $s_m = 1$ .
  - \* max<sup>m</sup> torque magnitude is independant of rotor resistance but the slip at which it occurs depends on  $R_2$ .
  - \* Max<sup>m</sup> torque is inversely proportional to leakage reactance of rotor at standstill.
- Therefore it will be designed as min<sup>m</sup> as possible with less depth slots.

#### \* Torque-slip c/s →



Generally;

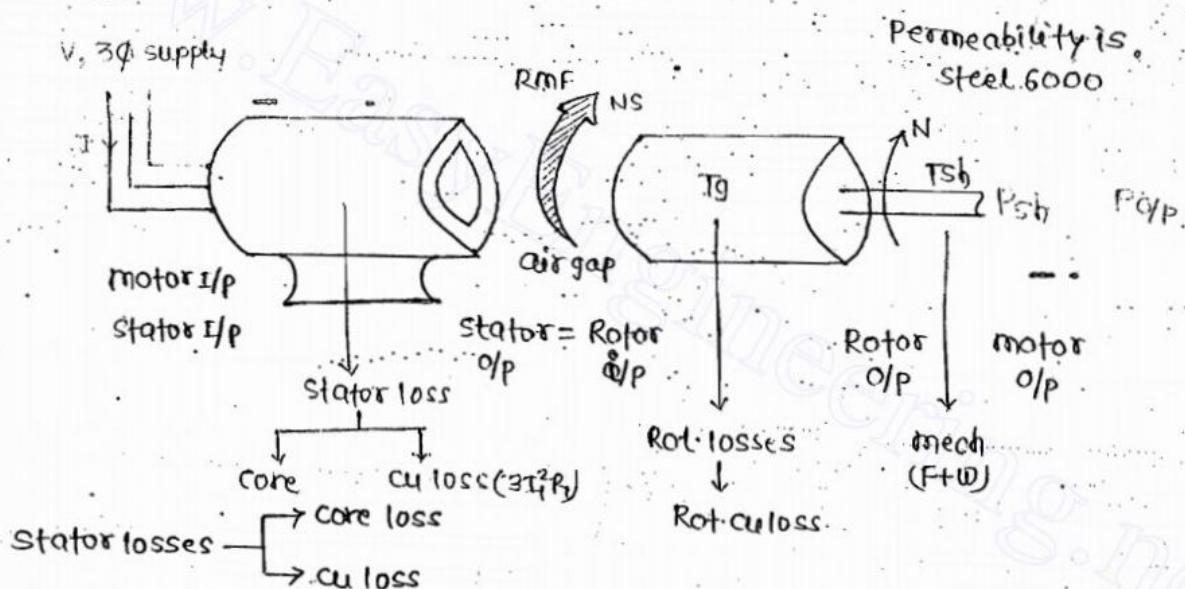
$$T_{max} > T_f$$

$$(T_{max} \approx 2-3 T_f)$$

$$\therefore (T_{st} \approx 1.5 T_f)$$

- \* T-s c/s are essentially straight line in the operating region (low slip). Every motor will have its max<sup>m</sup> capacity or capability to develop torque which occurs only at slip  $s_m$  if the load increases beyond it it can't deliver torque & it stops which is unstable region.
- \* It has excellent overload capability but not desirable to operate at over-loading but can be done for short duration if req.
- \* All the stable region is not operating region; it should be operated at low slip only due to  $\eta$  consideration.
- \* The max<sup>m</sup> torque is independent of rotor resistance but the slip & speed where it occurs depends on rotor resistance.
- \* If  $R_d \gg R_s$  max<sup>m</sup> torque occurs in the braking region.

\* Power stages  $\rightarrow$



Rotor losses  $\rightarrow$  Only cu losses

Mech. losses  $\rightarrow$  Frictional  
windage

\* There are no losses in the air gap.

$$\text{stator I/p} - \text{stator loss} = \text{stator o/p} = \boxed{\text{rotor I/p} = \text{air gap power}}$$

$$\text{Rotor I/p} - \text{Rotor cu loss} = \text{Rot. o/p}$$

$$\text{Rot. o/p} - \text{Rot loss} = \text{shaft (or) motor o/p}$$

$$\eta = \frac{\text{motor o/p (Psh)}}{\text{motor I/p} (\sqrt{3}V_L I_L \cos\phi)}$$

$$P = \frac{2\pi N T_g}{60}$$

$$\text{Rotor P_i/p} = \frac{2\pi N s T_g}{60} \text{ watts} \quad \mid \quad \text{Rot. P_o/p} = \frac{2\pi N T_g}{60} \text{ watts}$$

$$\text{Rotor P_i/p} - \text{Rotor P_o/p} = \text{Rot. cu loss} = \frac{2\pi T_g}{60} (N_s - N) = \frac{2\pi T_g}{60} \cdot S = \underbrace{\frac{2\pi T_g}{60} \cdot S}_{R_i^2/p \times S}$$

$$\text{Rotor cu loss} = S \cdot \text{Rot. P_i/p}$$

$$\text{Rotor P_i/p} - \text{Rotor P_o/p} = S \cdot \text{Rot. I/p} \Rightarrow \text{Rotor} = (1-S) \text{ Rotor P_i/p}$$

$$\frac{\text{Rotor P_o/p}}{\text{Rotor P_i/p}} = (1-S) = n_{\text{rotor}} = \frac{N}{N_s} \quad \begin{array}{l} (\text{Approx } \eta \text{ of IM.}) \\ (\text{Negl. mech. & start}) \end{array}$$

$$* \text{Core loss (iron)} + \text{mech (F+w)} = \text{constant loss.}$$

\* If IM is running at 950 RPM then its approx.  $\eta$  will be 90% because  $N_s$  taken as 1000 RPM in Indian condn like ( $F \rightarrow 50\text{Hz}$  etc). (Neglecting const. losses)

\* T developed  $\rightarrow$

$$T_g = \frac{60}{2\pi N_s} \times \frac{\text{Rotor power I/p}}{(\text{OR})} \quad \begin{array}{l} \text{Rot. power} \\ \text{Air gap power.} \end{array}$$

$$- \quad T_g = \frac{60}{2\pi N_s} \cdot \frac{\text{Rot. cu loss}}{S \cdot I_p^2} \longrightarrow 3I_2'^2 R_2$$

$$= \frac{60}{2\pi N_s} \cdot \frac{3I_2'^2 R_2}{S}$$

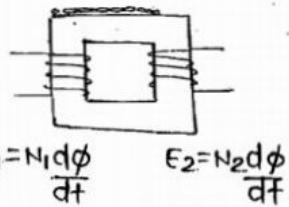
$$= \frac{60}{2\pi N_s} \cdot 3 \times \left[ \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}} \right]^2 \times \frac{R_2}{S} \quad \therefore I_2' = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

$$= \frac{60}{2\pi N_s} \times \frac{3 \cdot SE_2^2}{R_2^2 + (SX_2)^2} \cdot R_2$$

$$T_g = \frac{3 \times 60}{2\pi N_s} \frac{SE_2^2 R_2}{R_2^2 + (Sx_2)^2} \quad \text{N-m}$$

$$T_g = \frac{3 \times 60}{2\pi N_s} \times \frac{S(KE_1)^2 \cdot R_2}{R_2^2 + (Sx_2)^2} \quad \text{N-m}$$

$$K = \frac{\text{Rotor turns/phase}}{\text{stator turns/ph.}} = \frac{E_2 \text{ (stand)}}{E_1 \text{ (SHM)}}$$



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

\* Torque Ratio in terms of  $\frac{Sm}{S^2m} \rightarrow$

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

$$T_f \propto \frac{SR_2}{R_2^2 + (Sx_2)^2}$$

$$T_m \propto \frac{1}{2x_2}$$

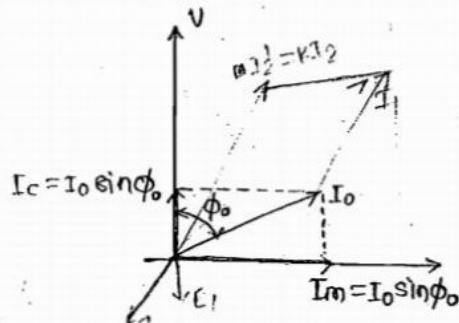
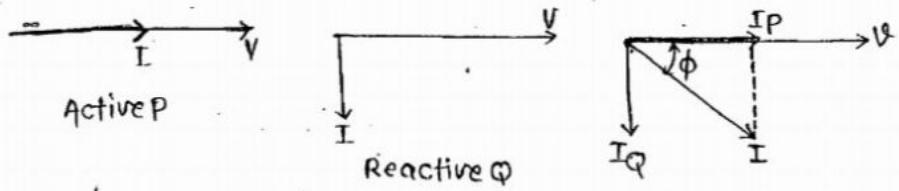
$$\begin{aligned} \text{Now; } \frac{T_{st}}{T_{max}} &= \frac{R_2}{R_2^2 + X_2^2} \times \frac{2x_2}{1} \\ &= \frac{2R_2 \cdot X_2}{X_2^2} = \frac{2R_2}{\frac{R_2^2}{X_2^2} + 1} \end{aligned}$$

$$\boxed{\frac{T_{st}}{T_{max}} = \frac{2Sm}{S^2m^2 + 1}}$$

$$\frac{T_f}{T_{max}} = \frac{SR_2}{R_2^2 + S^2X_2^2} \times \frac{2X_2}{1}$$

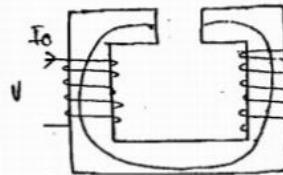
$$= \frac{2SR_2X_2/X_2^2}{\frac{R_2^2}{X_2^2} + S^2 \frac{X_2^2}{X_2^2}}$$

$$\boxed{\frac{T_f}{T_{max}} = \frac{2 \cdot S \cdot Sm}{S^2m^2 + S^2}}$$

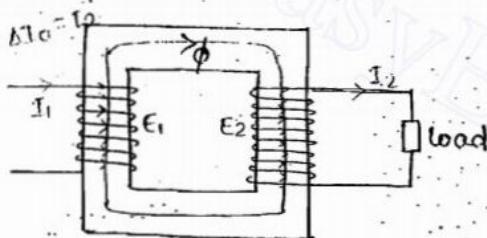


- \* Active power  $\rightarrow$  supply some losses
- \* Reactive power  $\rightarrow$  To maintain flux

No Load



\* draw more current to flowing flux in air gap because of high 2-6% rated reluctance in the air  
Highly lagging



$$I_2' = k I_2$$

$$I_2' \propto I_2$$

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

$$\phi_2' = \phi_2$$

\* IM ON NL  $\rightarrow$  \* It draws a large magnetising current around 30% of rated to establish flux (RMF) in the air gap of high reluctance.

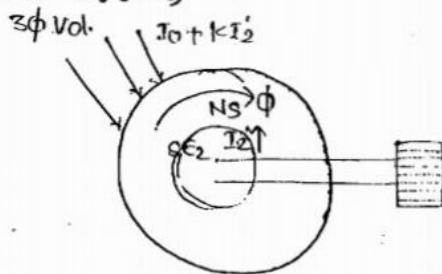
\* Only ZPF Lagging current will supply flux (magnetising current).

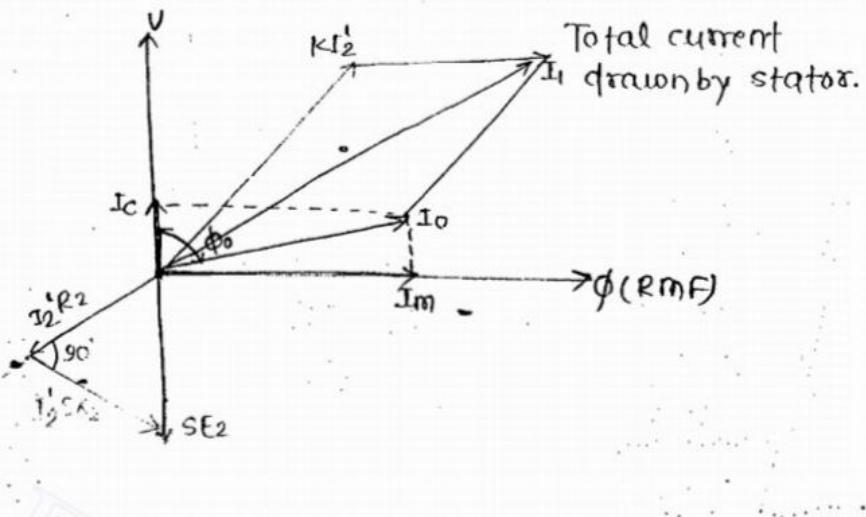
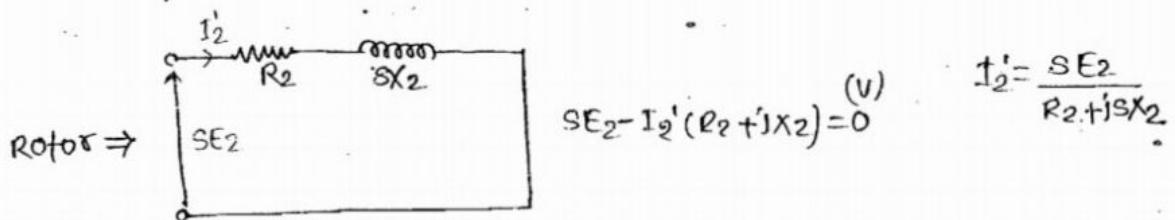
\* IM draws reactive power to establish flux in the air gap.

\* It draws active power for supplying its losses & load torque if loaded.

\* On NL as the magnetising current is very high it operates at low lagging PF

(less than 0.2 lagging)





- \* On load rotor current increase proportionally to produce its own flux in the air gap which is stationary w.r.t stator RMF. but opposes it acc to lenz law & reduce it.
- \* Therefore stator draws more current proportionally to maintain the flux const in the air gap.
- \* whenever rotor is loaded it will immediately call current from stator. ( $kI_2'$ ) with load PF improves but operate at low PF comparative to an eq. Xmer.

### Transformer

- (1) Ele. to ele. energy conversion through magnetic medium in high permeability core
- (2) Require less magnetising current
- (3) NL current 2-6% of rated
- (4) Low lagging PF on NL
- (5) PF improves with load.
- (6) Concentrated wdg.

### Induction motor --

Ele. to mech. energy conversion through magnetic medium in the air gap of high reluctance.

Requires large magnetising current.

Around 30-40% of rated.

Very much low lagging PF.

PF improves with load. but compare low.

Distributed wdg produce RMF.

(A) Contain core loss & cu loss only

stator core loss, no loss in air gap & rotor core loss negligible & includes mech. loss. with cu losses of stator & rotor.

(B) Induced emfs depends on turns ratio.

Induced emfs depends on turns ratio only at standstill but vary with slip under running.

(C) freq. of 1<sup>o</sup>, 2<sup>o</sup> same

freq. of stator, rotor same only at standstill but vary with slip.

(D) 2<sup>o</sup> is never sc

But rotor should be essentially sc. mech. loading across rotor shaft.

(E) Ele. loading across 2<sup>o</sup> terminals

leakage flux high & leakage reactance.

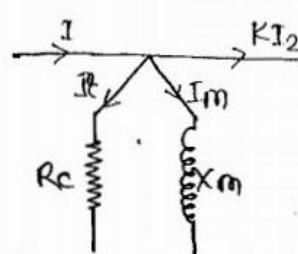
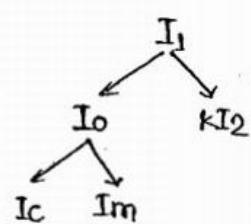
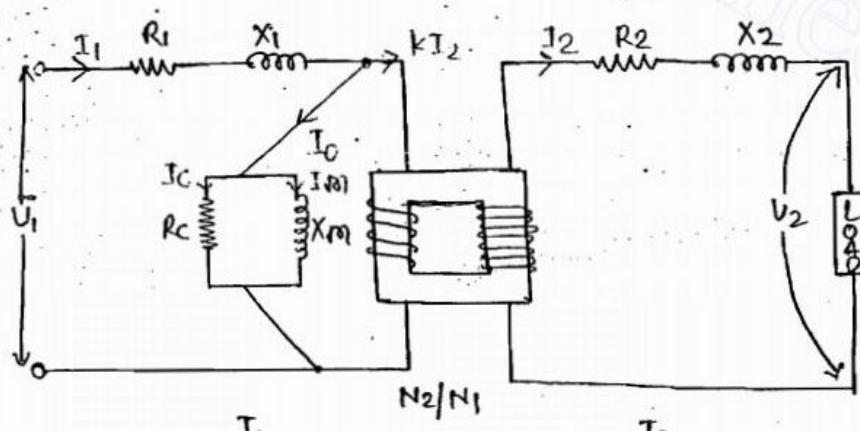
(F) Constant flux device

Constant flux m/c.

(G) Mutual ind<sup>n</sup>

Mutual ind<sup>n</sup>.

\* T/F eq; ckt Representation →



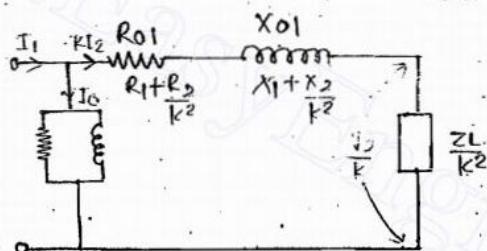
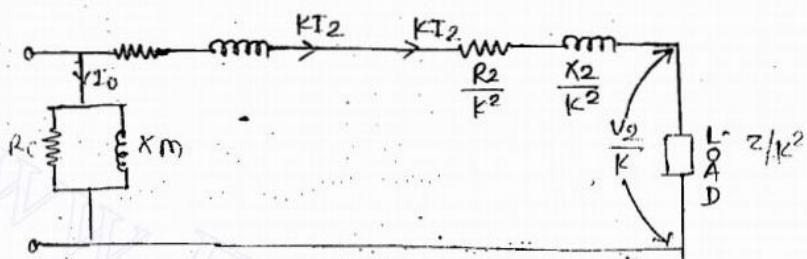
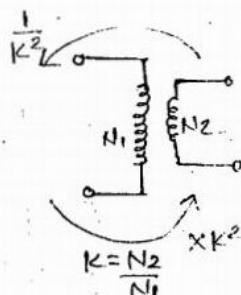
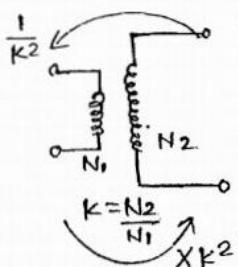
$$R_c = \frac{U_1}{I_c} \Rightarrow X_m = \frac{U_1}{I_m} \quad [\text{fictitious/imaginary value}]$$

$$I_c < I_m$$

$R_c, X_m$  depends on  $I_c$  &  $I_m$ .

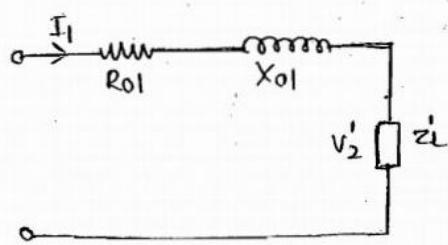
$$I_1^2 R'_2 \rightarrow I_2^2 R_2$$

$$R'_2 \Rightarrow \left(\frac{I_2}{I_1}\right)^2 R_2$$



approx eq. ckt Neglecting shunt branch

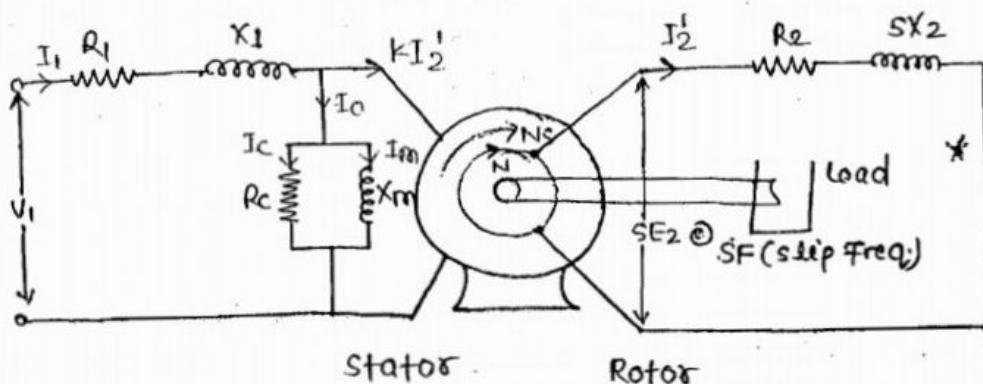
Ref to 1°



Note → As the principle of operation behaviour is identical to both TF & IM which is also called as rotating TF. The TF eq. ckt is used for representing IM. for analysis purpose.

\* However there are 2 major diff. which need to be resolved:-

- (i) freq. of rotor is slip freq.
- (ii) Loading is mech. across the shaft.



$S_{RMF}$  wrt stator @  $N_S$

$R_{RMF}$  wrt stator @  $S_{NS} + N$

∴ Rotor itself rotates @  $N$  in the same dirn of mag. Field

$$N_S - N + N$$

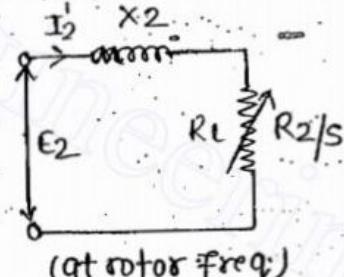
$$- \underline{N_S}$$

Note:- Both stator RMF & rotor RMF runs at syn. speed in the air-gap & make the rotor to rotate at any speed  $N$ .

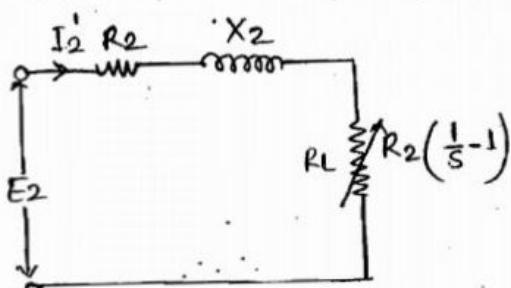
\* The absolute flux in space will always rotate at syn. speed wrt a stationary point in space of stator but wrt. rotor it is at  $S_{NS}$ .

$$I_2' = \frac{SE_2}{R_2 + jX_2 s}$$

$$I_2' = \frac{E_2}{R_2 + jX_2 s} \Rightarrow$$



(at rotor freq.)

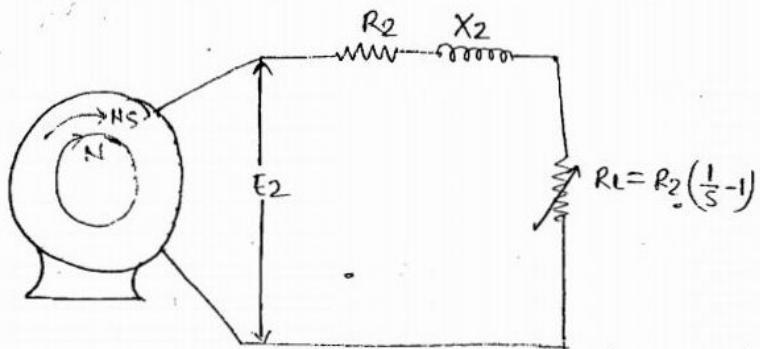


\* If  $I_m \rightarrow$  open (NL)

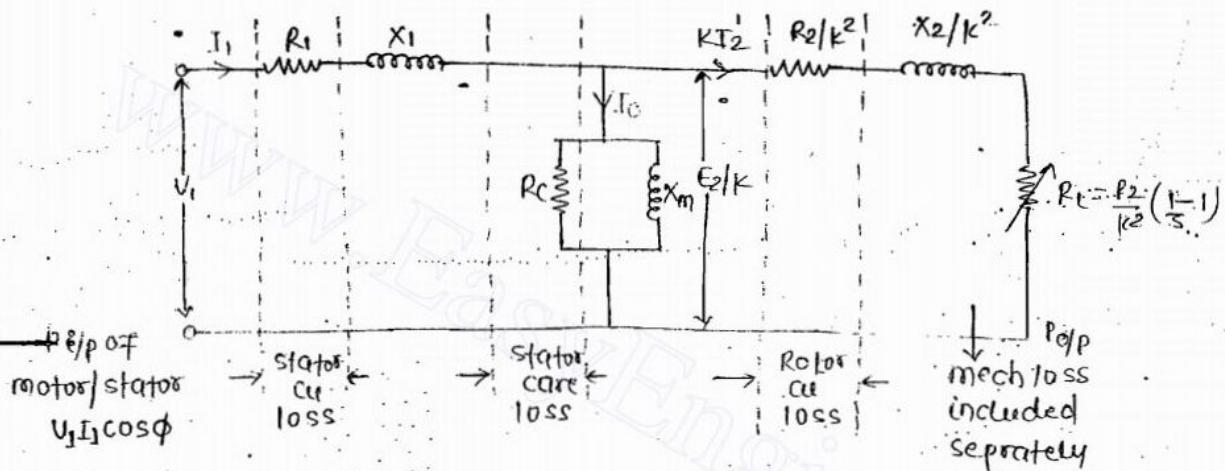
$s \rightarrow 0$   
 $R_L \rightarrow \infty$  (OC) like TF

\*  $I_m \rightarrow$  Rated load

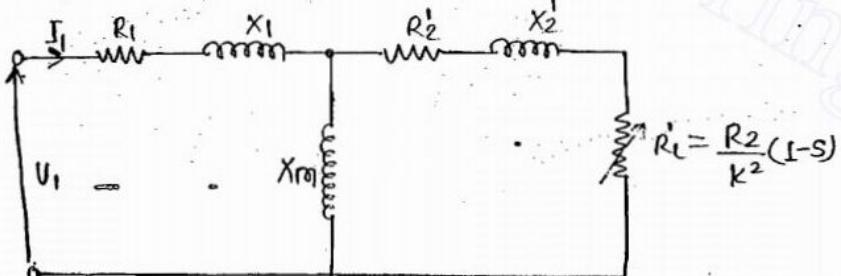
$s \rightarrow 1$   
 $R_L \rightarrow 0$  (SC)



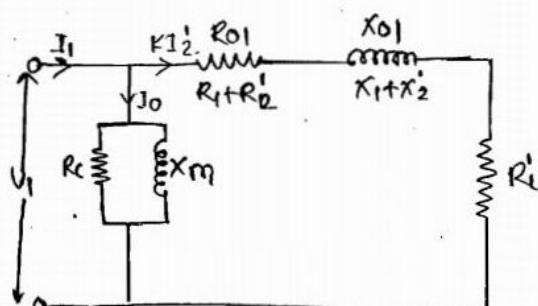
$$k = \frac{\text{Rotor turns/phase}}{\text{stator turns/phase}} = \frac{E_2 @ \text{stand still}}{E_1}$$



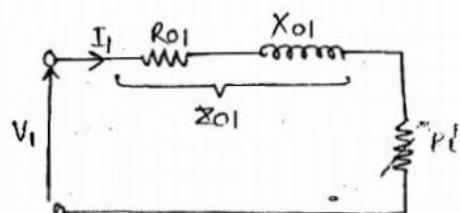
\* IEEE standard ckt representation → Shunt branch resistance is eliminated <sup>in the</sup> from std ckt but core losses & mech. losses should be included in net power calc. This will be accurate analysis.



\* Approx Eq. ckt →



Neglecting shunt branch  $\rightarrow$

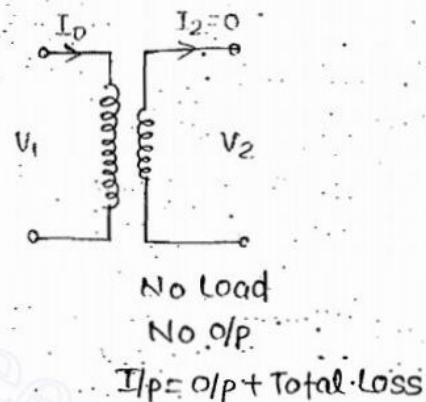
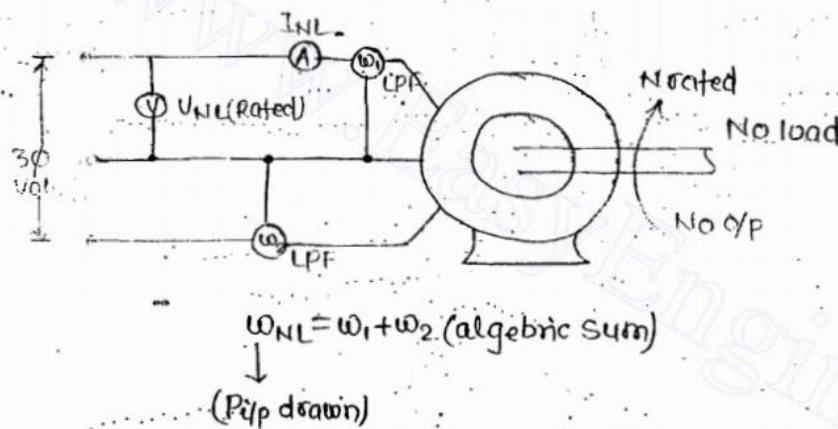


[DATE-07/12/14]

\* Determination of eq. ckt parameters  $\rightarrow$  It requires 3 tests to be performed:-

- (1.) NO Load
- (2.) Blocked rotor test
- (3.) DC test (OR) Voltmeter-Ammeter method.

(1.) NO Load test  $\rightarrow$



\* Apply rated vol. across the stator & allow it to run freely on NL.

\* Connect necessary meters & essentially LPF wattmeters are req.

\* The 3 $\phi$  power is measured using 2 wattmeter method & the total power is algebraic sum of both meter.

\* On the NL as o/p is 0 the i/p power drawn is to supply all the losses at NL. Therefore the wattmeter reading is concerned as loss.

Total loss = stator core loss ✓

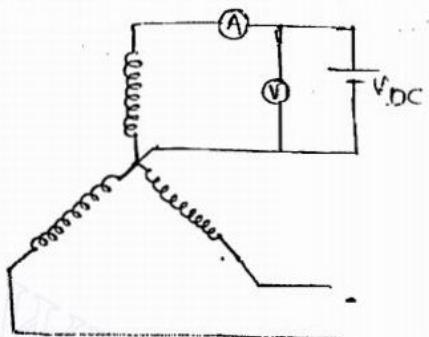
stator cu loss ✓

Rotor core loss  $\rightarrow$  Neglected due to slip freq. less

Rotor cu loss  $\rightarrow$  Neglected  
Mechanical loss ✓

- \* On NL the NL power drawn is considered to supply stator core.
- \* In order to cal. rotational or constant losses stator resistance need to be calculated to eliminate stator cu loss.

### 3.) DC test (OR) V-m, A-m method →



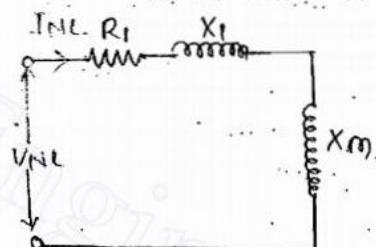
V/A Ratio  $R_{IDC}/\text{phase}$

$$R_{IAC/\text{ph.}} = \underbrace{1.2 - 1.6}_{\text{Skin effect}} R_{IDC/\text{ph.}} + \text{Hot resistance}$$

$$\omega_{NL} - 3I_{NL}^2 R_1 = \text{constant loss/Rotational loss}$$

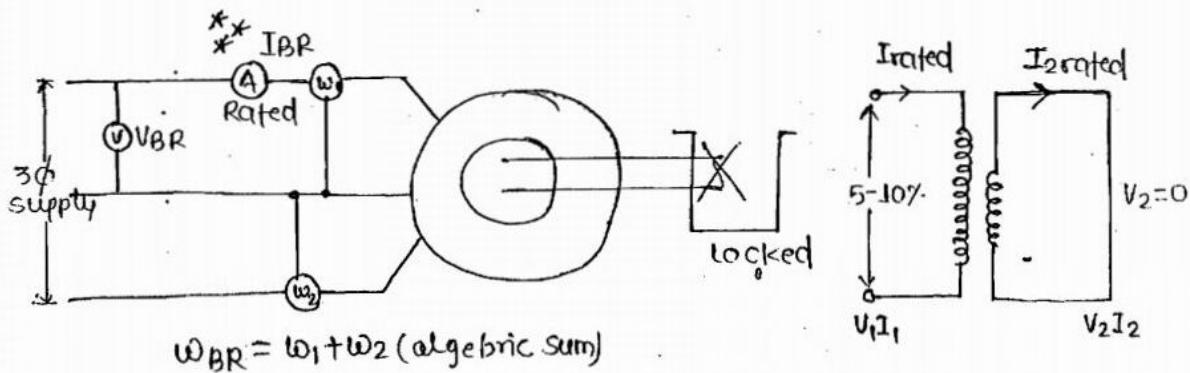
$$Z_{NL} = V_{NL}/I_{NL}$$

$$Z_{NL} = R_1 + j(X_m + X_d)$$



From the meter reading  $Z_{NL}$  is calculated, from blocked rotor test  $X_l$  is cal. & the magnetising reactance  $X_m$  is determined using the above eqn.

2.) Blocked Rotor test → The rotor is blocked initially to ensure no rotation. Vol. is applied across the stator carefully using the suitable auto Xmer to ensure rated current.

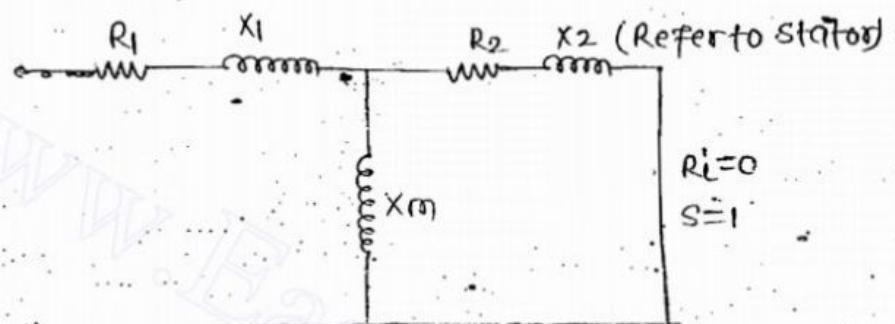


$$P = \frac{2\pi NT}{60} \quad (N=0)$$

P=0 [so we have right to take  $\omega-M$  reading as loss]

So  $\omega-M$  readings are  $\rightarrow$  Total losses

- stator core loss  $\propto$  (vol. is low)
- st. cu loss ✓ (Rated current)
- Rotor core loss  $\propto$  ( $\phi \downarrow, v \downarrow$ )
- Rotor cu loss ✓
- Mech. loss = 0 (Not running of motor)



Eq. ckt on blocked rotor cond?

\* This tests gives the information of cu loss at rated current cond?

$$\frac{V_{BR}}{I_{BR}} = Z_{BR} = R_{BR} + jX_{BR}$$

$$Z_{BR} = [R_1 + jX_1] + jX_m \| (R_2 + jX_2)$$

$$Z_{BR} = (R_1 + jX_1) + \frac{jX_m(R_2 + jX_2)}{j(X_m + X_2) + R_2} \times \frac{[R_2 - j(X_m + X_2)]}{[R_2 + j(X_m + X_2)]}$$

$$= (R_1 + jX_1) + \frac{jX_m[R_2^2 - jR_2(X_2 + X_m) + jR_2X_2 + X_2(X_2 + X_m)]}{R_2^2 + (X_2 + X_m)^2}$$

$$= (R_1 + jX_1) + \frac{jX_m[R_2^2 - jR_2X_m + X_2(X_2 + X_m)]}{R_2^2 + (X_2 + X_m)^2}$$

Equating imaginary terms

$$X_{BR} = X_1 + \frac{X_m[R_2^2 + X_2(X_2 + X_m)]}{R_2^2 + (X_2 + X_m)^2}$$

\*  $X_m$  is practically high compared  $R_2^2$   
 $(X_2 + X_m)$  is also high ..... let it be  $(X_{2m})$

$$X_{BR} = X_1 + \frac{X_m [R_2^2 + X_2 \cdot X_{2m}]}{R_2^2 + X_{2m}^2}$$

$$= X_1 + \frac{X_m [R_2^2/X_{2m} + X_2]}{[R_2^2/X_{2m} + X_{2m}]}$$

\*  $\frac{R_2^2}{X_{2m}}$  is practically very low

$$X_{BR} = X_1 + X_m X_2 = X_1 + \frac{X_m X_2}{X_2 + X_m}$$

$$X_{BR} = X_1 + \frac{X_m X_2}{\frac{X_2 + X_m}{X_m}}$$

$$= X_1 + \frac{X_2}{\left(\frac{X_2}{X_m} + 1\right)}$$

Practically low, negligible

$$X_{BR} = X_1 + X'_2$$

$X_2 \rightarrow X'_2$  (Because of refer to stator)

\* There is no practical method to separate or measure  $X_1, X'_2$ .

Therefore it is approximated as

$$X_1 \approx X'_2 \approx \frac{X_{BR}}{2}$$

Equating the real parts of eqn

$$R_{BR} = R_1 + \frac{R_2 X_m^2}{R_2^2 + X_{2m}^2}$$

$$= R_1 + \frac{R_2}{\left(\frac{R_2^2}{X_m^2} + \frac{X_{2m}^2}{X_m^2}\right)}$$

low

$$R_{BR} = R_1 + \frac{R_2}{(X_{2m}/X_m)^2}$$

$$R_2 = (R_{BR} - R_1) \left( \frac{x_{m2}}{x_{am}} \right)^2$$

$$R'_2 = (R_{BR} - R_1) \left( \frac{x_{2m}}{x_m} \right)^2$$

From blocked rotor test  $x_1, x'_2, R'_2$  & cu losses are calculated.

From both the tests all the eq. ckt parameters are evaluated including  $\eta$

$$\eta = \frac{\text{O/p}}{\text{O/p} + \text{Const} + \text{Variable}}$$

loss      loss  
↓          ↓  
Iron fric. windage      cu

\* separation of rotational losses → \* A NL test is performed to separate iron & mech. losses. using a suitable auto  $x_{mes}$

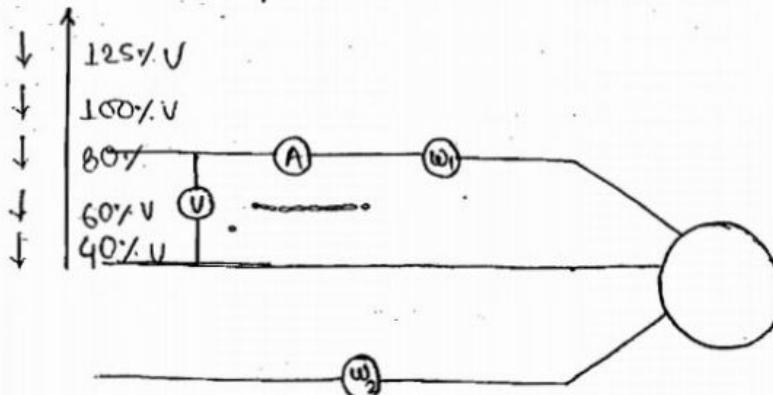
apply different vol. across the stator. from 125% rated to ground 40% rated.

\* As the motor is running on NL the torque requirement is very low & the variation of slip with variation is  $U$  is low upto a breakdown point.

Therefore in the testing cond'n the speed of motor is approx. same (variation is less)

$$T \propto SV^2 \quad (\because E \propto V^2)$$

Iron losses  $\propto \phi$ , mech. losses  $\propto N$



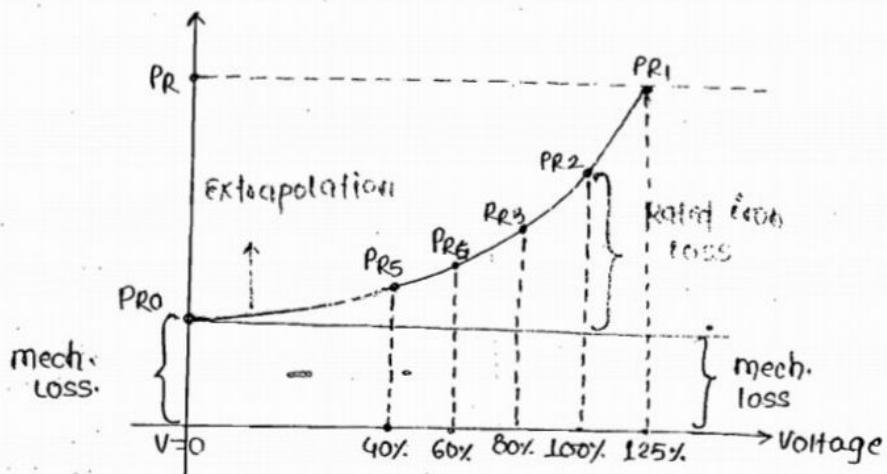
$$(1) \quad U_{NL1} \quad I_{NL1} \quad \omega_{NL1} \rightarrow \omega_{NL1} - 3I_{NL1}^2 R_1 = PR_1$$

$$(2) \quad U_{NL2} \quad I_{NL2} \quad \omega_{NL2} \rightarrow \omega_{NL2} - 3I_{NL2}^2 R_1 = PR_2$$

$$(3) \quad 80\% \quad \omega_{NL3} - 3I_{NL3}^2 R_1 = PR_3$$

$$(4) \quad 60\% \quad \omega_{NL4} - 3I_{NL4}^2 R_1 = PR_4$$

$$(5) \quad 40\% \quad \omega_{NL5} - 3I_{NL5}^2 R_1 = PR_5$$



(Curve is parabolic along with  $V^2$ )

#### \* Circle diagram →

- \* It is the graphical representation of approximate eq; ckt.
- \* Once a circle dia. is plotted any analysis parameter can be simply & rapidly determined (approximately) w/o approaching the motor.
- \*  $\text{W.L}$  The locus of current in a series RL ckt will make a circle with a dia.

$U/X$

- \* If a chord in a circle is bisected it passes through its center.
- \* In order to plot it is required data from NL test, blocked rotor test & the dc test.
- \* Circle dia. is plotted on a vertical Vol. or ref. axis. Therefore blocked rotor test values need to be adjusted to rated vol. base. for plotting circle dia.

No load test →  $V_{\text{rated}}$

$$V_{NL} \quad I_{NL} \quad \omega_{NL} = \sqrt{3} V_{NL} I_{NL} \cos \phi_{NL}$$

$$\star V_{\text{rated}} \leftarrow I_{NL} \quad \phi_{NL} = \cos^{-1} \left[ \frac{\omega_{NL}}{\sqrt{3} V_{NL} I_{NL}} \right]$$

Blocked Rotor → (5-10%  $V_{\text{rated}}$ ) →  $V_{BR}$

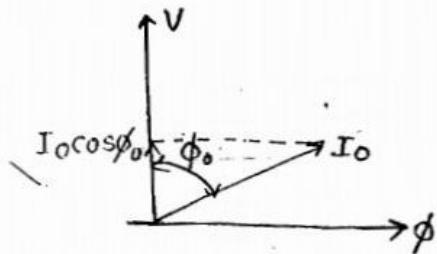
$I_{BR}$  } (values adjust to  $V_{\text{rated}}$ )  
 $\omega_{BR}$  }

$$V_{BR} \quad I_{BR} \quad \omega_{BR} = \sqrt{3} V_{BR} I_{BR} \cos \phi_{BR}$$

$$\text{If } V_{\text{rated}} \quad ?(I_{SN}) \quad \phi_{BR} = \cos^{-1} \left[ \frac{\omega_{BR}}{\sqrt{3} V_{BR} I_{BR}} \right]$$

$$I_{SN} = \frac{V_{\text{rated}}}{V_{BR}} \times I_{BR}$$

$$\begin{array}{l} I_{BR}^2 \quad W_{BR} \\ * I_{SN}^2 \quad ? W_{SN} \\ ** W_{SN} = \left( \frac{I_{SN}}{I_{BR}} \right)^2 \cdot W_{BR} \end{array}$$



\* As the circle dia. is plotted on vertical V-axis as a ref., all the vertical distances on the circle dia. represents active power in watts.

Steps →

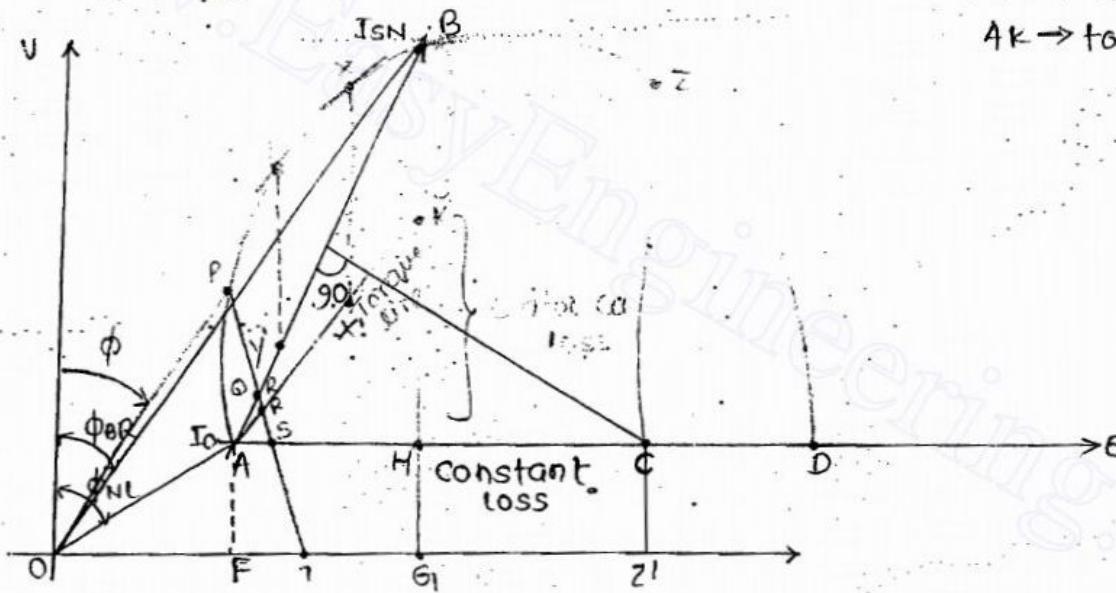
(1) Draw NL current wrt its PF angle with suitable scale

(2) Draw ISN wrt its PF angle  $\phi_{BR}$

(3) Bisect the o/p line to meet at point C on the horizontal line AE-C, as center & length of AC as radius.

A circle is plotted to meet ABD.

AB → o/p line.  
AK → torque line



\* The vertical distance length of BG represents total losses for a current ISN. As it is blocked rotor mode mech. losses are zero; but it gives sufficiently accurate value because rotor core losses are neglected under such cond?

\* length of BH represents variable losses i.e. stator cu loss & rotor cu loss for ISN.

\* From dc test stator cu losses are cal. For a current ISN value & using power scale a power point K is located where length of HK represents stator cu loss.

\* Consequently the other length BK represents rotor cu loss.

power scale:- watts/cm.

$$l(BG)_{\text{cms}} = \omega_{SN} (\text{watts})$$

$$1\text{cm} = \frac{\omega_{SN} (\text{watts})}{l(BG)_{\text{cms}}}$$

Join AK, which is called as torque line.

Data obtained from circle dia:-

- (1) max<sup>m</sup> torque :- Draw a tangent on circle parallel to torque line to meet at point X. Drop a vertical on to the torque line to meet at X'.

$$l(xx') \times \text{power scale} = T_{\text{max}} \text{ in watts}$$

↓  
Synchronous watts

$$T = \frac{60}{2\pi N_s} \times RPi/p$$

$T \propto P$

Constant

- (2) max<sup>m</sup> O/P → Draw a tangent parallel to o/p line to meet at point on the circle dia. Drop a vertical on to vertical line to meet at Y'.

$$l(yy') \times \text{power scale} = \text{max O/P in watts}$$

- (3) Starting torque → start

$$\begin{aligned} T &= \frac{60}{2\pi N_s} \times RPi/p \\ &= \text{const.} \times \frac{\text{Rotor cu/loss}}{s} \end{aligned}$$

$$T = \text{const} \times \frac{\text{Rotor cu/loss}}{s}$$

$$T_{st} \propto \text{Rotor cu/loss} \quad (s=1)$$

$T_{st} \propto \text{length of BK}$  in watts

$$T_{st} = \frac{60}{2\pi N_s} l(BK) \text{ max power scale (N-m)}$$

(4) I/P →

$$I/P = O/P + \text{Total losses}$$

Extend point C on to the circle dia. to meet at Z & the bottom axis to meet at Z'.

$$l(ZZ') \times \text{Power scale}$$

Eg:- From the test data given plot circle dia. & cal. all its performance parameter when the motor operates at full load.

\* Calculate the rated current of motor & locate a point P on the circle dia. so that length of OP represents  $I_{\text{rated}}$ .

Draw a vertical line parallel to Vol. axis to meet at point Q, R, S, T

$$l(ST) \times \text{Power scale} = \text{Const. Loss}$$

$$l(RS) \times \text{Power scale} = \text{Stator cu loss}$$

$$l(RQ) \times \text{Power scale} = \text{Rotor cu loss}$$

$$I/P = O/P + \text{total losses}$$

$$\boxed{I/P = PQ + TQ}$$

$$l(PQ) \times \text{Power scale} = O/P$$

$$l(PT) \times \text{Power scale} = I/P$$

$$\underline{l(TQ)} \times \text{Power scale} = \text{total loss}$$

$$\eta = \frac{O/P}{I/P} = \frac{PQ}{PT}$$

$$\text{Slip} = ? , \text{rotor cu loss} = s \cdot \text{Rotor power} \\ \frac{I/P}{I/P}$$

$$l(RQ) = s \cdot l(PR)$$

$$s = \frac{RQ}{RP}$$

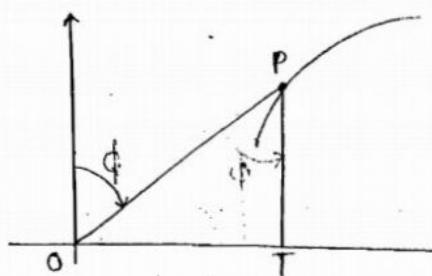
$$N = N_S(1-s)$$

Known

$$T_g = \frac{60}{2\pi N_S} \cdot l(RP) \times \text{Power scale} \quad \text{N-m}$$

$$T_{sh} = \frac{60}{2\pi N} \cdot I(PQ) \times \text{Power scale} \cdot \text{N-m}$$

Power Factor →



From Δ OPT

$$\cos\phi = \frac{PT}{OP}$$

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\* Starting methods → When rated vol. is applied across the stator of IM during starting  $N=0, S=1$ , it is eq to applying rated vol. across Xmers 1° when its 2° is sc.

- The rotor will have huge current which comes through stator. Therefore the motor draws extremely large current from supply which is not acceptable because it produce vol. dip in supply lines.
- It may not damage the motor as they are rugged in construction & accelerate quickly & the starting current is inrush.

- (1) Direct online starting (DOL)
- (2) Stator resistance / Reactance starting
- (3) Auto Xmers.
- (4) Star-delta
- (5) Rotor resistance

} Reduced vol.  
starting

(1.) Direct online starting →

- \* popular for 1φ & upto 5kw For 3φ because of cost is less.
- \* push ON/ push OFF

Overload → Bimetallic

Underload → when power is not present

\* It is not reduced vol. starting.

\* It has a push ON/ push OFF switch where the stator is directly connected to

- supply.
- \* starting current is very high but it is inrush.  
As the motor starts quickly.
  - \* It is only suitable to small rating.  
most popular under 2kW segment ( $1\phi$ ) as it is low cost.
  - \* There are 2 protection:-
    - (1) Overload protection using thermal elements like bimetallic.
    - (2) Undervolt protection to prevent the motor from unintentional start after a power failure.

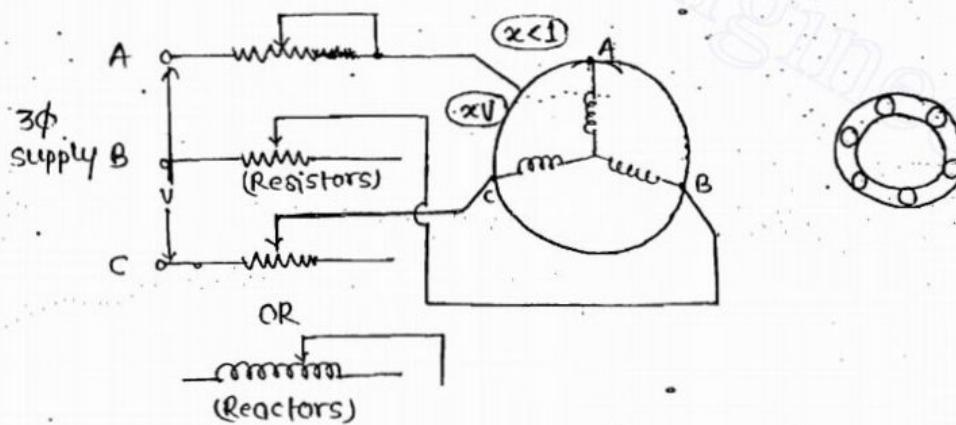
### (2.) Stator resistance / reactors starting $\rightarrow$

when we supply the stator excessive amt. of current flows in the rotor.  
so;

$$I_2 = \frac{E_2}{(R_2 + jX_2)} \rightarrow \text{Fixed}$$

$$E_2 \downarrow, I_2 \downarrow$$

$$\text{so; } E_2 \downarrow \rightarrow \phi \downarrow \rightarrow V_1 \downarrow$$



$$T_g = \frac{60}{2\pi N_s} \frac{\text{Rot. cu loss}}{s}$$

$$T_g = \frac{60}{2\pi N_s} \frac{3(I_2^2 R_2)}{s}$$

$$T_{st} \propto \frac{I_{st}^2}{S_{st}} \quad | \quad T_F \propto \frac{I_F^2}{S_F}$$

$$(S_{st}=1)$$

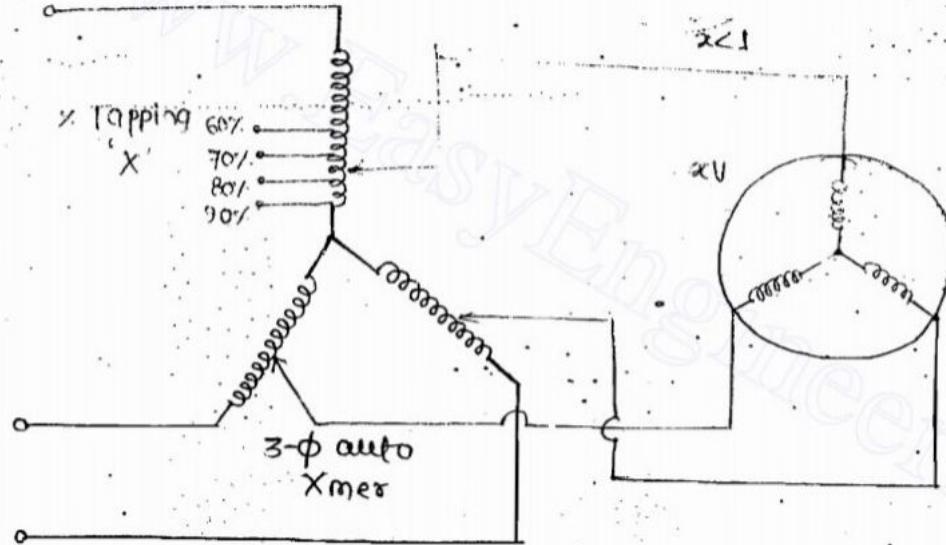
\*\*

$$\boxed{T_{st} = \left(\frac{I_{st}}{I_F}\right)^2 \cdot S_F}$$

$$\frac{T_{st}}{T_f} = \alpha^2 \left( \frac{I_{st}}{I_f} \right)^2 \cdot S_f$$

- \* By adding some external resistance in series with stator some vol. gets dropped & reduced vol. will appear across stator which correspondingly control the starting current.
- \* Reactors also can used where  $\eta$  is not greatly effected but pf of the motor will be low lagging & starting torque also less.
- \* The effect of starting torque is expressed in above relation.

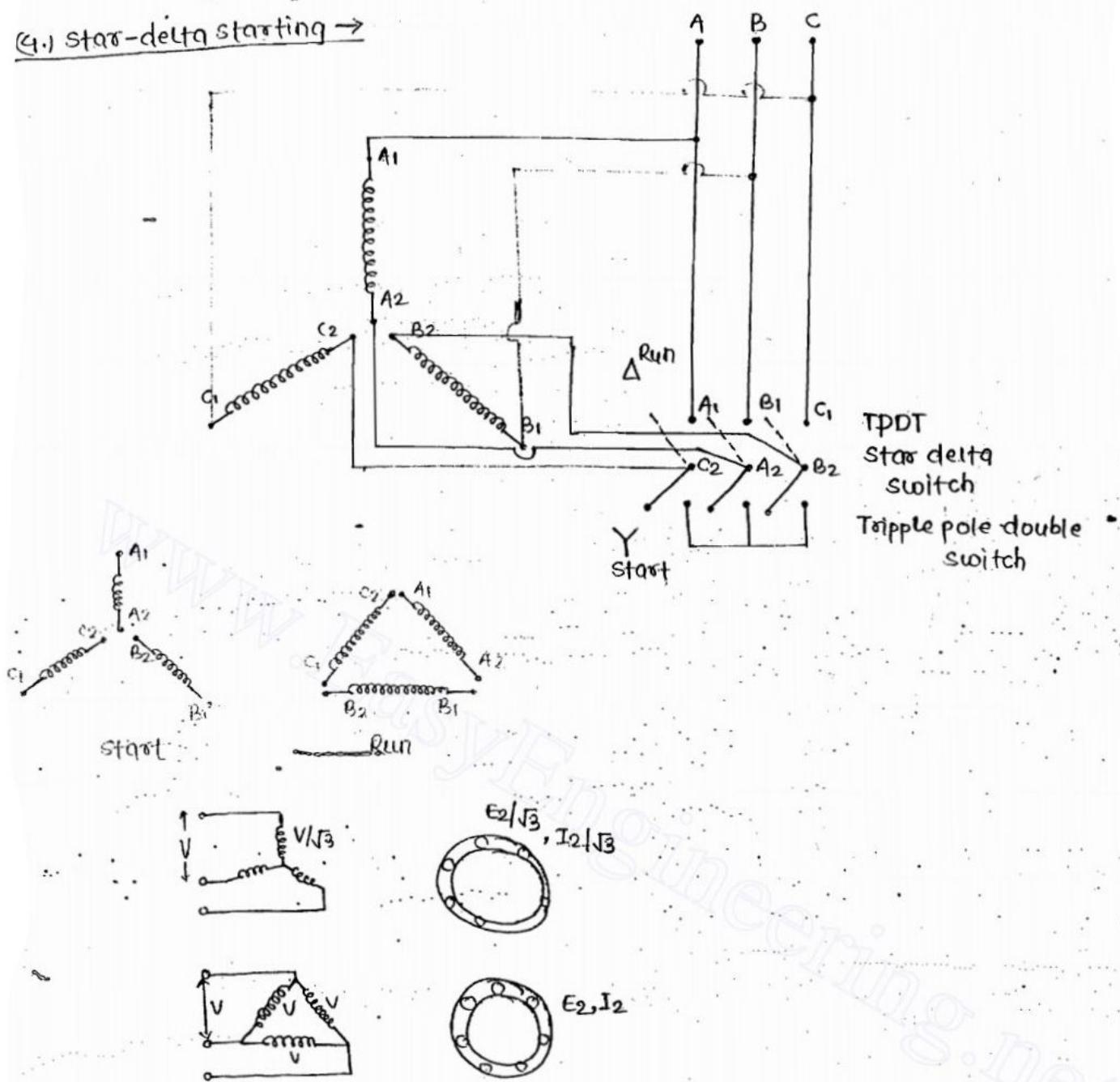
### (3) Auto Xmer starting →



- \* This is generally preferred for starting large rating  $I_{ms}$  due to its flexibility & high  $\eta$  but expensive method.
  - \* It require a suitable rating 3 $\phi$  auto Xmers.
  - \* Depending on % tapping ( $\alpha < 1$ )
- Depending on tapping starting current control & effect of starting torque expressed

$$\frac{T_{st}}{T_f} = \alpha^2 \left( \frac{I_{st}}{I_f} \right)^2 \cdot S_f$$

(Q.) star-delta starting →



\* It gives one step control on the starting current.

It is most simple & economic starter with a TPDT switch only.

The stator 3φ wdg is connected as shown.

It is suitable for motors which are designed for  $\Delta$  under running cond'.

1st the stator is connected to  $\lambda$  which results in reduced vol. & current in rotor about 57.7% only ( $V_{ph.} = V/\sqrt{3}$ ).

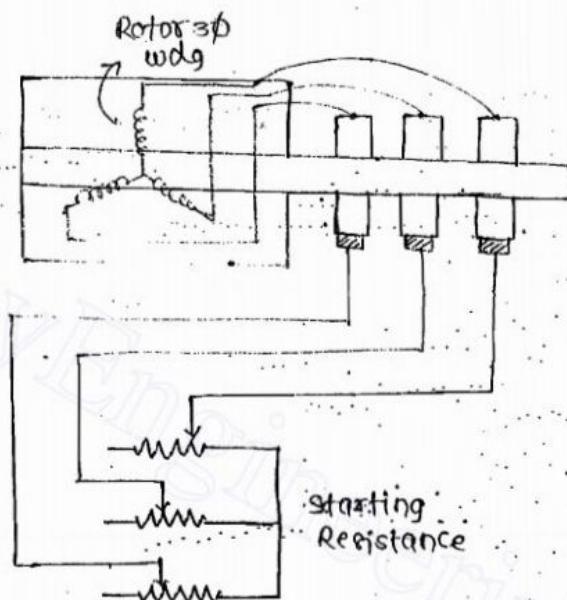
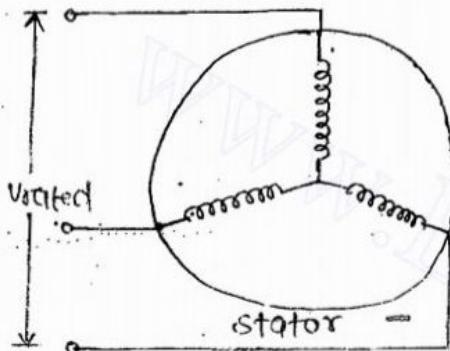
Under running the switch should be thrown out to  $\Delta$  atleast the motor reach 90% of rated speed for nominal rated operating cond' ( $v_r = V_{ph.}$ )

\* Not suitable for extra high vol. rating greater than 3.3kV because those motors stators are preferably designed for 1.

$$\frac{T_{st}}{T_F} = \frac{1}{3} \left( \frac{I_{st}}{I_F} \right)^2 \cdot SF$$

\* The ratio of starting to FL torque is expressed above.

### (5.) Rotor resistance starting →



$$T \propto (E_2 I_2 \cos \phi_2) \quad \begin{matrix} \uparrow \\ \text{very} \\ \text{Because of resistance} \end{matrix}$$

↓  
rated

\* This is technically best way to start IM.

\* It is fundamental method of starting slip ring motors by inserting some resistance into rotor of suitable value through slip rings & brushes.

\* This resistance will control the rotor current & motor current during starting while reducing the starting current to a required value starting torque is increased because the improved PF will dominate.  
However rated vol. is applied across the stator.

This are preferred for high starting torque appUlike electric traction

(52)  
32 (c)

$$\frac{Tst}{T_f} = x^2 \left( \frac{Ist}{I_f} \right)^2 S_f$$

$$1.5 = x^2 (7)^2 (0.05)$$

$$x = 78.25\%$$

$$(53) \quad (32) \quad \frac{Tst}{T_f} = \frac{1}{3} \left( \frac{Ist}{I_f} \right)^2 S_f$$

$$= \frac{1}{3} (7)^2 (0.05)$$

$$= 0.816$$

(54) (c) Because of no given any starting method, use basic formula.

$$\left( \frac{Tst}{T_f} \right) = \left( \frac{Ist}{I_f} \right)^2 S_f$$

$$0.5 = \left( \frac{Ist}{I_f} \right)^2 \times 0.05$$

$$\left( \frac{Ist}{I_f} \right) = 3.16$$

(60)  
33 (d.)

$$\frac{Tst}{T_f} = \left( \frac{Ist}{I_f} \right)^2 S_f$$

$$1 = \left( \frac{Ist}{I_f} \right)^2 (0.04)$$

$$\left( \frac{Ist}{I_f} \right) = 5$$

(64)  
33 (d.)

$$(0.3)^2 \rightarrow 80 \text{ N-m}$$

$$(0.6)^2 \rightarrow ?$$

### \* Speed control →

\* These are not popular like dc shunt motors when compared to effective speed control. even though the T-S c/s are identical, shunt motors are preferred because of their effective speed control.

\* Speed control can be done from stator side & rotor side (slipping)

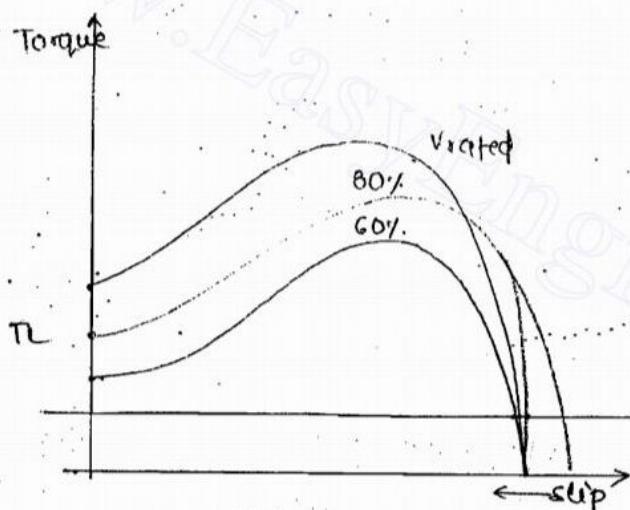
### \* Stator side →

- (1) Supply voltage control
- (2) Freq. ( $V/f$ )
- (3) Pole changing
- (4) Stator Resistance.

### \* Rotor side →

- (1) Rotor Resistance control
- (2) Slip power recovery
- (3) Cascading/Tandem connection.

### (1) Supply Vol. control →



- \* It requires an auto Xmer of suitable ratings for getting variable vol. If the motor runs at constant load or torque condn as the vol. reduces the motor will react by increasing its slip.
- \* Consequently speed reduces & operate at different speed. However for same load the motor will draw more current from supply & becomes inefficient.

(2) Freq. (V/F) control →

- \* freq. is varied by keeping V/F ratio constant in order to maintain flux density constant.
- \* Otherwise the stator & rotor core gets deeply saturated & motor draws large magnetising current.
- \* It requires expensive power electronic converter ckt for variable vol. & freq.

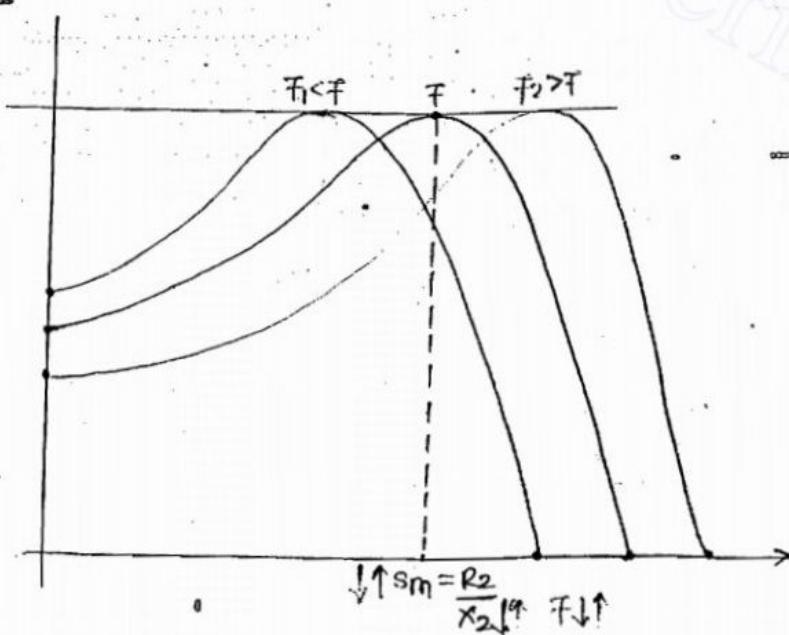
$$V_1 = E = 4.44 f N_1 \cdot B_m A$$

$$B_m \propto \frac{V}{f}$$

$$T_{max} \propto \frac{1}{N_S} \frac{E_2^2}{(2X_2)} = \frac{3 \times 60}{2\pi N_S} \left( \frac{E_2}{2X_2} \right)^2$$

$f : N_S$	$f : E_2$	$f : X_2$
$f_1 : N_{S1} = \left(\frac{f_1}{f}\right) N_S$	$f_1 : E_{21} = \left(\frac{f_1}{f}\right) E_2$	$f_1 : X_{21} = \left(\frac{f_1}{f}\right) X_2$

$$T_{max1} = \frac{1}{N_{S1}} \times \frac{E_{21}^2}{2X_{21}}$$



- \* Within the control range the max<sup>m</sup> & breakdown torque remain same.
- \* However it doesn't offer wide range as the voltage is also correspondingly reduced.
- \* Method is very expensive.

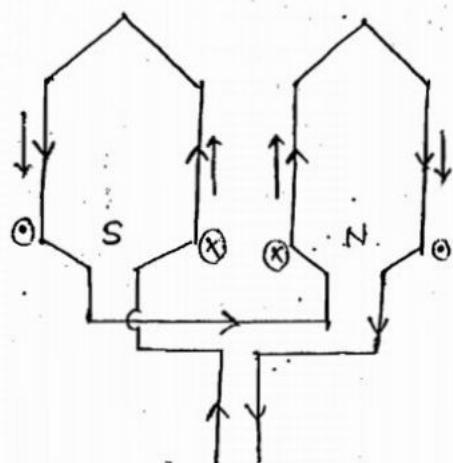
### (3) Pole changing →

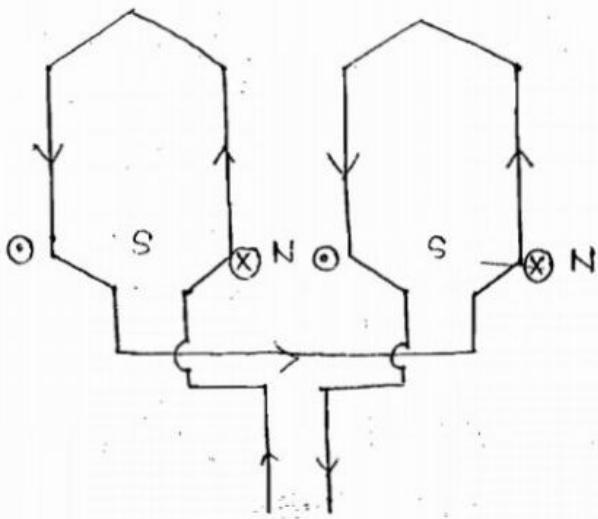
- (1) Multiple wedges
- (2) Consequent pole changing.

\* The stator slot contains 2 independent sets of wedges designed for different no. of pole.

e.g.: 2, 4 (OR) 4, 8.

- \* Depending on the speed requirement either wedge can be connected to the supply & other one left disconnected.
- \* The wedges are preferably in L. This will increase stator size & overall size of motor & motor becomes expensive & economically not advantages for more sets of wedges.
- \* Another alternate method is through switching the wedge externally for consequent pole formation in the stator.
- \* It supports only squirrel cage rotor because the poles are formed automatically & the rotor responds to any no. of poles on stator.





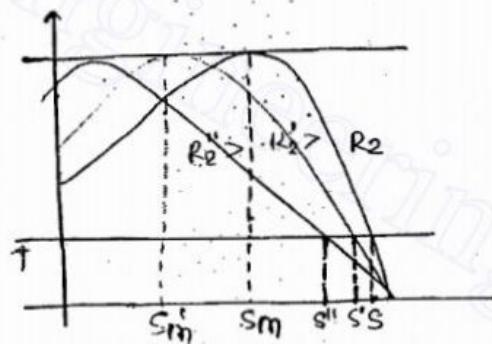
#### (4.) Stator resistance →

- \* It is the same method used start the motor.
- \* It is vantagenous starting than speed control because it will greatly effect  $i.e. \eta$  but preferred because of low cost for small rating.
- \* Principle is identical to vol. control.
- \* It requires only resistances to reduce vol. across stator.

#### \* Rotor side →

##### (i.) Rotor resistance control →

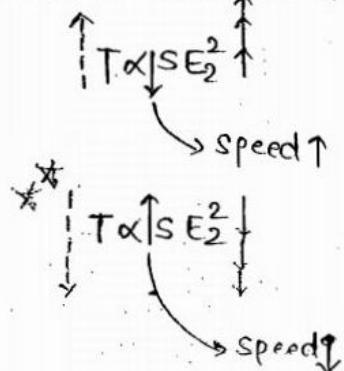
$$T \propto \frac{s}{R_2}$$



- \* In slipping motors external resistance can be added into the rotor ckt under running cond<sup>n</sup>
- \* If the motor runs at const. load (or) torque as the rotor resistance increased slip increase correspondingly to maintain torque on constant.
- \* As the rotor resistance increased with increased current the rotor loss increases gets overheated practically.
- Therefore it is not suitable for wide range (or) long duration.

## (2) slip power recovery →

- \* Injecting external vol. into the rotor through slip-rings at rotor freq. (or) slip freq; in order to obtain steady torque.
- \* However this control is also expensive & doesn't give a wide range. It can be done in 2 ways:-
- \* (i) Injecting the vol. to add the existing rotor vol.



- \* To maintain the torque const. slip reduce & speed increase
- \* (2.) Injecting the vol. to oppose the rotor vol. which reduces the vol. is rotor. & to main the torque the motor react by increasing its slip. consequently speed ↓

'subynchronous'

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## (3) Cascading/Tandem connection →

$$N_1 = Ns_1(1-s_1)$$

$$N_2 = Ns_2(1-s_2)$$

$$N_1 = \left(\frac{120F}{P_1}\right)(1-s_1)$$

$$N_2 = \left(\frac{120F}{P_2}\right)(1-s_2)$$

$$N_1 = N_2 = N$$

$$\left(\frac{120F}{P_1}\right)(1-s_1) = \left(\frac{120Fs_1}{P_2}\right)(1-s_2)$$

$$\frac{1-s_1}{P_1} = \frac{s_1 - s_1 s_2}{P_2} \quad (\because s_1 s_2 \rightarrow 0)$$

$$\frac{1-s_1}{P_1} = \frac{s_1}{P_2}$$

$$\frac{1-s_1}{s_1} = \frac{P_1}{P_2}$$

$$\frac{1}{s_1} - 1 = \frac{P_1}{P_2}$$

$$\frac{1}{s_1} = \frac{P_1 + P_2}{P_2}$$

$$s_1 = \frac{P_2}{P_1 + P_2}$$

$$N = \frac{120F}{P_1} \left(1 - \frac{P_2}{P_1 + P_2}\right)$$

$$N = \frac{120F}{P_1 + P_2}$$

+ cumulative cascading.

- differential cascading.

Individual operation:-

$$N_3 = \frac{120F}{P_1}, \quad N_1 = \frac{120F}{P_1 + P_2}, \quad N_4 = \frac{120F}{P_2}, \quad N_2 = \frac{120F}{P_1 - P_2}$$

- \* It requires essentially one slip ring motor.
- \* Both the motors are mechanically coupled as well as electrically connected to slip rings.
- \* This drive will offer 4 sets of speed with independent operation included.
- \* If the  $\phi$  seq. of 2nd motor is same it is cumulatively cascaded otherwise differential.

\* The poles should be different for 2 motors specially for differential cascading.

(32) (C)  $\frac{32}{29}$  MFC

Ques → A 50Hz 4P IM is running at 1200 rpm. What should be the freq. of vol. injected into rotor for obtaining steady torque?

Ans →

$$S = \frac{1500 - 1200}{1500} = \frac{1}{5}$$

$$SF = \frac{1}{5} \times 50 = 10 \text{ Hz}$$

\* Braking →

Braking is done to instantaneously to stop motor rapidly at required instant.

This is very essential particularly in manufacturing process of drives.

It is similar to braking in DC motors.

(1) Plugging → Reversing the  $\phi$  seq. by interchanging any 2  $\phi$  terminal across stator in running motor.

The rotor want to rotate in the opposite dir<sup>n</sup> due to which it come near 0 speed where an adequate mech. braking is applied. Otherwise there is a danger of motor rotating in reverse dir<sup>n</sup>.

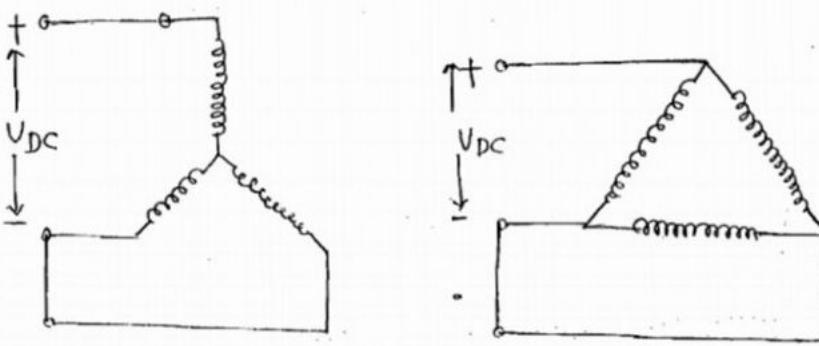
During plugging due to high relative speed (~~N<sub>A</sub>, N<sub>M</sub>~~) <sup>Not N<sub>R</sub></sup> high vol. current will appear in rotor. Motors undergo plugging should be design to stand this cond<sup>n</sup> which include high temp. rise.

However the time of plugging is small as the motor starts it will disconnected from supply.

(2) Dynamic → Disconnecting 3 $\phi$  supply across stator & a suitable dc. vol. will be applied across any 2 phases. It produces a constant stationary time varying flux in air gap & make rotor to stop quickly.

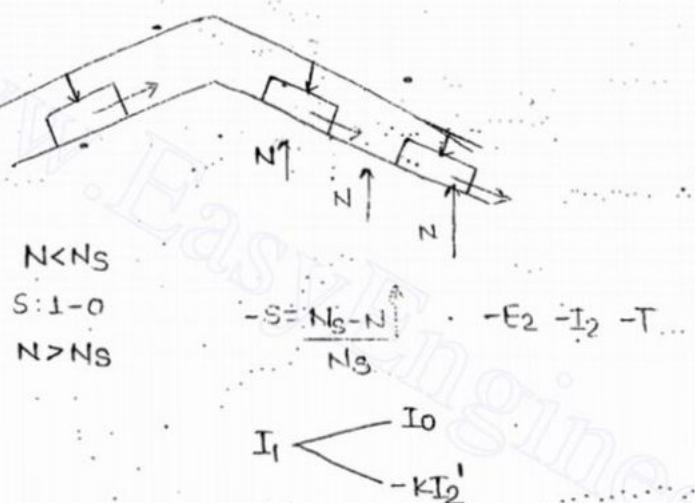
As the rotor rotates due to flux, emf, current & torque produce to oppose cause (relative speed)

Therefore motor stops quickly.



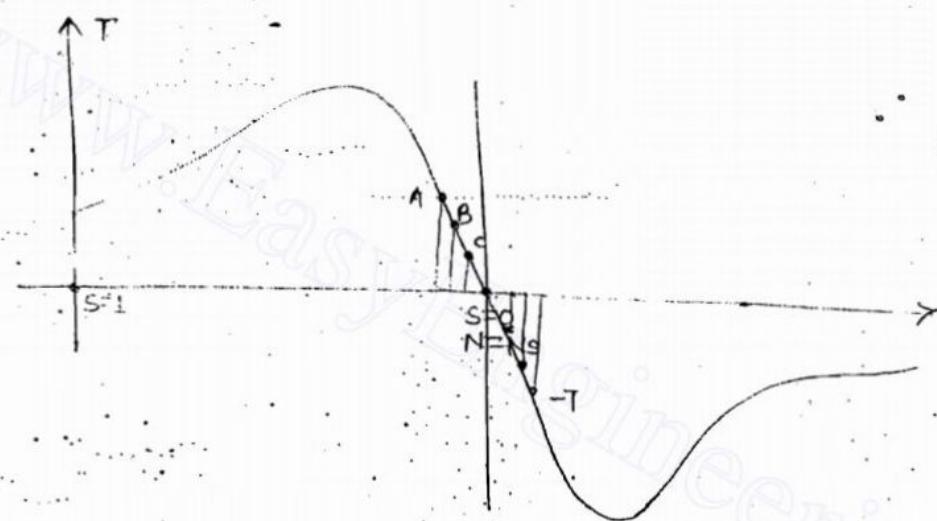
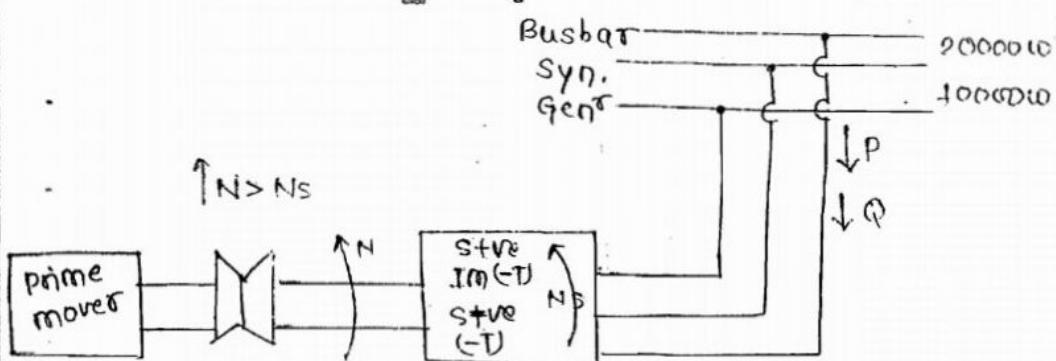
Note → There is no danger of speed reversal but induced currents in rotor should be control either from stator side (or) rotor side if its a slipping.

### (B) Regenerative Braking →



- \* This is not intentional braking & it won't stop the motor like above 2 b.
- \* But it will naturally produce a braking torque when motor is subjected to overhauling load & release some stresses for mech. braking sys.
- Therefore it is advantageous in mountain railways where slipping motors are preferred.
- \* When the motor increases its speed ( $N > N_s$ ) slip becomes -ve to develop -ve torque which produce braking.
- \* The rotor induced emf & current also reverses & consequently rotor component in stator will reverse. Therefore during this braking period it will act as ind<sup>n</sup> gen<sup>r</sup> while supplying the rotor component of current to supply lines instead of drawing it.
- \* In the period it continues to draw magnetising current from supply.

## \* Induction Generator →



- \* If an IM is connected to suitable prime mover & rotated greater than its syn. speed it act as Indn gen by supplying active power while drawing reactive power from bus (supply lines where it is connected)
- \* It can't operate alone as it requires  $Q$  when it is connected to  $\infty$  bus where syn. gen are operating across it the active power supplied to the bus freq depends on the freq of reactive power drawn from bus.
- Therefore in such condn in its operating region the freq of active power supplied is independant of speed variation.
- Therefore it is used for variable speed generation specially non-conventional like wind mills, mini hydro plants etc.

\* It act as reactive power burden on existing syn. gen<sup>r</sup>.

Therefore not preferred generally, but advantageous in specific power gen<sup>r</sup> as the m/c is simple in design, less cost, maintenance free operation, no hunting, stability prob & doesn't require any dc excitations.

\* In such emergency appl<sup>n</sup> it can be used a load as self excited Ind<sup>n</sup> gen<sup>r</sup>.

### \* self excited ind<sup>n</sup> gen<sup>r</sup> →

The principle is as similar to vol. build up in self-excited shunt gen<sup>r</sup>.

It requires some residual flux in rotor which is achieved through running m/c at IM for some time.

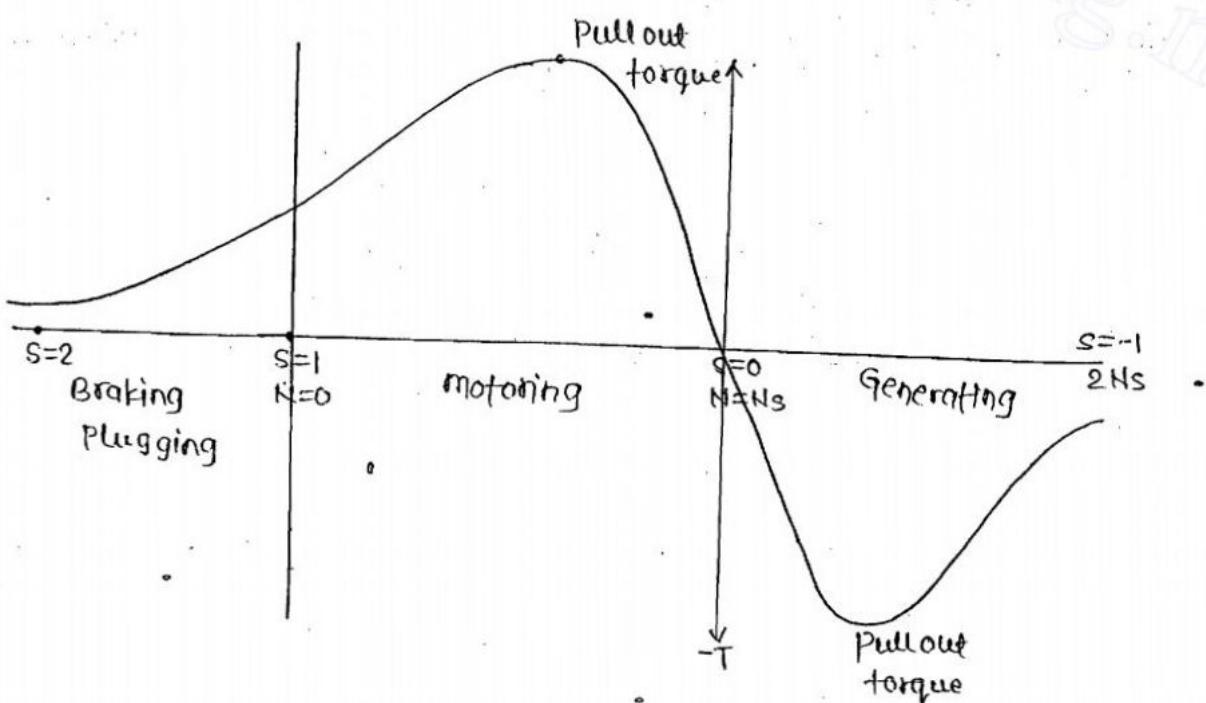
Once the rotor is rotated residual flux induce vol. in the stator where a capacitor bank is connected across it which supplies reactive power for flux development.

There is a cumulative build up of flux in air gap upto saturation of stator & rotor cores.

This is not suitable for loads which demand high reactive power eg:- large IM while starting.

The capa. bank should supply the reactive power demand of gen<sup>r</sup> as well as load.

Effective control is required to control reactive power otherwise bus vol. will vary.



## \* Special Constructions →

Square cage Im Rotor → Generally around 90% motors are sq. cage type because of there own ad.

\* But the basic limitation is due to there low starting torque.

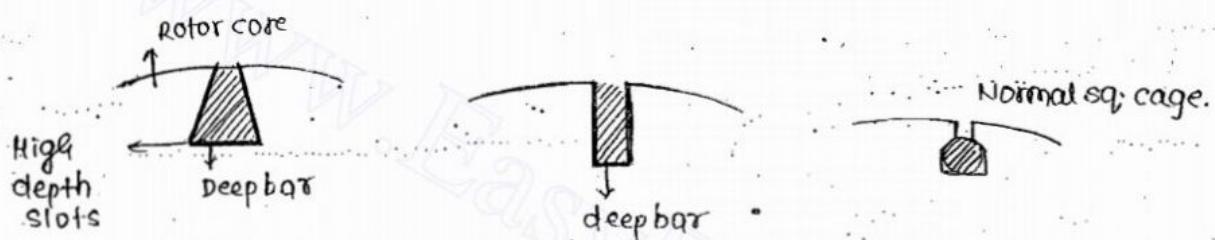
\* In order to increase there starting torque w/o effecting there n<sub>r</sub> must some special constr. are adopted.

\* The principle of cons is based on skin effect.

(1) Deep bar

(2) Double cage

\* Deep bar →



\* The rotor contains high depth slots where deep bars are placed & solidly sc with 2 end rings.

\* During starting motor freq. is supply freq. Skin effect dominates & the current want to flow only on the top region of deep bar.

Therefore it offers high resistance to starting current which increase the starting torque while reducing starting current.

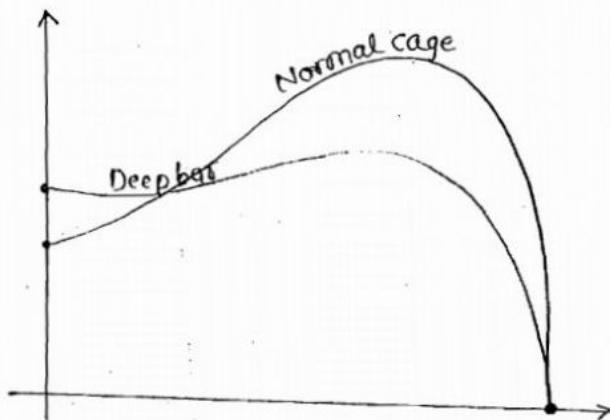
\* When the motor runs the motor freq. is slip freq. very low.

Therefore skin effect is negligible.

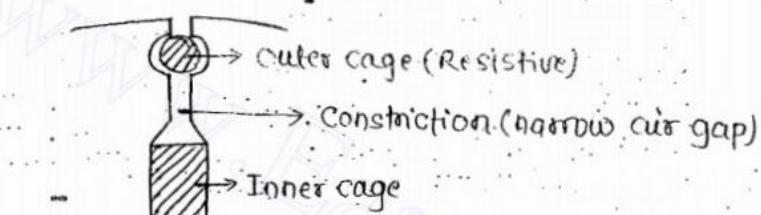
\* Consequently the current shifts into bottom region which offer low resistance & running n<sub>r</sub> are not affected.

\* Due to deep slot (or) bar the leakage reactance at stand still is high.

Therefore this motors have less max<sup>m</sup> (or) breakdown torque not suitable for high rating loads (or) doesn't have good overload capability used for small rating apph comparatively which demand high starting torque.



\* Double cage →



\* It contains 2 cages :-

- (1) Outer cage with small cross-sectional area high resistance.
- (2) Inner cage is large cross-sectional area less resistance.

\* which are solidly sc with end rings on both sides

\* During starting the freq. of rotor is supply freq. & starting current only flows in outer cage which offer high resistance to result in high starting torque while reducing starting current.

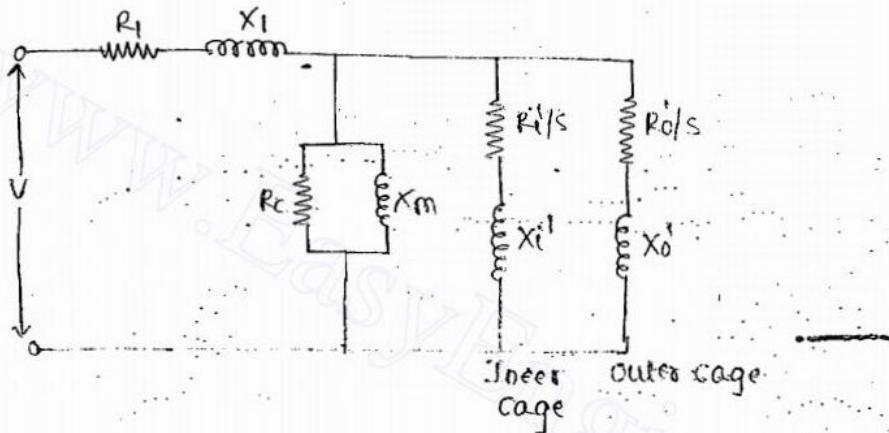
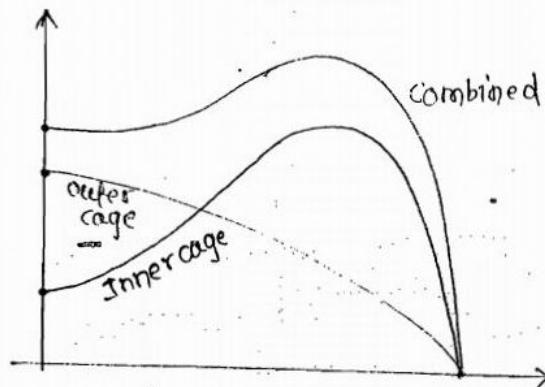
\* Under running condn rotor freq. will be negligible & skin effect is quite low.

Therefore the current shifts into inner cage which offer low resistance.

Starting torque increased w/o effecting running h must.

\* The basic diff. b/w deepbar & double cage lies in constriction (narrow air gap b/w 2 cages).

\* It reduce leakage reactance of rotor at stand still & result in more max<sup>th</sup> or breakdown torque compare to deep bar.



\* These special constructions are rarely preferred for specific apph. specially less ratings compared to sq. cage but demand high starting torque.

\* for large rating high starting torque requirements slip ring motors are preferred.

DATE-10/12/14

Crawling →

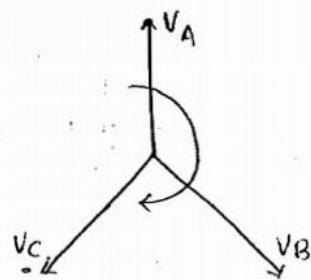
Odd  
 →  $3m$        $3, 9, \dots$   
 →  $3m-1$        $5, 11, \dots$   
 →  $3m+1$        $7, 13, \dots$

Fundamental (f)

$$V_A = V_m \sin \omega t$$

$$V_B = V_m \sin (\omega t - 120^\circ)$$

$$V_C = V_m \sin (\omega t - 240^\circ)$$

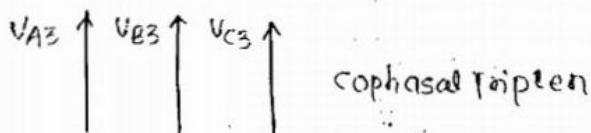


### 3rd harmonics (3f)

$$V_{A3} = V_m 3 \sin \omega t$$

$$V_{B3} = V_m 3 \sin 3(\omega t - 120^\circ) = V_m 3 \sin 3\omega t$$

$$V_{C3} = V_m 3 \sin 3(\omega t - 240^\circ) = V_m 3 \sin 3\omega t$$



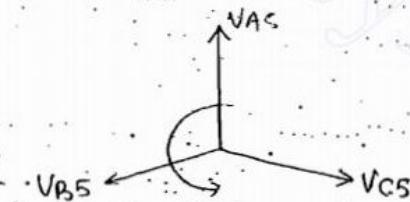
\* They have no mutual  $\phi$  displacement & called as cophasal which doesn't support 3 $\phi$  sys. & can't exist easily.

### 5th harmonics →

$$V_{A5} = V_m 5 \sin 5\omega t$$

$$V_{B5} = V_m 5 \sin 5(\omega t - 120^\circ) = V_m 5 \sin (5\omega t - 240^\circ)$$

$$V_{C5} = V_m 5 \sin 5(\omega t - 240^\circ) = V_m 5 \sin (5\omega t - 120^\circ)$$



\* They have mutual  $\phi$  displacement 120° support 3 $\phi$  nature, exist easily but they have opposite  $\phi$  seq. to that of fundamental.

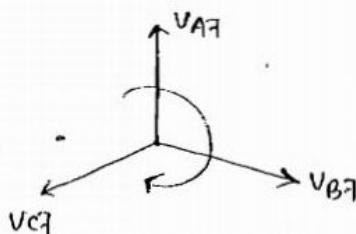
Therefore there affect will be in the braking region of 1m ( $s > 1$ )

### 7th harmonics →

$$V_{A7} = V_m 7 \sin 7\omega t$$

$$V_{B7} = V_m 7 \sin 7(\omega t - 120^\circ) = V_m 7 (7\omega t - 120^\circ)$$

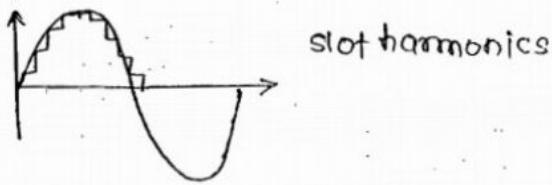
$$V_{C7} = V_m 7 \sin 7(\omega t - 240^\circ) = V_m 7 (7\omega t - 240^\circ)$$



- \* They are having mutual  $\phi$  displacement of  $120^\circ$  exactly  $3\phi$  nature, easily exist & they are as identical to fundamental with same  $\phi$  seq.

5th  $\rightarrow$  Braking  
 7th  $\rightarrow$  motoring

- \* If harmonics applied in the supply they known as time harmonics.



- \* If a fundamental is produced by  $p$  no. of poles then fictionally a 5th harmonic is produced by  $5p$  & 7th is produced by  $7p$  no. of poles.

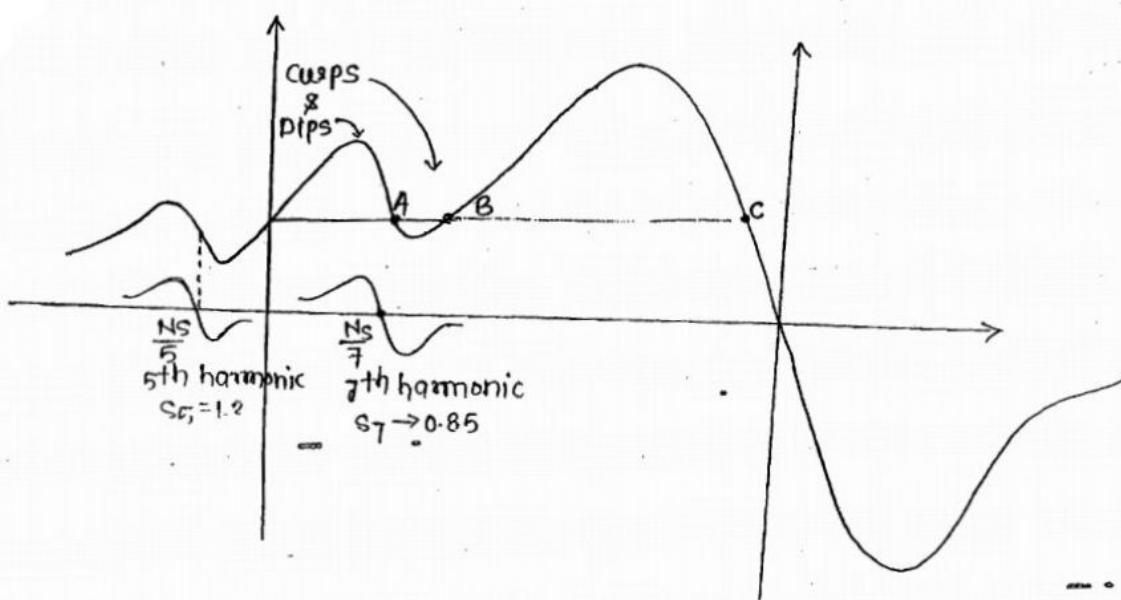
$$N_{5f} = \frac{120f}{5p} = \frac{Ns}{5}$$

$$S_5 = \frac{Ns - \frac{Ns}{5}}{Ns} = \frac{6}{5}$$

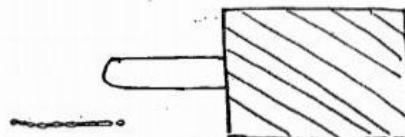
$$N_{7f} = \frac{120f}{7p} = \frac{Ns}{7}$$

$$\therefore S_7 = \frac{Ns - \left(-\frac{Ns}{5}\right)}{Ns} = \frac{6}{5} \quad \text{Because of plugging}$$

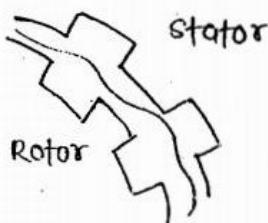
$$= 1.2$$



- \* It is a different behaviour of sq. cage IM to run at reduced speed around  $N_s/7$  during starting.
- \* Due to time/slot harmonics the flux distribution will gets distorted & contains harmonics in it.
- \* The most effective harmonics is 7th in motoring region & 5th in the braking region. They distort fundamental T-S.C/S in there operating regions & corresponding slips.
- \* If the motor starts with low starting torque it may fall near  $N_s/7$  & runs stably supplying a particular load torque even though (point A) Even though it is a stable point it is not desired operating pt. due to high slip, high current, huge noise, high loss, low speed.
- \* If starting torque high e.g. slipping there is no effect of crawling even though it contain harmonic content inside.
- \* In order to eliminate crawling effect due to harmonics stator wdg is uniformly distributed & short pitched.
- \* Fractional slot wdg's, semi closed slots are preferred.
- \* The rotor slots are also skewed for better flux distribution & elimination of harmonic content.



- \* With skewing it will also produce uniform torque smooth running with reduced noise (magnetic hum).



### \* Cogging →

- \* It is a tendency of magnetic locking b/w stator & rotor teeth due to alignment b/w them.
- \* If the rotor & stator slots (or) teeths are exactly equal & parallel to each other the alignment torque b/w them will dominate the accelerating torque specially in sq. cage motors as there starting torques are low (reduced Vol. starting).
- \* Rotor refuse to start & being stationary with locking is known as cogging.
- \* To eliminate this rotor slots are essentially skewed (inclined or twisted) skewing also increase the resistance of rotor bars & produce high starting torque comparatively.
- \* But the running  $\eta$  is comparatively low.
- \* Skewing also increases leakage reactance & reduce max<sup>m</sup> torque comparatively. "While designing Im the slots of stator & rotor will made different & also doesn't contain common factors b/w them but the no. of poles should be same."

### \* Comparison b/w sq. cage & slip ring Im →

- \* Net air gap of sq. cage is comparatively low & req. less magnetising current & operate at better PF.
- \* Rotor resistance of solid bars in sq. cage is comparatively low & the  $\eta$  is comparatively more.
- \* The end ring doesn't contain overhang but in slip ring due to overhang & increased depth of slot leakage reactance is comparatively more.
- \* Max<sup>m</sup> (or) breakdown torque & overload capacity is comparatively more in sq. cage.
- \* Construction is simple; low cost; mech. strong, less weight, maintenance free operation.

\* When rotor fed the absolute flux in space rotates at an speed  $N_s$  wrt.  
rotor & runs at slip speed ( $N_s - N$ ) wrt. stator (or) stationary point  
at space.

(5) (d) (26) (b.) (77) q  
(1) (28)

## \* Inverted IM (or) Rotor Fed $\rightarrow$

SRMF wrt stator at

\* If an IM is supplied with  $3\phi$  supply across its rotor by closing its stator it is called as IM rotor fed.

\* It operates normally but rotor runs at opposite dirn.

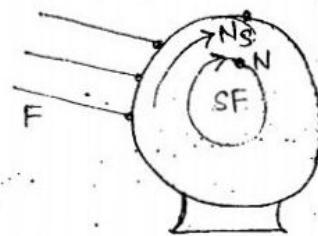
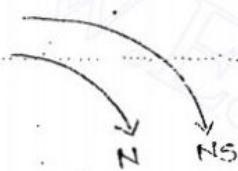
\* It can be done only in slipping type as the rotor is accessible through slip ring & brushes but conventionally motors are operated through stator.

SRMF wrt. stator at NS

RMF wrt. stator at  $S_N S + N = N_S$

As rotor itself rotates at N in direction of mag. field

SRMF & RMF wrt. rotor:  $N_S - N = S_N S$



\* When rotor is fed with supply with freq. f, it will produce RMF at speed  $N_S$  wrt rotor. cut the stator induced emf, current produce torque & want to make stator rotate.

\* As the stator is fixed part & rotor is designed for rotation inability to make the stator rotate will result in the rotor rotating in the opposite dirn to that of magnetic field.

Rotor RMF wrt. rotor at  $N_S$

~~rotor RMF wrt. stator at stationary point,  $N_S - N = S_N S$~~   
(or) stationary point  
in space

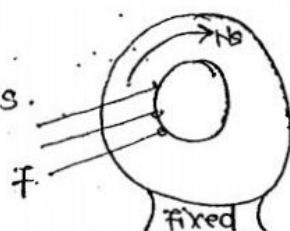
If stator freq. is SF, therefore stator RMF wrt. stator is at  $S_N S$ .

SRMF wrt. stator at  $S_N S$

SRMF & RMF wrt. rotor at  $S_N S - (-N) \Rightarrow S_N S + N$

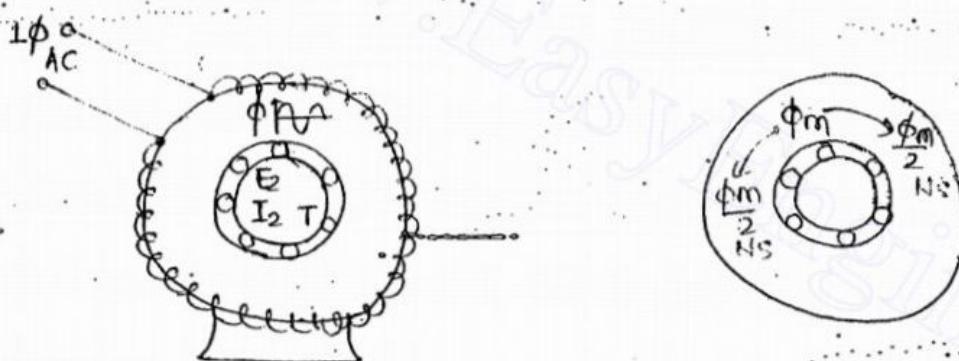
$\uparrow$   
 $N_S$

$\therefore$  rotor rotate in opposite dirn.



Single phase  
Ind<sup>n</sup> motors

- \* If the fuse blows off in  $3\phi$  motors when running at light weight condn it won't stop but continue to run as  $1\phi$  motor with reduced speed & increased current.
- \*  $1\phi$  motor are popular because of there small ratings 1w to 1kW & domestic supply is  $1\phi$ .
- \* There construction is as identical to  $3\phi$  motors.
- \* Stator contain  $1\phi$  wdg for 2, 4, 6 no. of poles generally.
- \* Depending on the starting method adopted stator wdg differs.
- \* Rotors are essentially squirrel cage type with skewing.
- \* The basic limitation of  $1\phi$  motors compare to  $3\phi$  is due to there non-self starting nature which can be analised acc. to double field revolving theory. The complete analysis, eq. ckt representation is based on this theory.



When a  $1\phi$  supply is applied across stator containing one wdg a pulsating (or) alternating magnetic field is produced.

It links with rotor & results in induced emf as the rotor is essentially closed it develops current & torque but rotor doesn't start.

If an external force applied the rotor continues to rotate in the dir<sup>n</sup> of force & reaches its rated speed.

This behaviour is analysed acc. to double field revolving theory.

Acc. to this theory a pulsating magnetic field contains 2 magnetic fields running at synchronous speed at equal magnitude ( $\phi_m/2$ ) & in opposite dir<sup>n</sup>.

$$\text{forward: } \phi_f \quad \phi_{m/2} \quad N_s \quad T_f \quad N \quad S_f \Rightarrow S_f = \frac{N_s - N}{N_s} = s$$

$$\text{Backward: } \phi_b \quad \phi_{m/2} \quad N_s \quad T_b \quad N \quad S_b \Rightarrow S_b = \frac{N_s + N}{N_s} = \frac{N_s + N - N_s + N_s}{N_s} = \frac{2N_s - (N_s - N)}{N_s} = 2 - s$$

\* As the rotor is subjected to both fields the entire operating region of 1φ motor will be considered b/w 2 extreme boundary cond'n 0 & 2.

at start  $s=1$

$S_f = 1, S_b = 1$

motoring region for 1φ rm

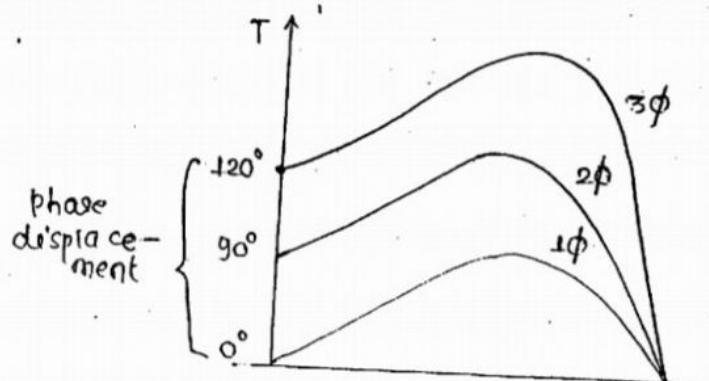
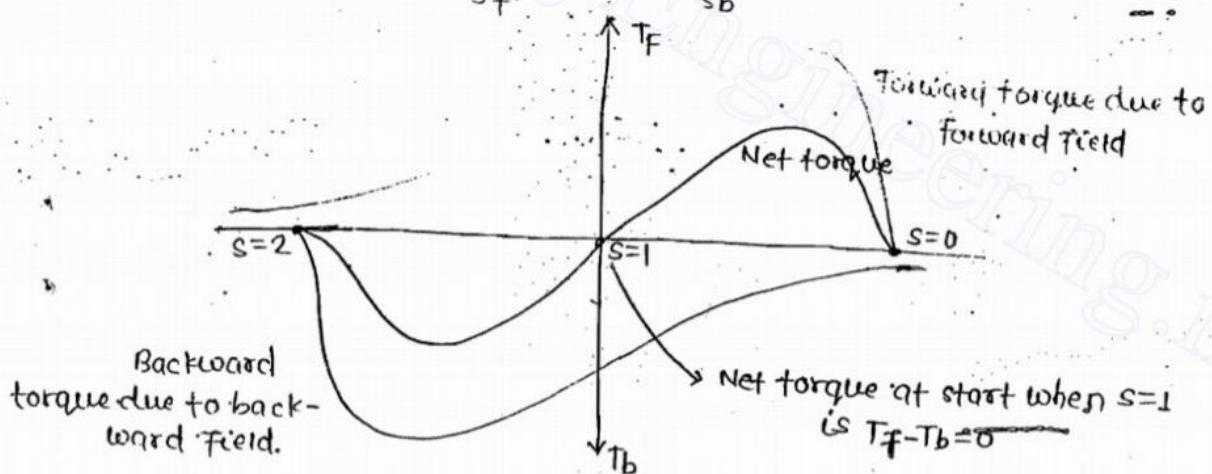
Running  $s=0$

$S_f = 0, S_b = 2$

$s = (0, 1, 2)$

$$T_g = \frac{60}{2\pi N_s} \times \frac{RCL}{s}$$

$$T_f \propto \frac{I^2 R_2}{S_f} ; \quad T_b \propto \frac{I^2 R_2}{S_b}$$



\* RMF with 2-φ supply →

$$\begin{aligned}\phi_A &= \phi_m \cos \omega t \\ \phi_B &= \phi_m \sin \omega t\end{aligned}$$

at  $\omega t = 0$ :  $\phi_A = \phi_m$ ,  
 $\phi_B = 0$

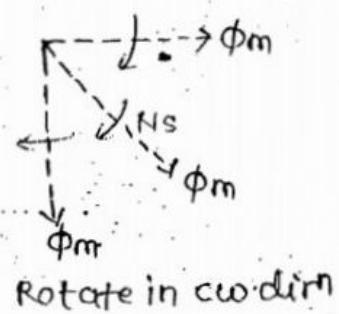
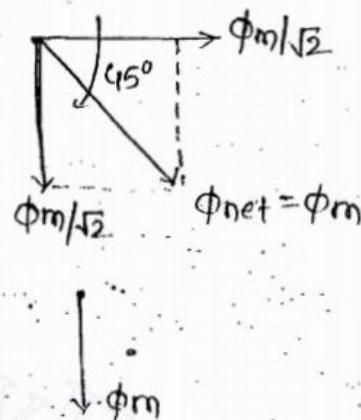
at  $\omega t = 45^\circ$ :  $\phi_A = \phi_m/\sqrt{2}$

$$\phi_B = \phi_m/\sqrt{2}$$

at  $\omega t = 90^\circ$ :  $\phi_A = 0$ ,

$$\phi_B = \phi_m$$

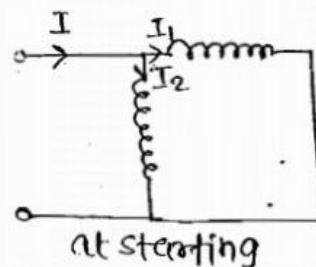
$$\longrightarrow \phi_m$$



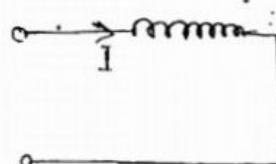
If we want to change the dirn of field then reverse the phase seq.

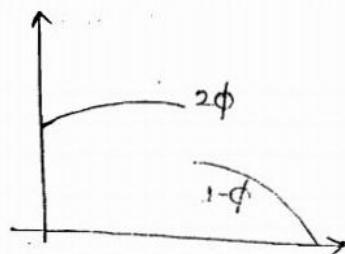
$$\begin{aligned}\phi_A &= \phi_m \sin \omega t \\ \phi_B &= -\phi_m \cos \omega t\end{aligned}$$

\* Like a 3φ supply a 2φ supply also produce RMF which rotates at syn. speed but with reduced strength  $\phi_m$  only.



split 1φ into 2 parts & connect parallel.

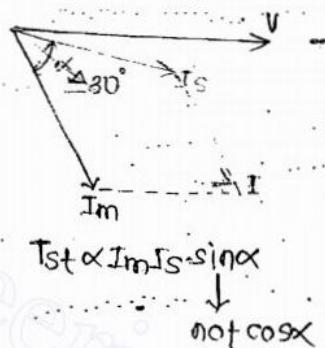
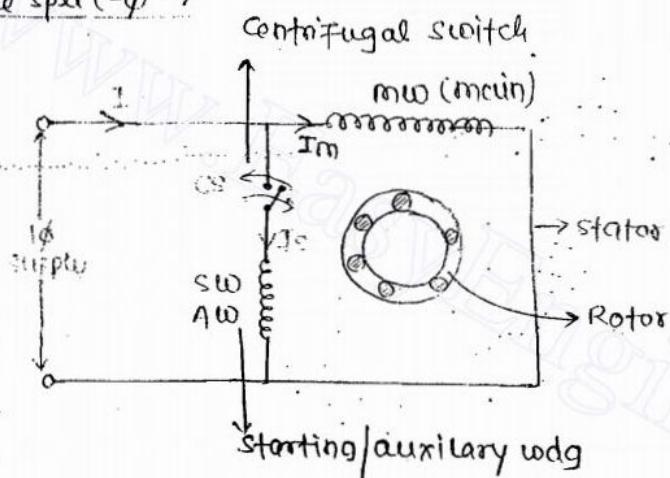




\* Depending on starting method adopted 1-φ motors are classified into 2 types:-

- (1) Split-phase →
    - Resistance split phase/split phase
    - capacitor start
  - (2) Split-pole → capacitor start & capacitor run/capacitor run motor.
- ↓  
shaded pole.

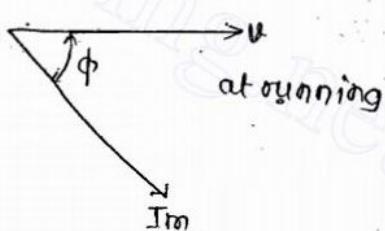
\* Resistance split-φ →



\* This is most popular for motors rating around 250W only.

\* Stator contains split φ wdg (2 wdgs):-

- (i) main wdg (running wdg) which is having large no. of turns more inductive naturally
- (ii) starting (or) auxiliary wdg which is having less no. of turns intentionally made highly resistive with thin cond't.



\* This will introduce an angle of displacement b/w both current in wdgs  $I_m$  &  $I_s$  around  $\alpha = 30^\circ$ .

\* It is sufficient to produce starting torque for small rating motors around 250W but not suitable for high inertia loads about 250W ratings.

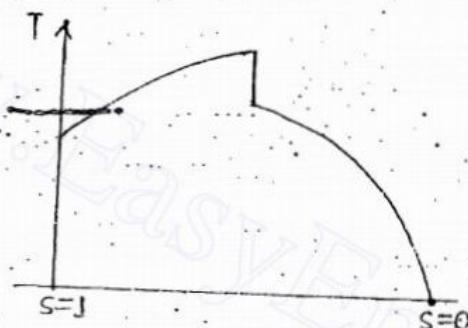
\* These are not suitable for frequent starting & stopping but for continuous operation in its segments.  $\alpha$  is low current drawn high.  
(Because of temp. rise in the resistor).

Applicn

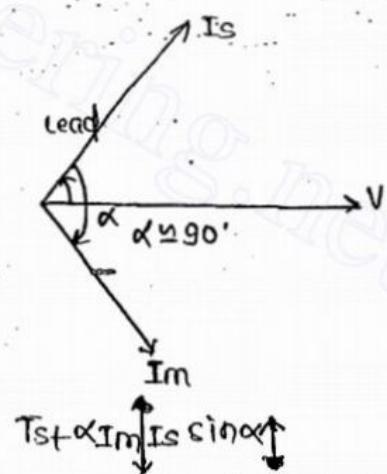
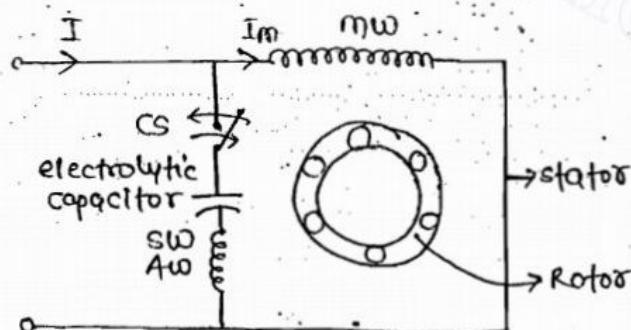
250W  
Domestic/sump motors

Centrifugal motors.  
Fans/ blowers.

\* Once the motor starts & reaches 80% of rated speed the centrifugal switch gets opened to isolate starting wdg from supply. & motor continues to run with main wdg only.



### (2) Capacitor start $\rightarrow$



- \* In order to create a large  $\phi$  diff. b/n  $I_m$  &  $I_s$  ( $\alpha \approx 90^\circ$ ) a capacitor is included in series with starting wdg through a switch.
- \* As  $\alpha$  is high the starting current drawn is comparatively low.
- \* It has high starting torque & used for high inertia load (hard to start) of 250-750W.
- \* As the motor reaches near rated value of speed the centrifugal switch will get

Opened & ~~this~~<sup>dis</sup> connects both capacitor & starting wdg.

\* Under running condn it is quite similar resistance split phase starting.  
This is preferred for frequent startings & stopping load specially.

### Applications →

250-750W

Fans/ blowers

sump pumps / centrifugal pump

refrigerator units, AC, washing m/c, grinders etc.

### Electrolytic capacitor → cost effective

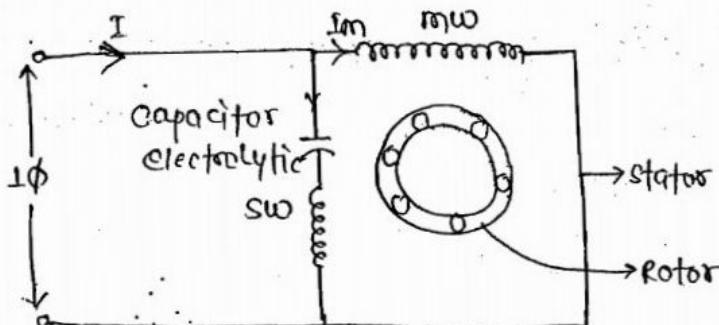
### (3.) Capacitor start / capacitor Run →

\* There is no centrifugal switch & the capa. is continuously connected to supply along with starting wdg.

\* The design cost is high comparatively because the starting wdg should be efficient.

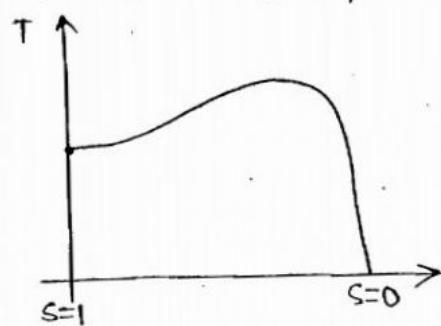
\* It starts & run as perfect 2φ motor but capacitor start motor start as 2φ motor but run as 1φ motor with low PF.

\* capacitor run motors are popular because of their silent operation with smooth T-s.c/s & good starting as well as running torques.

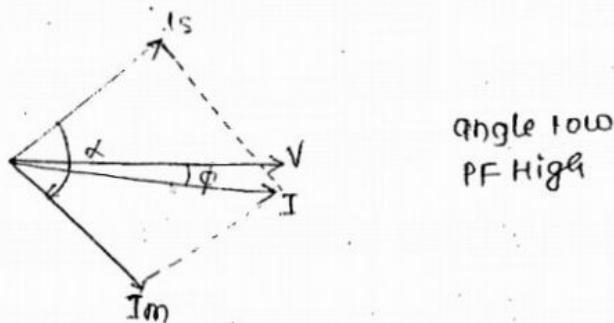


### Applic?

All ceiling fans, AC & motors in (fans/blowers/pumps) of ratings 750-1000W



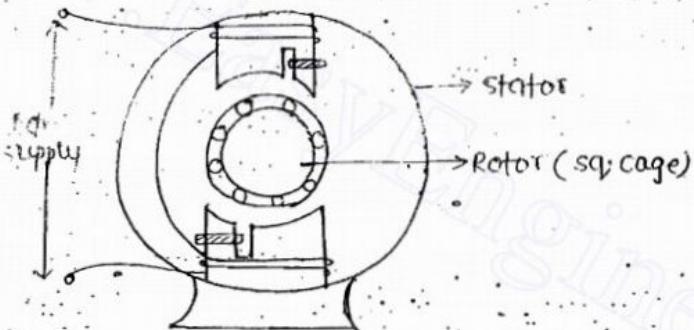
\* As the capacitor is continuously connected 2 small range capacitor are used in parallel with switching option externally, depending starting & running torque they can be switched.



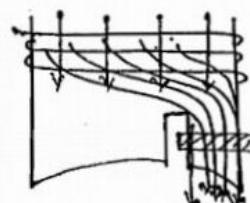
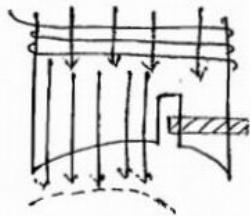
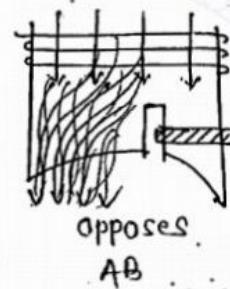
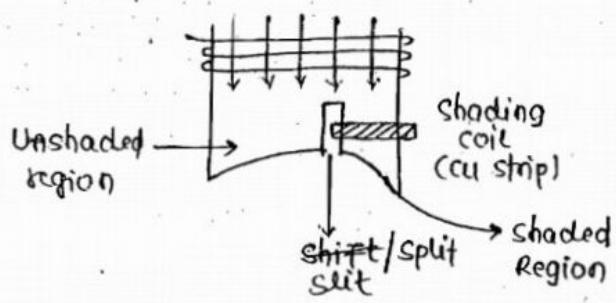
$$P = VI \cos \phi$$

$$\cos \phi = \frac{P}{VI}$$

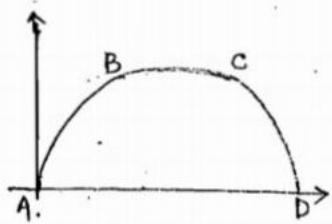
\* Shaded pole →



[1-50W Ranges]  
Toys



C.D



### Application →

Toys...

Small Fans/ Desk Fans

Cooling Fans in laptop

Xerox m/c

Advertisement displays.

Compact appliances like Hair dryers etc.

\* It is popular for its compactness & widely used in small ranges than 500W.

\* Stator is totally different from split phase type

\* It contains projected poles with a split & cu strip. It's solidly closed in one region of pole called as shaded region.

\* At instant AB the rate of change of flux linkage is +ve, EMF induced in the shading coil produce current & its own flux to oppose the main flux coming out of the pole

Therefore all the flux lines gets crowded in unshaded region at instant BC rate of change of flux linkage is very low & EMF induced current & flux of shading coil negligible

Therefore the flux distributes uniformly through out the pole

\* At instant CD Rate of change of flux linkages are in the -ve manner.

Therefore the opposition will be in +ve manner which makes the flux lines crowded in shaded region.

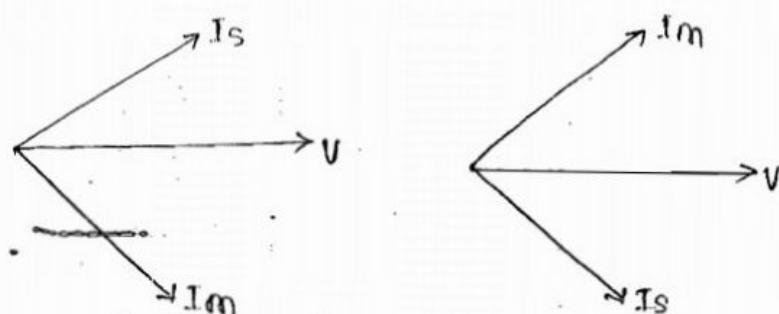
\* This will create a moving coil RMF in air gap under all the poles. However starting torques are very low & non-uniform magnetic field results in the non-uniform speeds & torque.

\* In order to reverse the dirn of rotation of splitphase motor:-

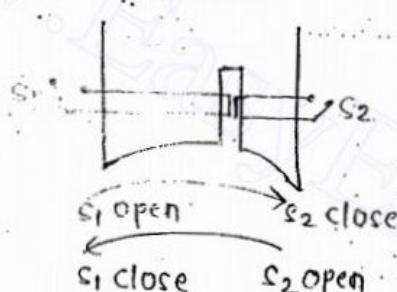
(1) Either reversing mw terminals.

(2) Either reversing sw terminals.

(3) Interchanging capacitor from starting wdg to main wdg.



\* By reversing both mw & sw (or) reversing supply terminals doesn't change the dirn of rotation of motor.



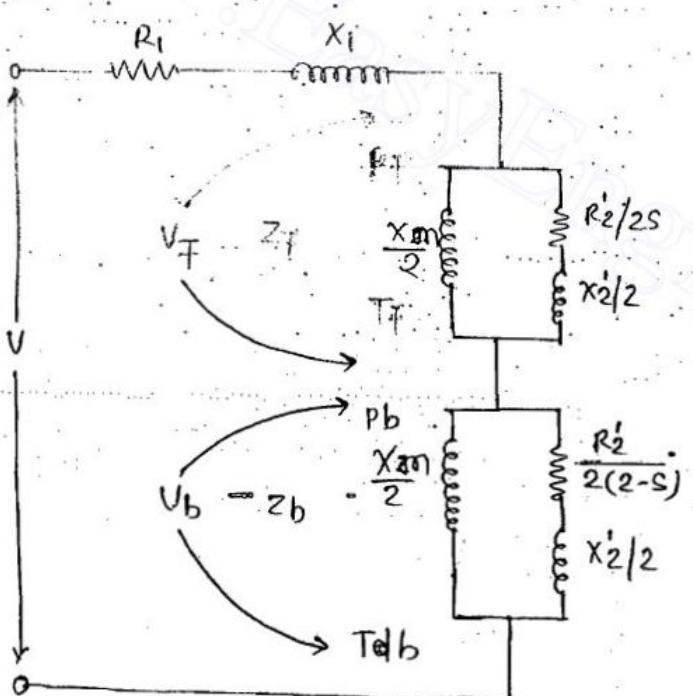
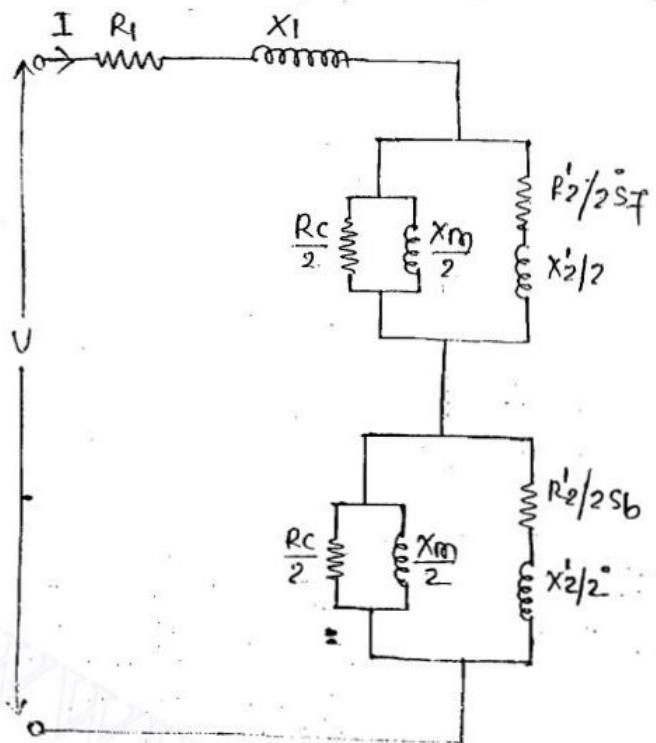
\* The flux always moves from unshaded to shaded region only.  
Therefore it requires 2 shading coils which can be externally switch.

\* Equivalent circuit representation →

\* The motor is represented on eq. ckt for further analysis.

\* In 1φ motors the representation acc to double field revolving theory.

\* Acc. to this as the rotor is reacting to both forward & backward fields it will be one stator 2 rotor representation as shown below.



$$* \quad z_1 = R_1 + jX_1$$

$$* \quad z_f = j\frac{X_m}{2} \parallel \frac{R'_2}{2s} + j\frac{X'_2}{2}$$

$$= R_f + jX_f$$

$$* \quad z_b = j\frac{X_m}{2} \parallel \frac{R'_2}{2(2-s)} + j\frac{X'_2}{s}$$

$$Z_{eq} = Z_L + Z_f + Z_b$$

$$I = \frac{V}{Z_{eq}}$$

$$I \angle \phi \quad \therefore PF = \cos \phi \text{ (angle)}$$

$$\text{Power i/p to forward rotor} \rightarrow I^2 R_f = P_f$$

$$\text{Power i/p to backward rotor} \rightarrow I^2 R_b = P_b$$

$$\text{Net P/i/p to rotor (OR) Air gap power} = P_f - P_b$$

$$\text{Power o/p of motor} = (1-s)(P_f - P_b)$$

For accuracy in the analysis from eq. circuit while calculating net power calc iron, friction & windage (const. or rotational losses) should be included while eliminating shunt branch resistance  $R_s$  from actual ckt

$$\text{Net shaft/motor o/p} = (1-s)[P_f - P_b] - \text{Rotational loss}$$

$$\eta = \frac{\text{Shaft o/p}}{\epsilon \cdot \text{Input}} = \frac{(1-s)[P_f - P_b] - [\text{Rotational loss}]}{V_1 \cdot \cos \phi}$$

$$\text{Gross torque } T_g = \frac{60}{2\pi N_s} \text{ Rot. P/i/p}$$

$$T_g = \frac{60}{2\pi N_s} (P_f - P_b)$$

$$\text{Shaft torque } T_{sh} = \frac{60}{2\pi N} \text{ shaft o/p}$$

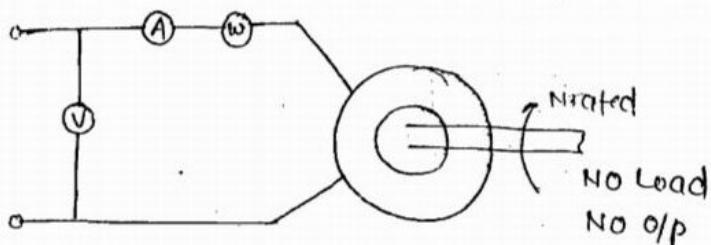
$$T_{sh} = \frac{60}{2\pi N} P_{sh}$$

$$\text{Shaft o/p} = P_{sh} = (1-s)[P_f - P_b] - [\text{Rotational loss}]$$

### \* Determination of eq; ckt parameter →

It requires determination of 3 tests to be conducted in order to find out the parameters of eq; ckt as similar to 3φ motors.

#### (1) NO Load test →



\* Apply rated vol. across the given 1φ Im & allow it to run freely on NL.

$$I_p = o/p + \text{loss (total)}$$

$$I_p = \text{loss}$$

- stator cu loss
- stator core loss
- Rotor cu loss × (current is low)
- Rotor core loss × (sf is small)
- mech. loss

\* It requires LPF wattmeter to measure NL power i/p.

\* The wattmeter reading is considered to be containing stator core loss + mech. loss + small stator cu loss.

#### (2) DC test →

\* Apply small vol. (dc) across the stator by connecting a v-m & ammeter.

\* Ratio of  $V/I$  gives dc resistance.

\* It is adjusted to ac value by multiplying with suitable factor around 1.5.

$$R_{1Ac} = 1.5 R_{Dc}$$

$$\omega_0 - I_0^2 R_1 = \text{Rotational loss (iron, friction & windage)}$$

\* From stator resistance value rotational loss is calculated.

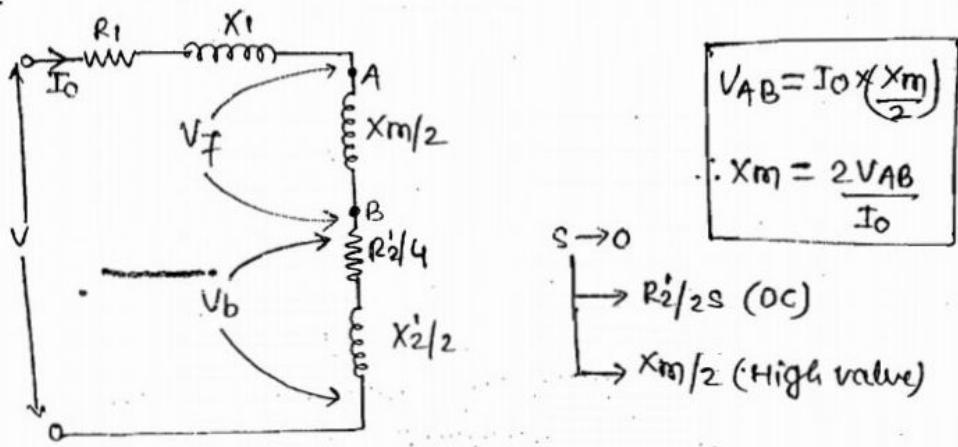
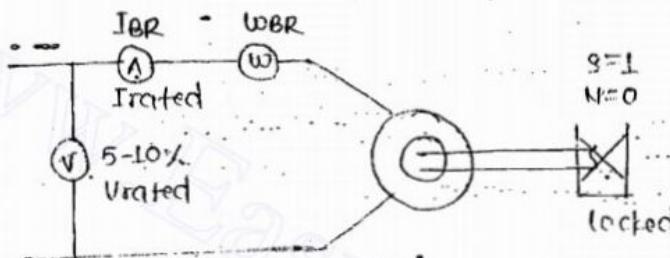


Fig:- Eq. ckt at No Load

### (3.) Blocked Rotor test →

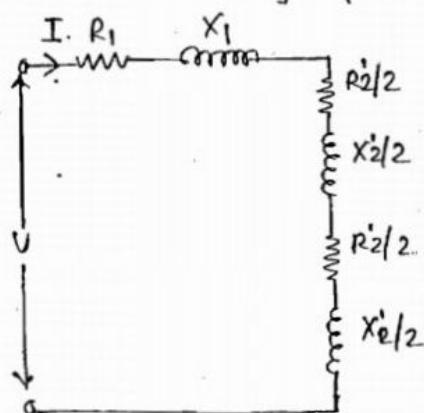


\* Rotor is initially blocked & small vol. is applied across stator through a suitable auto Xmer while insuring rated current drawn by motor.

- Total loss →
  - stator cu loss
  - stator core loss  $\propto$  ( $V$  is least)
  - Rotor cu loss
  - Rotor core loss  $\propto$  ( $V$  is least)
  - Mech. loss  $\propto$  ( $N=0$ )

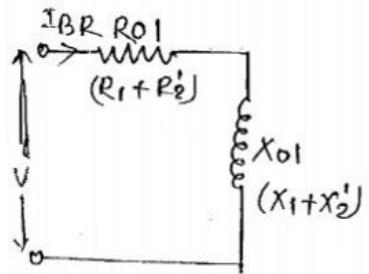
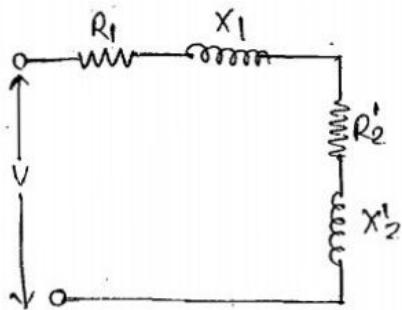
wattmeter reading → Only cu loss

\* In this test wattmeter reading represent both stator & rotor cu losses.



$s=1$

Fig:- Eq. ckt on blocked rotor cond?



$$W_{BR} = (\text{stator+rotor}) \text{ cu loss}$$

$$= (I^2 R_1 + I^2 R_2') = I^2 R_{01}$$

$$= I_{BR}^2 \cdot R_{BR}$$

$$W_{BR} = I_{BR}^2 \cdot R_{BR}$$

$$R_{BR} = \frac{W_{BR}}{I_{BR}^2}$$

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

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

$$X_1 = X_2' \approx \frac{X_{BR}}{2}$$

$$X_{BR} = X_{01} = X_1 + X_2'$$

$$Z_{BR} = Z_{01}$$

$$\eta = \frac{\text{O/p}}{\text{O/p} + \text{Const loss} + \text{cu loss}} = \frac{\text{I/p} - \left[ \frac{\text{const loss} + \text{cu loss}}{\text{I/p}} \right]}{\text{I/p}}$$

\* Comparison b/w 3φ & 1φ IM →

\* 3φ power capacity is more than that of 1φ.

\* for a same rating 1φ motors are comparatively having more size, cost, low torque & run with a noise due to backward field.

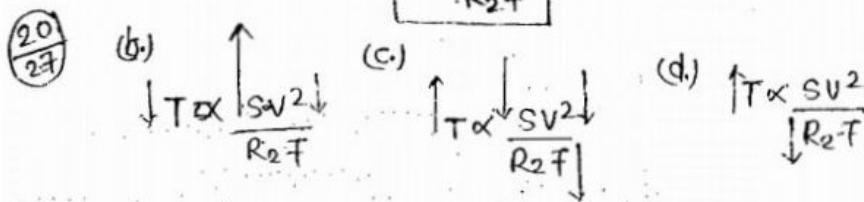
Cost also comparatively more in 1φ because of Auxiliary wdg, switch & capacitor.

\*~~comparision b/n~~

\* 3φ motors are more efficient than 2φ.

\*\*

$$T \propto \frac{SV^2}{R_2 F}$$



(27)  $T \propto SV^2$ ,  $\frac{T_2}{T_1} = \left(\frac{S_2}{S_1}\right) \left(\frac{V_2}{V_1}\right)^2$

(28)  $S_m = \frac{1200 - 1000}{1200} = \frac{1}{6}$

$$S_m = \frac{1}{6} = \frac{R_2}{X_2}$$

$$X_2 = 7.2$$

$$R_2 = X_2 \text{ (max m torque)}$$

$$X_2 = R_2 + R_2' \text{ (series add)}$$

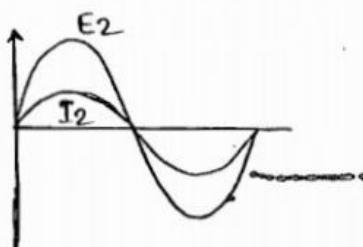
$$R_2' = 7.2 - 1.2 = 6 \Omega$$

(29) \* Commutator converts Ac  $\rightarrow$  dc, therefore in the extra load freq. is 0.

\* If there are slip rings the freq. across them is slip freq.

\* freq. wrt brushes on the commutator will be supply freq. (or) stator freq. only.

(30)



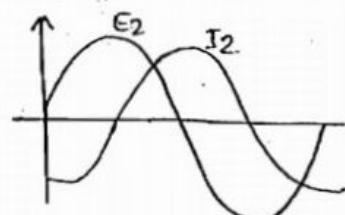
Pure Resistive

$$\phi = 0$$

$$\cos\phi = 1$$

$$T \propto E_2 I_2 \cos\phi_2$$

$$T \propto f_1 f_2 \sin\phi$$

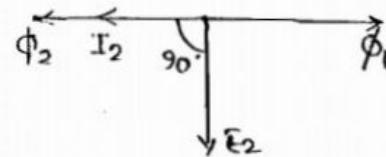
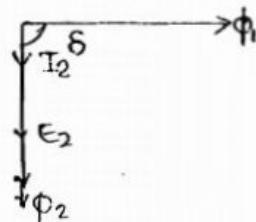


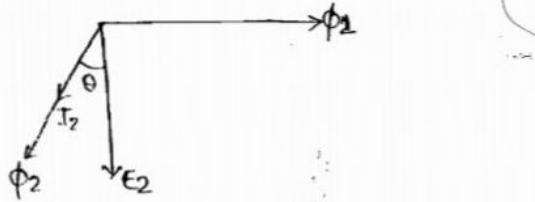
Pure inductive

$$\phi = 90^\circ$$

$$\cos 90^\circ = 0$$

$$T \propto E_2 I_2 \cos\phi_2$$





$$\frac{38}{30} T \propto \frac{SV^2}{F}$$

$$\frac{\sqrt{N_s}}{2} = \frac{120f/2}{P}$$

$$\frac{T_2}{T_1} = \frac{s_2}{s_1} \left( \frac{V_2}{V_1} \right)^2 \left( \frac{f_1}{f_2} \right)$$

$$\sqrt{s_2} = 2s_1$$

slip speed constant

$$\frac{44}{31} \text{ Stator core loss} = 1.5k + 1200w \approx 2700w$$

$$\text{Rotor cu loss} = 900w$$

$$\text{Mech. loss} = 1050w$$

$$P = \sqrt{3} V_{L1} I_{L1} \cos\phi - 2700w$$

$$\frac{46}{31} s = \frac{1500 - 1410}{1500}$$

2000 → total

$$(1-s) 2000 \rightarrow 1880$$

$$P = I^2 R$$

$$I = \sqrt{\frac{P}{R}}$$

$$\frac{48}{31} V_1 = 400V, f_1 = 50, N = ?$$

$$V_2 = 240V, f_2 = 30Hz$$

$$\frac{V_1}{f_1} = \frac{V_2}{f_2} ; V_2 = 240V$$

$$s_1 = \frac{1500 - 1440}{1500}$$

$$s_1 = 0.04$$

$$T \propto \frac{SV^2}{F}$$

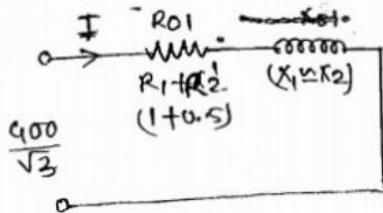
$$\frac{T_2}{T_1} = \frac{s_2}{s_1} \left( \frac{V_2}{V_1} \right)^2 \left( \frac{f_1}{f_2} \right)$$

$$s_2 = 0.06$$

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

$$= \frac{120 \times 30}{4} (1 - 0.06) = 840$$

(49)  
32



$$T_g = \frac{60}{2\pi N_s} \cdot \frac{RCL}{S^2 I}$$

$$= \frac{60}{2\pi N_s} \times 3I^2 R \times$$

$$T_g = \frac{3 \times 60}{2\pi N_s} \times \left[ \frac{400/\sqrt{3}}{[1.5+j2.4]} \right]^2 \times 0.5$$

(50)  
32

$$\eta = \frac{10000}{10000 + 1002 + 1354}$$

NL	BR
$15^2 A$	72.00
20A	?

(51)  
32

$$\frac{T_{st}}{T_f} = 1.5 \quad \frac{T_m}{T_f} = 3 \quad \frac{T_{st}}{T_m} = \frac{1}{2} = \frac{(2\beta m)}{sm^2 + 1}$$

(61)  
33

In HIL test watt-meter reading represent iron, friction & windage but iron losses are separated to represent as shunt branch.  $R_c$  in the actual eq; circ

(62)  
33

$$T \propto \frac{s}{R_2}$$

$$R_2 \propto s$$

$$\frac{0.2s}{0.2s + 0.5} = \frac{0.03}{?}$$

(63)  
33

$$\begin{cases} 50 \text{ Hz} \rightarrow 1500 \\ 30 \text{ Hz} \rightarrow 900 \end{cases}$$

Possible speeds  
may be  
 $1500 \pm 900$

(74)  
34



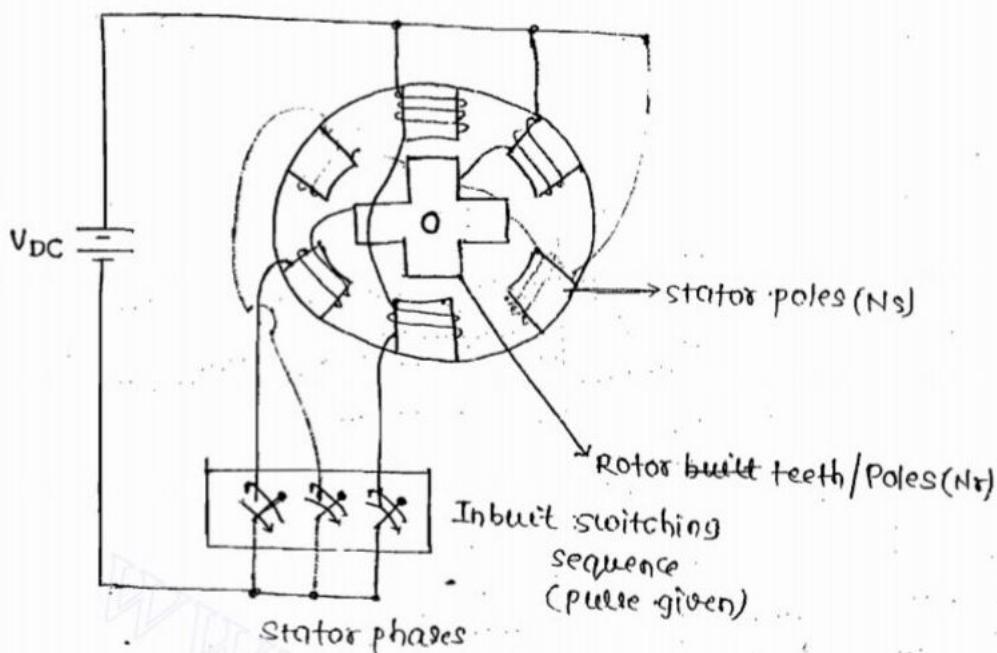
(75)  
35

$$f = 48 \text{ Hz}$$

$$N_s = \frac{120(48)}{6}$$

$$N = 936$$

\* Stepper motor →



$$\text{Step angle } \alpha = \frac{N_s - N_r}{N_s \cdot N_r} \times 360$$

(OR)

$$\alpha = \frac{360^\circ}{m \times N_r}$$

\* These are not meant for continuous rotation but rotor rotates in steps by reacting to the pulses given by drive ckt acc to switching seq by a step angle  $\alpha$  in mech. degree.

\* It can be designed depending on no. of poles & teeth in the stator & rotor.

\* They can be permanent magnet or variable reluctance type.

\* If step freq. is high (pulses are high or microstepping) then the rotor becomes uncontrollable due to its inertia which is called as slew range.

Small Ranges → less than 1W to few watts

Available & popular

Timing devices (clocks.)

Printers, type writers, fax

Computer controls

Robotics.

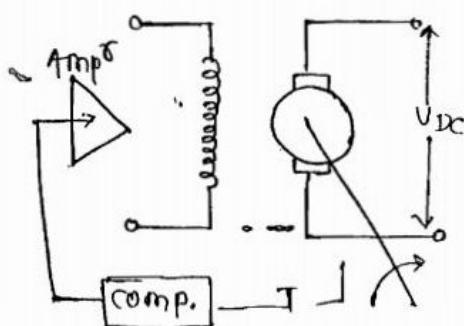
### \* AC series motor/Universal →

- \* If 1φ AC supply is applied across dc series motor it continues to run at the torque due in both half cycle but the torque is pulsating & not a uniform torque
- \* However directly dc series motors are not used but specially designed.
  - (1) Stator & rotor contains high grade si-steel laminations to reduce iron loss.
  - (2) Field wdg turn will be comparatively reduced.
  - (3) Arm. reaction, particularly commutation is not successful because of high reactance in the arm. coils.
  - (4) Sparking at the brushes will produce high maintenance repairs which need to be taken care with cw compensated wdg for large ratings.
- \* These motors are popular specially less than 1kW ratings because of their high speed (5000-20000 rpm) & high torque within compact size.
- \* Due to pulsation in torque they make more noise.
- \* Exclusively preferred for food processing like mixers/juicers, vacuum cleaners, portable hand tools like drilling m/c, wood saw's/ sewing m/c, recent automatic washing m/c.
- \* Ac series motors are of high rating around 500HP are used for some traction purposes but with reduced grid frequency are 25Hz only.

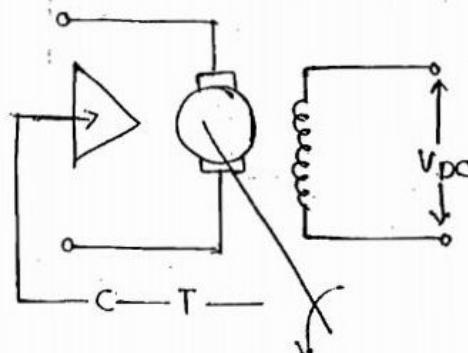
### \* Servo motors →

Servo mechanism → Automatic control sys.

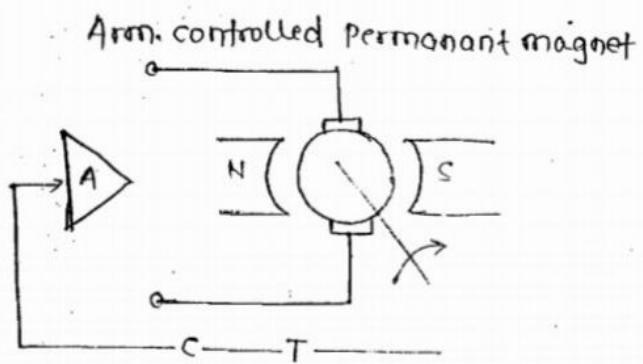
Field controlled DC SM



Arm cont. dc SM.



- \* Compared to field control arm. control servomechanism is fast acting.
- \* Arm. control permanent magnet is most popular dc servo motors due to its simple compact design, efficient & no requirement of field wdg & excitation.



### Servo motors

DC

AC

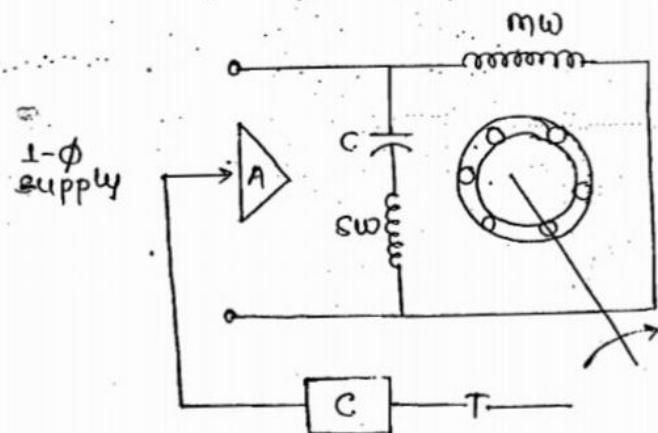
#### Application →

Control motors used in control sys. apps., radars, process control,  
Position controlling, tracking systems.

#### AC servo motors →

2- $\phi$  IM

1 $\phi$  IM (Capacitor Run type)

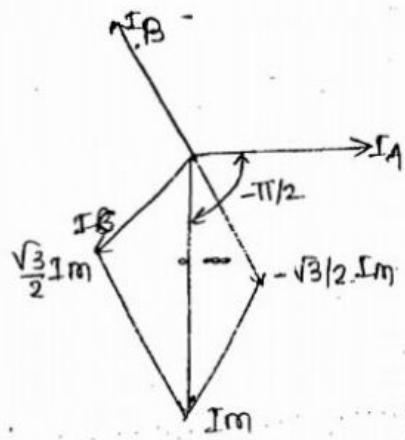


\* Ac servo-motors are basically 1 $\phi$  IM capacitor run type.

\* for quick response their rotor diameters are small & more axial length.

Compared to conventional there X/R ratio of rotor is low. to get linear T-S c/s for effective response.

(16)  
49



(22)  
51

$$\frac{R_2}{2(2-s)}$$
$$s = \frac{1500 - 1425}{1500}$$
$$s = 0.05$$

8