ALTERNATOR

Working Principle

→ Electro magnetic induction.

When the flux linking a conductor changes, an emf is induced in the conductor.

→ Same as DC Generator

Armature - rotate
Field —— Stationary

* But in Alternator

Armature - Stationary
Field —— rotating

→ The direction of induced emf can be found by Flemings Right Hand rule

* Why Armature coil is stationary & field is rotating?

i) The o/p can be directly taken from armature without brush-contact.

ii) Easy to insulate for High voltage upto 30 kV or more.

iii) The field winding has low voltage DC supply which can easily be insulated.

iv) The armature can easily be cooled by proper ventilation.

Construction & Parts of Alternator

*

(1) Armature (Stator)

(a) Frame

→ Not for carrying magnetic flux but ~~for~~ hold the armature stamping & winding in position.

→ Ventilation is maintained with the help of hole cast in the frame.

(b) Stator Core

→ Supported by stator frame & is build ~~made~~ up of laminations of magnetic iron / steel alloy.

→ To avoid eddy current loss & heating.

Wide Open | Semi closed | Closed

Wide Open

→ easy ~~in~~ winding

→ But due to air gap flux distribution emf generated has ripples.

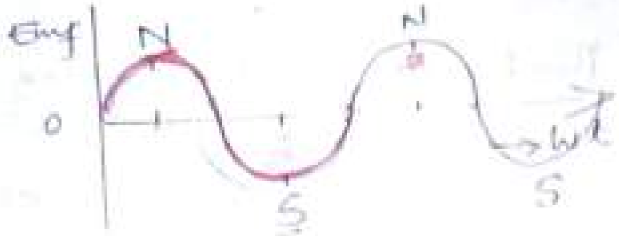
Closed

→ Hard to put coil in it.

→ donot distort air gap flux

→ ~~no~~ emf ~~has~~ no harmonics

* Speed & frequency



One cycle of emf generated on a coil when one pole pair passes over the coil.

$P \rightarrow$ no. of poles in field

$N \rightarrow$ speed of rotor (rpm)

$f \rightarrow$ frequency of generated emf

frequency of generated emf in one revolution $= \frac{P}{2}$

frequency of emf per minutes $= \frac{PN}{2}$

$N \rightarrow$ min

$\frac{N}{60} \rightarrow$ sec

frequency of emf $= \frac{PN}{2 \times 60}$

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

* Synchronous Speed

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

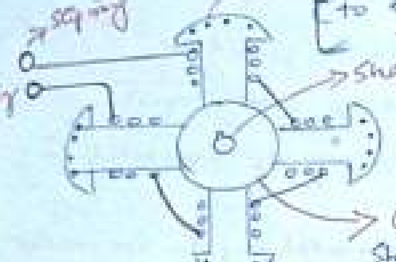
To have 50Hz frequency

P	2	4	6	10
N_s	3000	1500	750	600

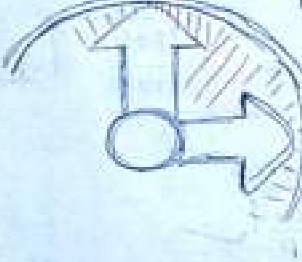
① Salient Pole

Salient → Protruding / Projecting

The pole is projected out from the surface of rotor core.



→ The air gap is not uniform.



Poles are such designed that the flux distribution is sinusoidal as a result generated emf is sinusoidal.

→ ① Due to windage loss it operated slowly.

(ii) Large nos of poles on the rotor

(iii) Large diameter & short axial length.

(iv) Hydel power plant.

Non-salient pole

→ 2/3rd of rotor periphery slots are cut at regular interval.

→ Unslotted portion form pole faces

→ High grade Ni-Chrome-Mo Steel.

→ less centrifugal force.

→ High speed of operation.

→ less windage loss - less noisy bcz of uniform air gap.

→ driven by Steam or Gas turbine

→ Turbo-alternator.

* Excitation System for Alternator -

Small M/C → pilot exciter (dc generator permanent magnet)

Medium M/C → AC exciter (3ϕ ac gen) AC is rectified & supplied through slip ring & brushes

Large M/C → slip ring need to avoided ✕ high speed sliding contact

→ Brushless DC excitation

* EMF eqⁿ of an Alternator $\boxed{E = \frac{d\phi}{dt}}$ Faraday's law

$E_{av}/\text{conductor} = \dfrac{\phi_{cut} \text{ per revolution (Wb)}}{\text{time taken for one revolution (sec)}}$

$E_{av}/\text{conductor} = \dfrac{P\phi}{60/N} = \dfrac{P\phi N}{60}$

$\phi \rightarrow$ flux per pole
$P \rightarrow$ No. of poles
$N \rightarrow$ revolution/minute (r.p.m.)

But; $f = \dfrac{PN}{120}$

$\Rightarrow 2f = \dfrac{PN}{60}$

Compare

$E_{av}/\text{conductor} = 2f\phi$

$E_{av}/\text{phase} = 2f\phi Z_P$

$E_{av}/\text{phase} = 4f\phi T_P$

$Z_P \rightarrow$ conductors in series per phase
$T_P \rightarrow$ Turns of coil/phase
$(Z_P = 2T_P)$

Form factor $= \dfrac{RMS}{Avg} = 1.11$ [for sine wave]

$\Rightarrow RMS = ff \cdot Avg.$

$E_{rms}/\text{phase} = 1.11 \times 4f\phi T_P$

$$\boxed{E_{rms}/\text{phase} = 4.44 f\phi T_P}$$

$\phi \rightarrow$ flux per pole (Wb)
$f \rightarrow$ frequency
$T_P \rightarrow$ Turns of coils per phase

$V/f \longrightarrow$ Variable frequency drive 3ϕ IM

* Armature Winding

- The winding where voltage is induced.

Turn – consist of two conductors.

Coil – Several turns in series

Winding – Several coil in series

$$\boxed{\theta_{ele} = \frac{P}{2}\theta_{mech}}$$

$\theta_{ele} \rightarrow$ electrical degree
$\theta_{mech} \rightarrow$ mech. degree
$P \rightarrow$ No. of poles

Pole pitch ($\Rightarrow \theta_{el} = 180°$)

- Angular distance betw two adjacent poles

Coil pitch

The distance betw the two side of coil is coil-pitch.

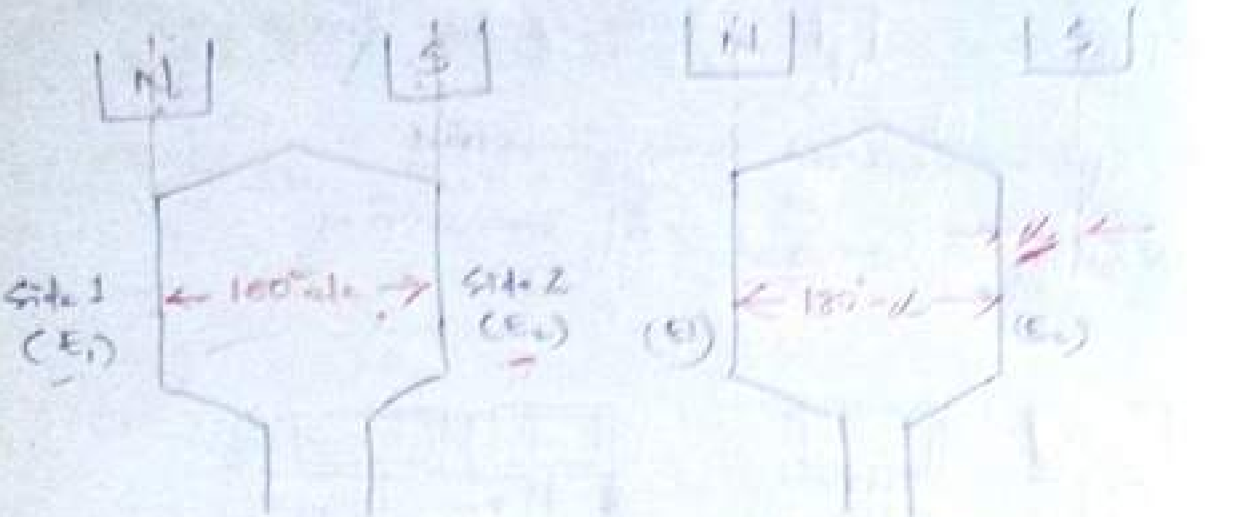
Full pitch

Pole pitch = Coil pitch

Short-pitch / Fractional-pitch coil

If coil pitch < Pole pitch

• Pitch factor [Coil-span factor] (K_c)



Full pitch

Short pitch

$E_c = E_1 + E_2$
$= 2E$
(Arithmatic sum)

$E_c = E_1 + E_2$
$= 2E\cos(\alpha/2)$
(phasor sum)

$$K_c = \frac{\text{Voltage generated in short pitch}}{\text{Voltage generated in full pitch}}$$

$$K_c = \cos\alpha/2$$

→ Saving conductor as winding ends are short

→ Harmonics are eliminated from the generated emf; wave form is improved.

Advantages of Distributed winding

① Reduce Harmonics in generated emf; improved waveform

② Diminishes armature reaction.

③ Even distribution of conductors helps for better cooling

④ Stator core is fully utilized, as conductors are evenly distributed over the stator periphery.

Distribution factor / Breadth factor (K_d)

Concentrated winding:

The side of coil of given phase are concentrated in a single slot under a pole.

→ voltage induced were in phase with each other

$E_c = T * E$ → induced emf per turn
↳ Nos of turns

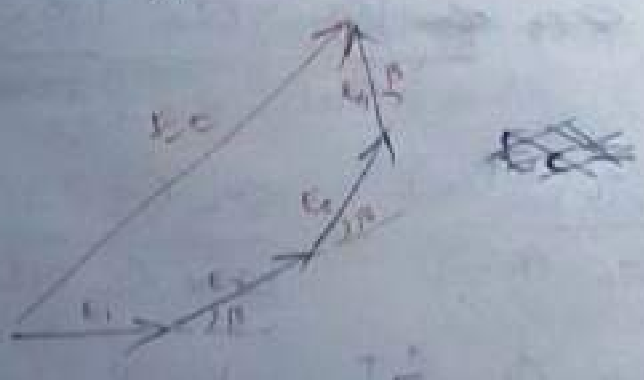
But; Coils are not concentrated in single slot but distributed in number of slots — form — POLAR GROUP.

→ Voltage induced is not in phase but differ by an angle "β" (Angle betn slots).

$$m = \frac{\text{Slot}}{\text{Pole} \times \text{phase}}$$ (Slots per pole per phase)

β = angular displacement betn adjacent slots (electrical degree)

$$\beta = \frac{180^\circ}{\text{slots/pole}} = \frac{180^\circ * \text{Pole}}{\text{Slots}}$$



$$K_d = \frac{\text{Phasor sum of } E_c}{\text{Arithmetic sum of } E_c} = \frac{\sin(m\beta/2)}{m \sin(\beta/2)}$$

↳ distributed voltage / Concentrated voltage

Actual voltage Generated

$$E_1 = 4.44\, \phi_{pole} f\, T_{phase} K_c K_d$$

$K_w = K_c K_d$ → "winding factor"

$E_L = \sqrt{3}\, E_p$ (Y connection)
↳ line ↳ phase

Q. A 3φ, 50Hz, 8 pole AH (Y-connected) with 120 slots & 8 conductors/slots
$\phi_{pole} = 0.05\,Wb$ sinusoidally distributed.
Determine phase & line voltage.

Ans Assuming full pitch ; $\alpha = 0°$
$K_c = \cos \alpha/2 = 1$

M = slots per pole per phase

$$\Rightarrow m = \frac{120}{8 \times 3} = 5$$

$$\beta = \frac{180° \times \text{Pole}}{\text{Slots}} = \frac{180 \times 8}{120} = 12$$

$$K_d = \frac{\sin(m\beta/2)}{m \cdot \sin(\beta/2)} = \frac{\sin(30°)}{5 * \sin(12°)} = 0.95$$

$$E_1 = 4.44\, \phi_{pole} f\, T_{phase} \cdot K_d \cdot K_c = 1699\,V$$

$E_L = \sqrt{3} E_p = 2942.8$

$$T_{phase} = \frac{48 \times 120}{2 \times 3} = 160$$

* Armature Reaction:

The effect of Armature flux on the rotor field flux is called AR.

AR effect changes with load type.

(I) AR: unity pf

$\overrightarrow{I_a} \rightarrow E_a$

$\phi_f \xrightarrow{90^\circ} E_a \xrightarrow{0^\circ} I_a \xrightarrow{0^\circ} \phi_a$

$E_a = N\frac{d\phi}{dt}$ (E_a always lag ϕ_f by 90°)

$E = \frac{d\cos\omega}{dt}$

$E = \cos\omega$

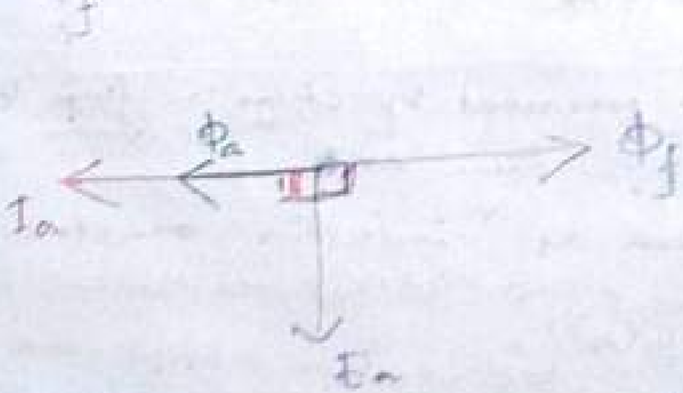
→ Cross-magnetizing effect.

→ ϕ_a lags by 90° wrt ϕ_f

→ Distort the main field flux.

(II) AR: lagging pf ZERO

$\phi_f \xrightarrow{90^\circ} E_a \xrightarrow{90} I_a \xrightarrow{0^\circ} \phi_a$

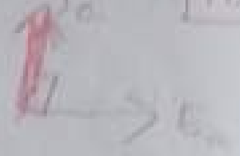


→ Demagnetizing effect

→ Opposes & weaken the main field flux

→ Emf generated will be decreased ($\because E \propto \phi\downarrow$)

(III) AR: unity leading Pf.



$$\Phi_f \xrightarrow{90^\circ} E_a \xrightarrow{-90^\circ} I_a \xrightarrow{0^\circ} \Phi_a$$

⟹ Magnetizing effect.

⟹ It strengthen the main field flux

⟹ Emf generated will increase ($E \propto \phi$)

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* Synchronous Impedance

Mag flux ⟶ EMF generate

$$\Phi_f \to E_{ex}$$

$$\Phi_{AR} \to E_{AR}$$

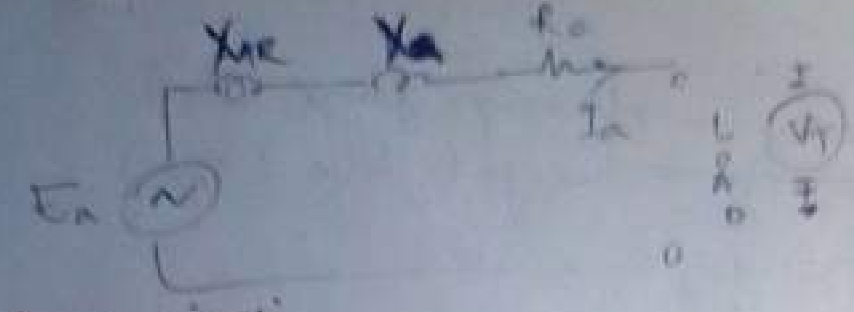
$E_a = E_{ex} + E_{AR}$ (effect of AR added)

E_{AR} → emf generated by change in flux by a current in same ckt.

So, taken as "Inductive reactance".

$E_{AR} = -j(X_{AR}) I_a$ — X_{AR} → Fictitious reactance; I_a → Armature current cause AR

$V_T = E_a - jX_{AR} I_a - jX_a I_a - R_a$



Armature 'cct'

Leakage Reactance

The flux set up by I_a which does not contribute to the useful flux of the m/c is Leakage flux.

This leakage flux ~~induced~~ sets up a self-induced emf in Armature windings.

1. Slot leakage
2. Tooth head leakage
3. Coil-end leakage

Now;

$$V_T = E_a - j\underbrace{(X_{AR} + X_a)}_{X_s} I_a - I_a R_a$$

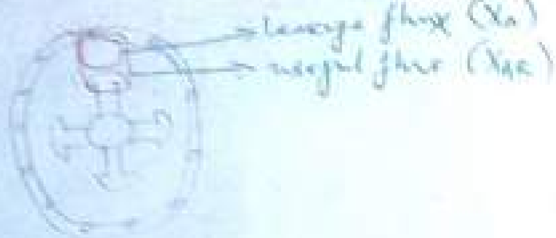
$X_s \rightarrow$ Synchronous reactance

$$= E_a - Z_s I_a$$

$Z_s = R_a + jX_s$ → Synchronous Impedance

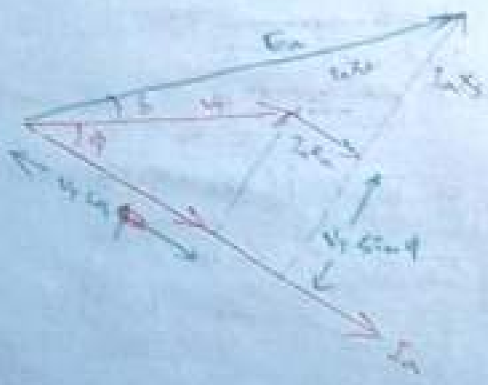
$X_s \rightarrow X_a + X_{AR}$ → Armature Reaction; X_a → leakage reactance

$Z_s \rightarrow jX_s + R_a$ → R_a: Armature resistance; jX_s: fictitious reactance.



* Equivalent phasor diagram [illegible]

(I) Lagging pf load.

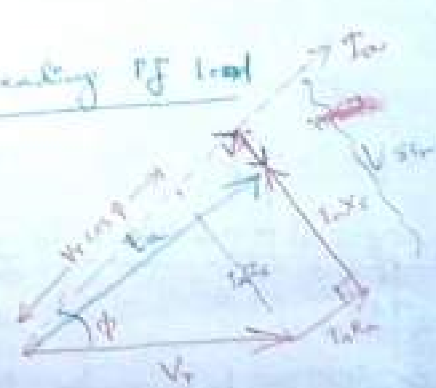


$$E_a = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$$

(II) Unity pf load

$$E_a = \sqrt{(V + I_aR_a)^2 + (I_aX_s)^2}$$

(III) Leading pf load



$$E_a = \sqrt{(V\cos\phi + I_aR_a)^2 + (V\sin\phi - I_aX_s)^2}$$

δ → power angle ($E_a - V_t$)
→ Torque angle
It varies with the load.

$$\left[\vec{E_a} = \vec{V_t} + \vec{I_a} Z_s \angle\theta\right]$$

* Voltage Regulation (teach after OC test)

✓ The rise/change in voltage at terminal when load is reduced from full load to no-load, keeping field current & speed constant.

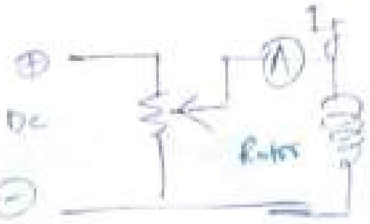
$$VR = \frac{E_a - V_1}{V_1}$$

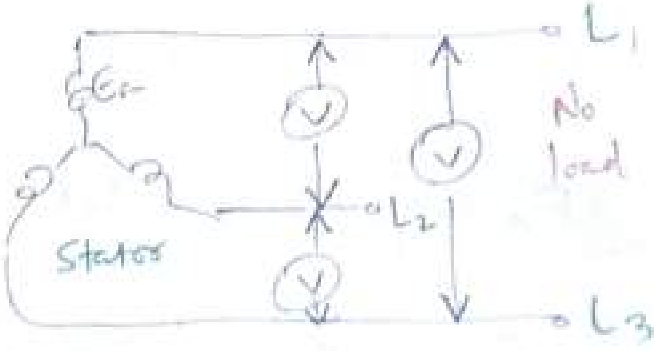
V_1 → rated full load voltage
E_a → no load voltage (generated voltage).

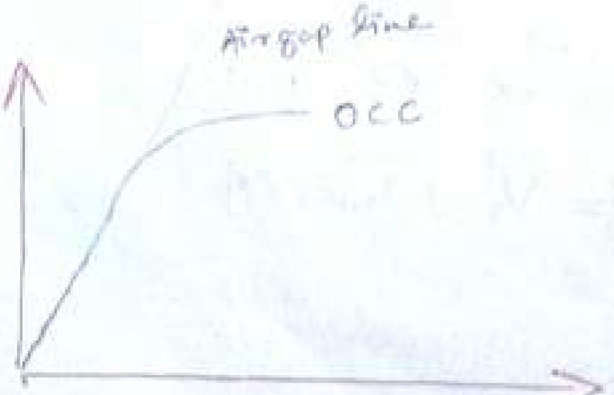
⇒ VR depends upon the "load".

* Testing of Alternator (To measure Z_s)

① OC test

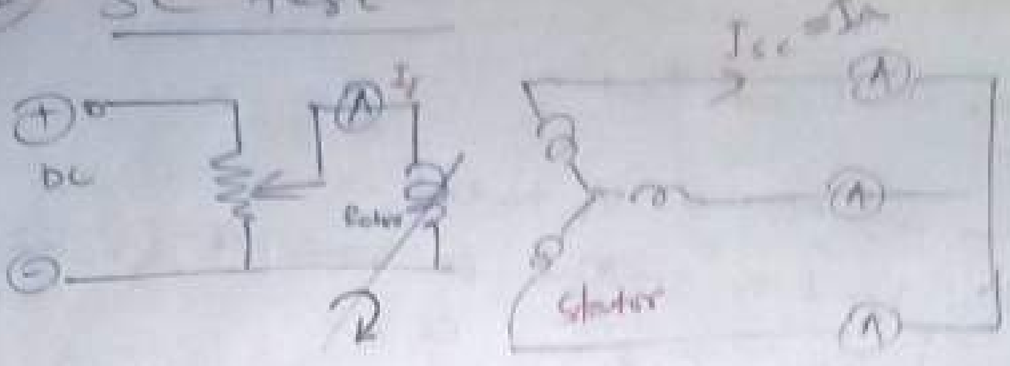






field current (I_f) is increased from 0 to 125% gradually

(II) SC test



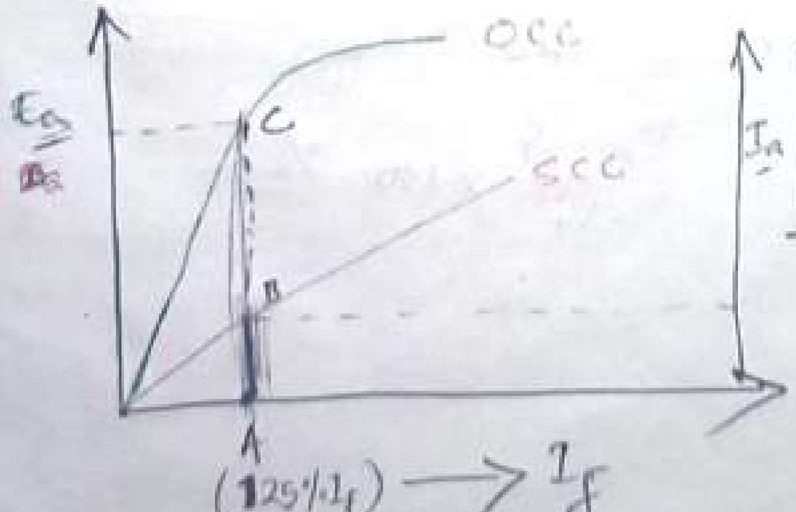
rotor is run at N_s

I_f is gradually increased from 0 to 125%

$$Z_s = \frac{\text{OC voltage } (E_a)}{\text{SC current } (I_a)} \Bigg|_{I_f = \text{same}}$$

(125% I_f)

$$X_s = \sqrt{Z_s^2 - R_a^2}$$



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

* Voltage Regulation

(A) Direct Load Test

(i) Run @ N_s & V_T rated

(ii) The load is varied until I_a (A) = rated value @ given pf

(iii) Then Load is removed & N_s, I_f const. We measure E_a.

(iv)
$$VR = \frac{E_a - V_T}{V_T} \times 100\ \%$$

(v) This method is applicable for small power rating Alternator (5 KVA)

(B) Synchronous Impedance method (EMF method)

(i) replacing effect of AR by fictitious reactance

$$~~V =~~ E_a - Z_s I_a$$

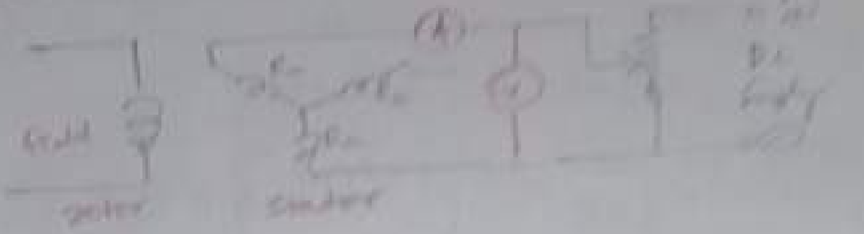
(ii) Z_s is measured from OC & SC test

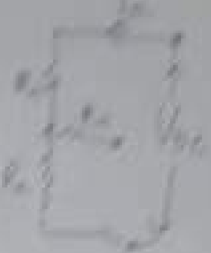
(iii) then; E_a is calculated

$$E_a = V_T + Z_s I_a$$

(iv)
$$VR = \frac{E_a - V_T}{V_T} \times 100\ \%$$

DC test (Ra in OC & SC Test of Alternator) [11]





$$\frac{V}{I} = 2R_{ac} \Rightarrow R_a = \frac{V}{2I}$$

Then;

$$X_s = \sqrt{Z_s^2 - R_a^2}$$

$(\because Z_s = R_a + jX_s)$

Q) A 550V, 55kVA, 1φ Alternator has a resistance $(R_a) = 0.2\,\Omega$. $I_f = 10A$ produces $I_{sc} = 200A$ on SC test & $E_0 = 450V$ on OC test. Calculate X_s & voltage regulation @ full load with pf = 0.8 lagging.

$$X_s = \sqrt{Z_s^2 - R_a^2}$$

$$Z_s = \frac{E_0}{I_{sc}}\Big|_{I_f} = \frac{450}{200} = 2.25\,\Omega$$

~~$X_s = \sqrt{2.25^2 - 0.2^2}$ [illegible]~~

$$X_s = \sqrt{2.25^2 - 0.2^2} = 2.24\,\Omega$$

$$VR = \frac{E_0 - V}{V} \times 100$$

$V = 550V$

$$E_0 = \vec{V} + \vec{I_a Z_s}$$

[illegible]

* ||el Operation of alternator

(i) Multiple alternator can supply a bigger load than a single alternator.

(ii) During light load, one or more altentor may be shut down.

(iii) Suitable for scheduled maintenance; while other m/c maintain continuity of supply.

(iv) If there is breakdown of a generator, there is no interruption of Power supply.

(v) In order to meet inc future demand of load, more m/c can be added without disturbing the original set up.

(vi) The cost of generation is reduced when gen opt in ||el.

* Condition for ||el operation

Loaded m/c → running m/c

newly connected m/c → incoming m/c

(i) The phase sequence of the busbar voltage & i/c m/c must be same.

(ii) The voltage must be same.

(iii) No phase difference betn busbar & i/c m/c voltage.

(iv) freqcy of generated voltage must be same.

* Synchronization

The process of one machine in ||el with other machine / infinite busbar is known as synchronization.

✓ The process of matching the [illegible] & frequency of a generator [illegible] infinite bus / [illegible]

V_T same
f is same
phase sequence

* Infinite Bus

A system of constant [illegible] and constant [illegible]

Connection of [illegible]

has no [illegible]

(1) V_T is constant [illegible] i/c m/c [illegible]

(2) f remain constant [illegible] rotation [illegible]

(3) [illegible] Z_s [illegible] $\simeq 0$ [illegible]

[illegible] in ||el.

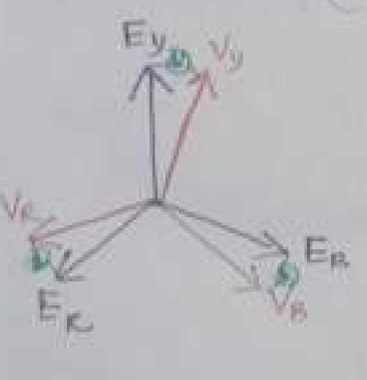
(I) Synchronizing lamp (3 dark lamp method)

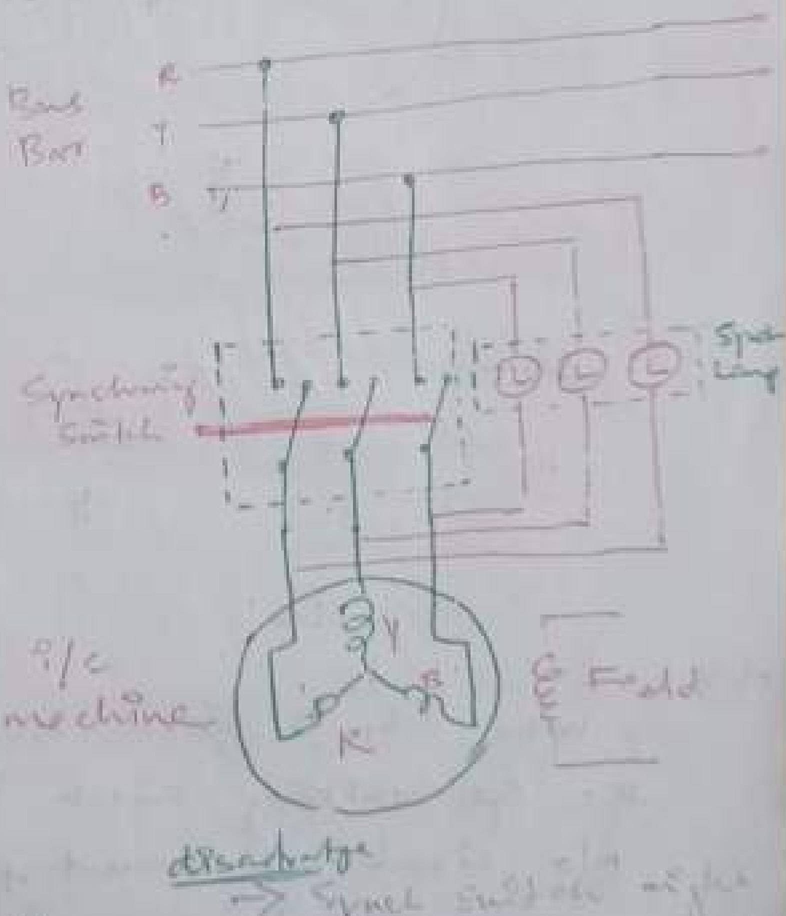
(i) Prime mover is started & s/c is brought up near rated speed.

(ii) I_f is adjusted such that V_t is equal to bus bar voltage.

fading { (iii) 3 lamps flicker @ equal rate if "f" of s/c m/c is different than bus bar.

If two phases are were changed { (iv) If all lamp will not bright & dark [illegible] the same time, phase sequence are not correct.





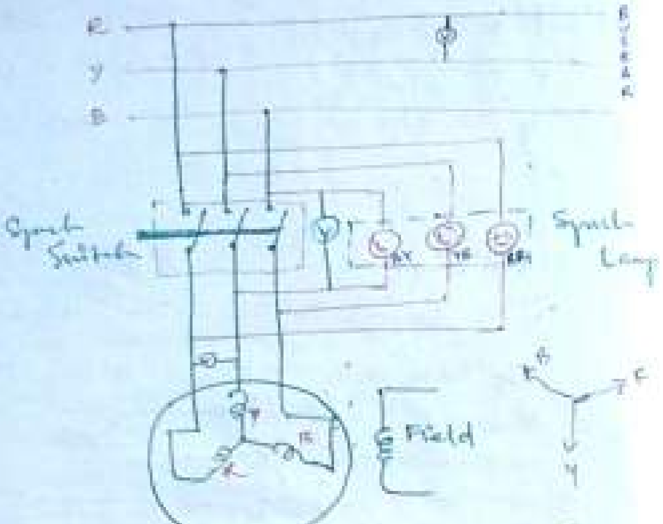
disadvantage

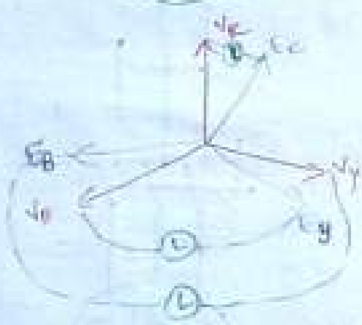
→ Sync switch might be closed @ high voltage as though lamp seen dark.

∴ A large switching current may flow.

→ Lamp doesn't indicate [illegible]

If two phases are interchanged | [illegible]





Adv → When L_1 is dark & L_2, L_3 are bright the Synchronising switch is closed.
No circulating current flow

Dis → "f" of I/c m/c is still not known.

→ The pos^n of printer indicate that the ϕ "phase diff" betn Busbar & incoming alternator

→ f (I/c m/c) → same → Printer constant

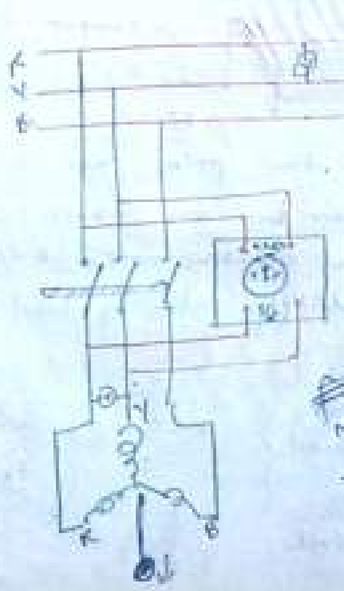
f → low → ——— → printer rotate in one direction

f → fast → rotate in other direction

Speed of rotation $\propto$ (Phase diff betn Bus & I/c m/c)

→ It gives no info about phase sequence

to change "f" → Speed of Prime mover (DC motor) is adjusted $N \propto \left[\frac{E_b}{\phi}\right]$



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

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

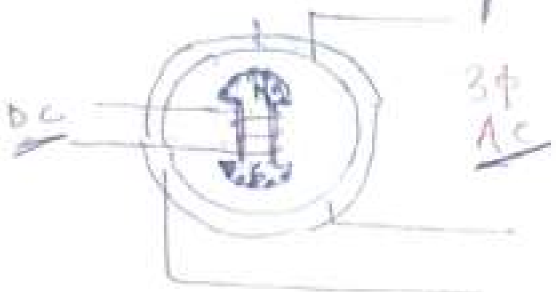
$E_g = 4.44 f \phi K_w T_{ph}$

$[E_g \propto f]$

THREE PHASE SYNCHRONOUS MOTORS

It is a m/c that convert AC elec. power to mech power at a constant speed called Synchro motor.

It is "doubly excited machine".



* Construction

Stator - Same as generator
rotor - salient pole
- cylindrical pole

Damper Winding -

Placed on the pole face & ||el to sh.

End of copper bar are short ckted.

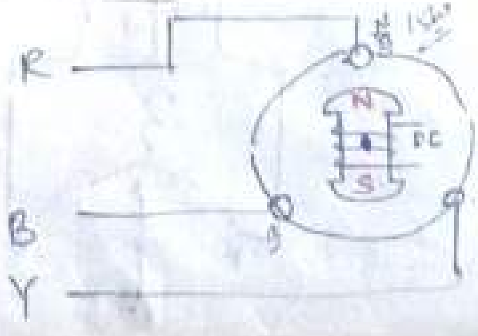
It helps in starting the S/M.

Increase stability during load transient

* Principle of Operation

→ stator field rotate @ synchronous speed in air gap -

→ Field current is steady (DC)/constant.



→ The two of magnetic field in machine.
→ Rotor will try to align with the stator field.

→ Stator rotating magnetic field & tends to "drag" the rotor along; as if north pole on the stator "locks in" with a south pole of the rotor.

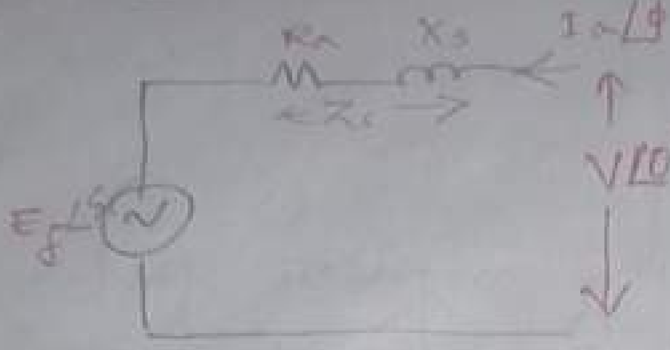
* Why synchronous motor is not SELF starting?

→ At starting rotor is stationary.
→ When a pair of rotating stator poles sweep across the stationary rotor pole @ N_s, the stator pole tends to rotate in one direction & then in other direction.
→ However, bcz of rotor inertia, the stator field slides by so fast that rotor can't follow it.
→ Hence, rotor does not move & starting torque is ZERO.

* Features of SM/c

1. While running it maintain constant speed
2. Not inherently self starting: to be brought into synchronism by other means
3. Can be operated under wide range of PF
4. It stops when load torque is more than T_{max} of

* Equivalent Phasor diagram



KVL;

$$\vec{V} = \vec{I_a}(R_a + jX_s) + \vec{E_f}$$

$E_f \rightarrow$ excitation voltage.

$V \rightarrow$ Terminal Voltage supplied

$I_a \rightarrow$ Armature current drawn by m/c per phase from the supply.

R_a

$X_s \rightarrow$ Synchronous reactance per phase.

$Z_s \rightarrow$ Impedance per phase

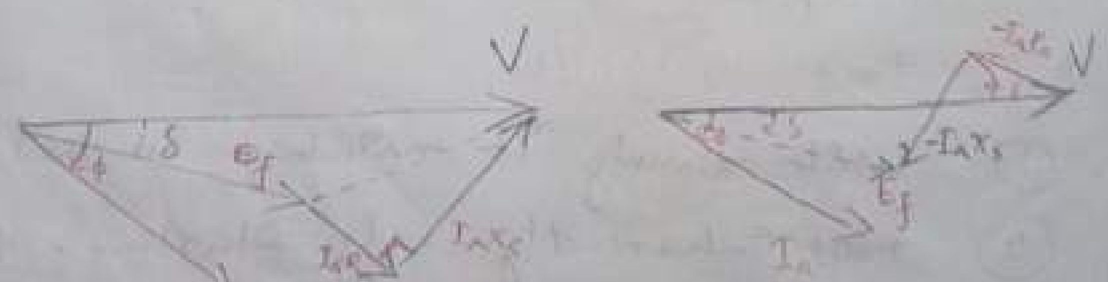
$\phi \rightarrow$ Pf angle

$\delta \rightarrow$ Torque / Load angle
Phase diff betn V & E_f

KVL;

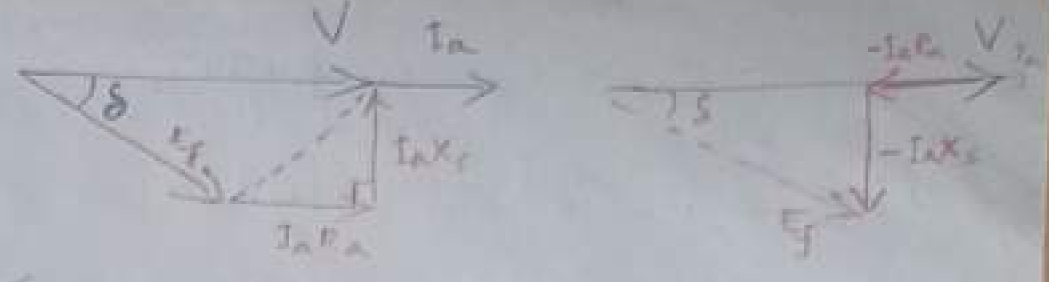
$$\vec{V} = \vec{E_f} + \vec{I_a}(R_a + jX_s)$$

$$\Rightarrow \vec{E_f} = \vec{V} - \vec{I_a}R_a - j\vec{I_a}X_s$$

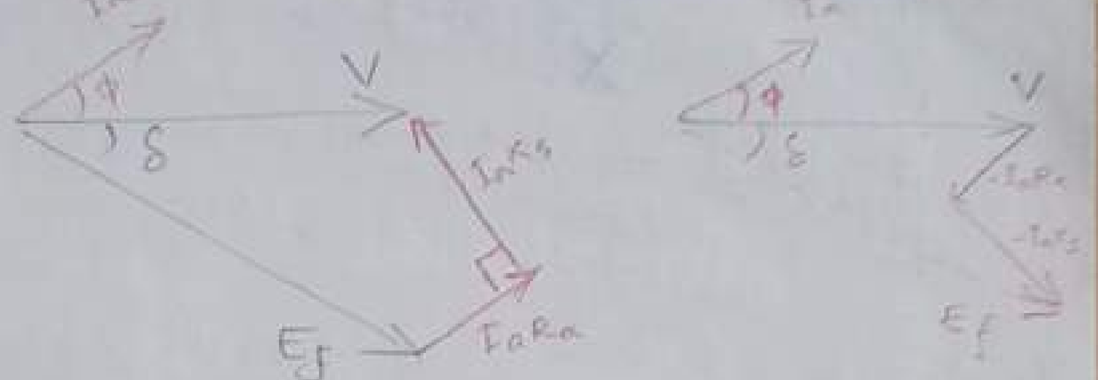


(Lagging PF)

$$E_f = \sqrt{(V\cos\phi - I_aR_a)^2 + (V\sin\phi - I_aX_s)^2}$$

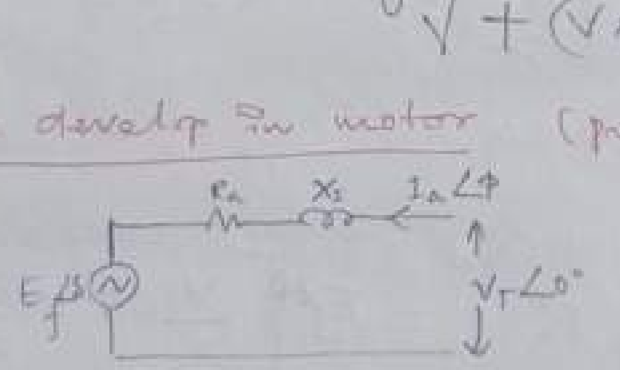


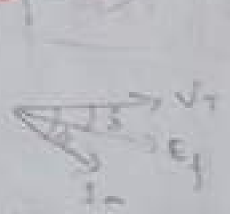
(Unity PF) $E_f = \sqrt{(V - I_aR_a)^2 + (-I_aX_s)^2}$



(Leading PF) $E_f = \sqrt{(V\cos\phi - I_aR_a)^2 + (V\sin\phi + I_aX_s)^2}$

* Power develop in motor (put θ = ϕ)





$E_f = V_T - I_aZ_s$

$\Rightarrow I_a = \dfrac{V_T - E_f}{Z_s} = \dfrac{V\angle 0° - E_f\angle\delta}{Z\angle\phi}$

$\phi = \tan^{-1}\left(\dfrac{X}{R}\right)$

$$I_a = \frac{V\angle -\phi - E_f\angle -(\phi+\delta)}{Z_s}$$

$I_a^* = \dfrac{V\angle\phi}{Z_s} - \dfrac{E_f\angle\phi+\delta}{Z_s}$

→ Bcz Voltage is used as reference [illegible]

→ I can be used [illegible], I_f I is negative

* P_{in}

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

$\Rightarrow S_{in} = \vec{V}\cdot\vec{I_a}^* = V\left[\dfrac{V\angle +\phi - E_f\angle +(\phi+\delta)}{Z_s}\right]$

$\Rightarrow S_{in} = \dfrac{V^2\angle\phi}{Z_s} - \dfrac{E_fV}{Z_s}\angle(\phi+\delta)$

To match convention [Reactive power & Active power Polarity]

But $R_a << X_s$

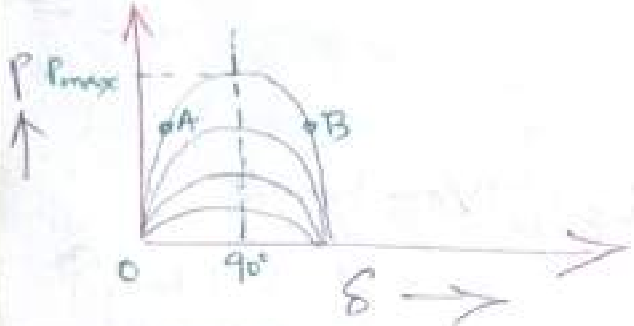
$Z_s \simeq X_s$; $\phi = 90°$

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

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

$$\boxed{P_{in} = \frac{E_f V}{X_s}\sin(\delta)}$$

$$\boxed{P_{max} = \frac{E_f V}{X_s}} \quad @\ \delta = 90°$$



A → stable region

B → Unstable region (will make rotor out of synchronism)

* **Pout** (Pmech)

$S_o = P_o + Q_o$

$$\Rightarrow S_o = E_f I_a^* = E_f\angle\delta \left[\frac{V}{Z_s}\angle\phi - \frac{E_f}{Z_s}\angle\phi+\delta\right]$$

$$\Rightarrow S_o = \frac{VE_f}{Z_s}\angle(\phi-\delta) - \frac{E_f^2}{Z_s}\angle\phi+\delta-\delta$$

$$\Rightarrow S_o = \frac{VE_f}{Z_s}(\phi-\delta) - \frac{E_f^2}{Z_s}\angle\phi$$

$$\boxed{P_{out} = \frac{VE_f}{Z_s}\cos(\phi-\delta) - \frac{E_f^2}{Z_s}\cos(\phi)}$$

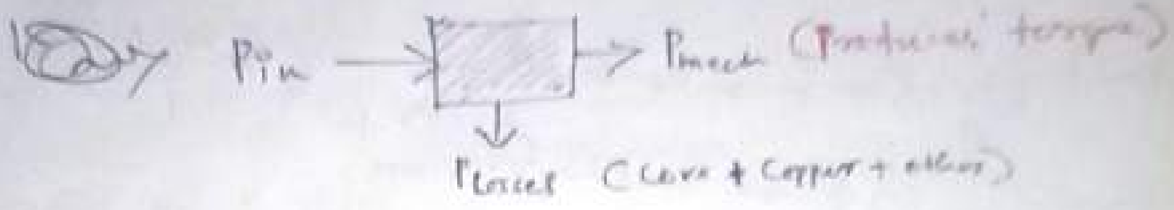
$P_{o/max} = \frac{VE_f}{Z_s}$ @ $\phi = \delta \simeq 90°$

* Torque

$$P_o = \tau \omega$$

$$\Rightarrow \tau = P_o / \omega$$

$$\Rightarrow \tau = \frac{V E_f}{\omega Z_s} \cos(\phi - \delta) - \frac{E_f^2}{Z_s \omega} \cos(\phi)$$



* Q_{in} (X)

③ $$Q_{in} = \frac{V}{X_s}(V - E_f \cos\delta)$$

① $$Q_{in} = \frac{V}{Z_s}(V\angle\phi - E_f \angle(\phi+\delta))$$

② $$Q_{in} = \frac{V^2}{Z_s} \sin\phi - \frac{E_f V}{Z_s} \sin(\phi+\delta)$$

(X)

I. if $V - E_f \cos\delta = 0$

$\Rightarrow V = E_f \cos\delta$ (operating @ UPF)

Normaly excited

II. if $V > E_f \cos\delta$

$Q_{in} = +ve$

underexcited motor

Absorb lagging VAR (lagging PF)

III. if $V < E_f \cos\delta$

$Q_{in} = -ve$

Absorbing leading VAR = operating @ lead PF.

* Effect of varying I_f (excitation) and load constant

$$P_o = \frac{E_f V}{X_s} \sin\delta = V I_a \cos\phi$$

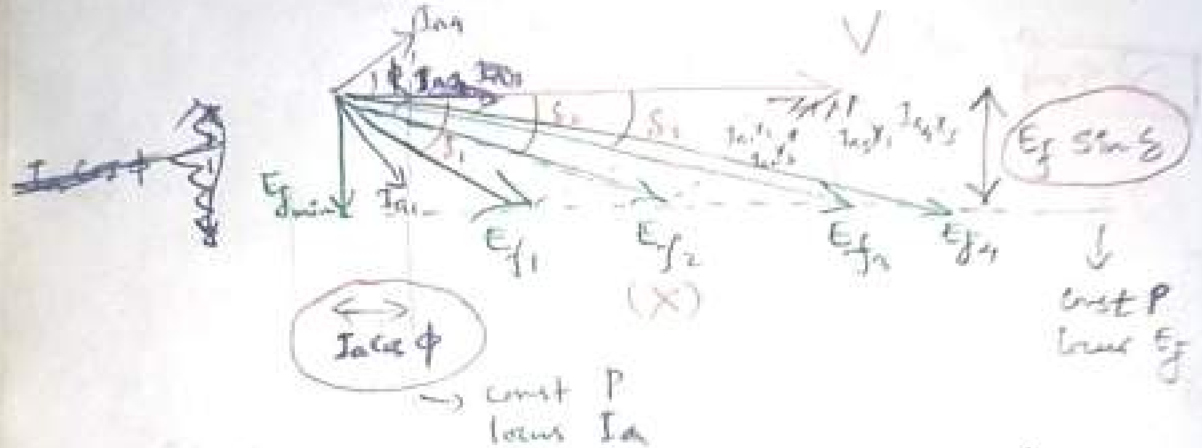
$V, X_s \rightarrow$ constant

$P_o \rightarrow$ constant ($\because$ load is constant)

$E_f \sin\delta =$ constant

$I_a \cos\phi_1 =$ constant

$\vec{V} = \vec{E} - \vec{I_a} X_s$



$\uparrow E_f \propto I_f \uparrow$ ($\because \uparrow E_f \propto \omega\phi \uparrow$)

but $E_f \sin\delta$ is constant

$\rightarrow I_a X_s$ varies $\rightarrow I_a$ varies but $I \cos\phi$ is constant

Since, $I_a(jX_s) = V - E_f$

$$\Rightarrow I_a = \frac{V - E_f}{jX_s}$$

'I_a' must remain $\perp^r$ to drop "$-I_a X_s$"

$\left.\begin{array}{l} E_f \sin\delta = \text{const} \\ I_a \cos\phi = \text{const} \\ I_a \perp^r \text{ to } jX_s I_a \end{array}\right\}$ Constraints.

$E_{f1} \sin \delta_1 = E_{f2} \sin \delta_2 = E_{f3} \sin \delta_3$

$I_{A1} \cos \phi_1 = I_{A2} \cos \phi_2 = I_{A3} \cos \phi_3$

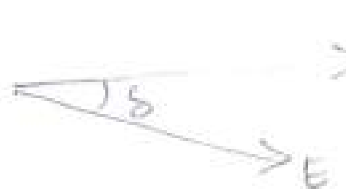
Conclusion

(i) As $\uparrow I_f \rightarrow \uparrow E_f$
First I_a decreases & then increases again

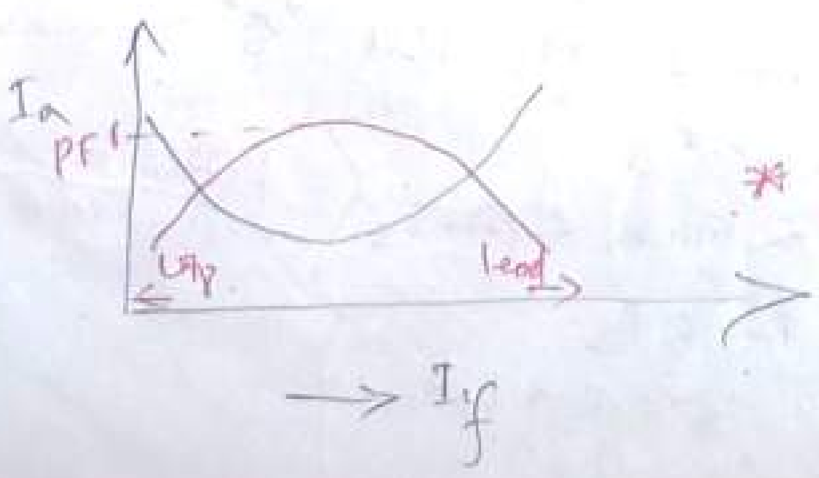
(ii) For Small E_f ;
I_a is lagging and the motor is an "LR" load.
Consume Q power

(iii) As $E_f \uparrow$
I_a comes in phase with V
Motor becomes purely "R" load. } Normal Excitation

(iv) As $E_f \uparrow$ further
I_a becomes leading
Motor becomes Capacitive load.
Consume "-Q"
Supply Q power to the system.



if $E \cos \delta < V$; → lagging PF
if $E \cos \delta > V$; → leading PF



* V Curve

* Effect of varying load of I_f = constant

$N_s, I_f, E_f, X_s, V_t \rightarrow$ constant

$E_f \rightarrow [\propto \phi \omega]$ constant

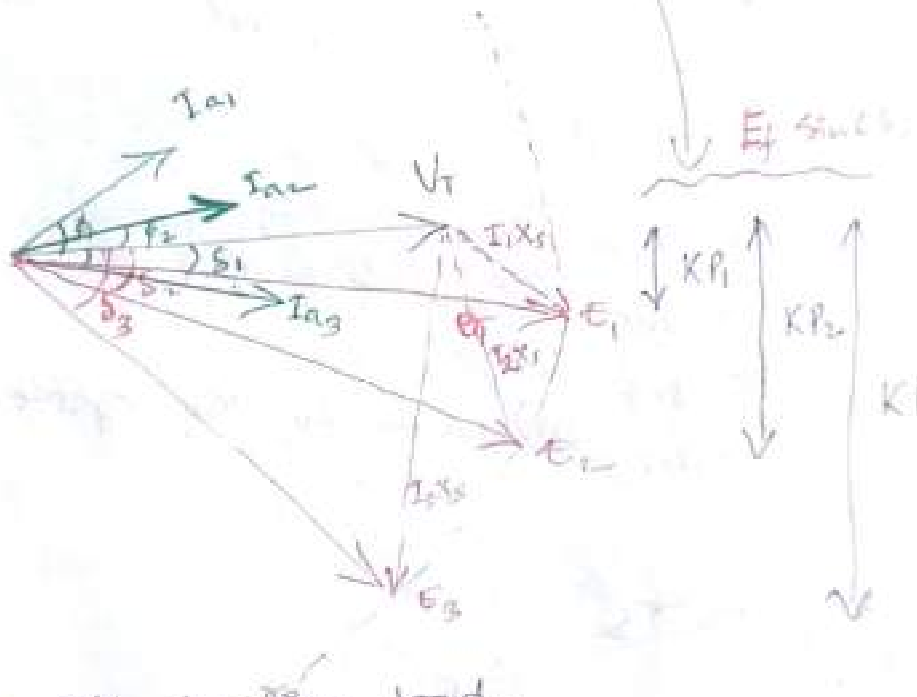
We have:

$$P = \frac{V_t E_f}{X_s} \sin\delta = V_t I_a \cos\phi$$

$$\uparrow P\left(\frac{X_s}{V_t}\right) = E_f \sin\delta \uparrow$$

(const) (const)

$$\Rightarrow PK = E_f \sin\delta$$



Start with leading load.

-> load is increased.

rotor momentarily slow down

$$\uparrow \tau_{ind} = \frac{V_t E_f}{X_s} \sin\delta \uparrow$$

-> rotor run @ N_s but "δ" increases

$E_1 = E_2 = E_3$

$\sin\delta_1 < \sin\delta_2 < \sin\delta_3$

$P_1 < P_2 < P_3$

$I_1X_s < I_2X_s < I_3X_s$

$I_1 < I_2 < I_3$

} With increase in load

Conclusion (when load is increased

(i) Motor run @ N_s (~~as Ef const~~)

(ii) Torque / Load angle "δ" ↑

(iii) E_f remain constant

(iv) I_a drawn from supply increase

(v) "φ" phase angle increases in lagging direction. Load ~~is~~ can be increased till motor reach pullout torque.
(i.e. ~~...~~ T_{po})

Torque

(I) ~~Def~~ Pull-in torque

A SM is started as IM till it runs @ 95-95 % of N_s.
Then DC excitation is given to the rotor & it pulls into synchronism with the stator rotating magnetic field.

It is the maximum ~~or~~ constant torque @ V_{rated} & f_{rated} : under which a motor will pull a connected load into synchronism ~~with~~ when DC motor excitation is applied.

II. Running Torque

It is the torque developed by the motor @ runnig condn. (∝ Power rating ∝ ω

III. Pull-out torque

P ∝ Tω → (const)

It is the maximum torque that motor can develop @ V_{rated} & f_{rated} without losing synchronism

Synchronous motor V-curve

$\uparrow$ Load $\rightarrow$ $\uparrow I_a$ $\rightarrow$ $\uparrow$ [illegible] $\rightarrow$ [illegible] $\rightarrow$ $\uparrow I_f$

($\uparrow I_a$)

Results/effect of Hunting

1. loss of synchronism
2. Same may cause V_t variation = producing undesirable lamp flicker
3. Large mechanical stress on rotor
4. Temperature of machine rises & machine loss increase

Hunting / Phase swinging

@ Normal condition $\tau_e = \tau_{load}$

$$\uparrow \tau_e = \frac{3 V E_f}{\omega_s X_s} \sin\delta \uparrow$$

When there is change in load ($\uparrow$)

$\uparrow \tau_{load}$

$$\tau_e - \tau_{load} = J \frac{d\omega}{dt}$$

(ω → angular velocity of rotor; J → moment of inertia)

The motor slows down a bit & 'δ' is increased to restore the torque equilibrium & ~~speed~~ N_s

→ $\uparrow \delta \Rightarrow \uparrow \tau_e \rightarrow \uparrow N$ till it reaches N_s.

→ The phenomenon of oscillation of the rotor about its final equilibrium position after ~~load~~ changing load is called Hunting

~~Dampers bars/winding~~

Cause of Hunting

(i) Sudden change of load
(ii) Fault in system
(iii) Sudden change in 'I_f'
(iv) cyclic variation of load torque

* Reduction of Hunting

① Use damper winding.

② Use of flywheel.

Can prime mover mounted with heavy flywheel. Increase J of rotor & help in maintaining the rotor speed.

* Damper Winding/bars

→ Copper bars on pole faces are short circuited at both end placed ||el to the shaft.

→ Changing ϕ_a → E_d generated $\left(\frac{d\phi}{dt}\right)$ → I_d flows → ϕ_d produces → tries to catch up ϕ_a → Run

↳ till 95% N_s

Uses

① Starting of SM (Self starting)

② Reduce hunting phenomenon. oscillation in

* Starting of SM (After Damper Winding)

① With the help of Damper winding

② With external prime mover

$\downarrow s = \frac{n_s - n}{n_s} \uparrow$

→ external motor drives the SM & brings it to synchronism. (IM with 2 pole less than SM)

→ SM is synchronised ~~as a~~ with the bus bar as a synchronous generator.

→ Then prime mover is disconnected.

→ Now m/c run as SM & load can be connected to it.

→ $\tau_{NL} < \tau_{FL}$

* Application of SM

→ Constant speed application.

→ ① High P ; High N_s compressor
② Blower
③ ~~[illegible]~~ main line traction.
④ As Variable inductor/capacitor, in power transmission line to regulate voltage.
⑤ Synchronous condenser ~~[illegible]~~ to provide IM VAR (Q) in industries.
(.) Explain it

$$Q_{in} = \frac{V}{X_s}\left(V - E_f \cos\delta\right)$$

(+) → lagging (Under Excited)

(−) → leading (Overexcited) (Supply VAR)

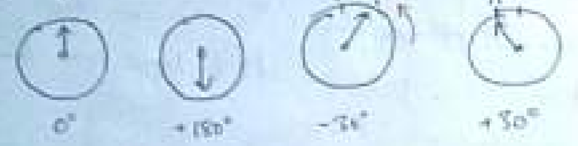
THREE PHASE T/F

→ For large power transfer
→ Step up & step down voltage in various stage of power system n/w.

Y → star
Δ → Delta

* 3φ T/F Group

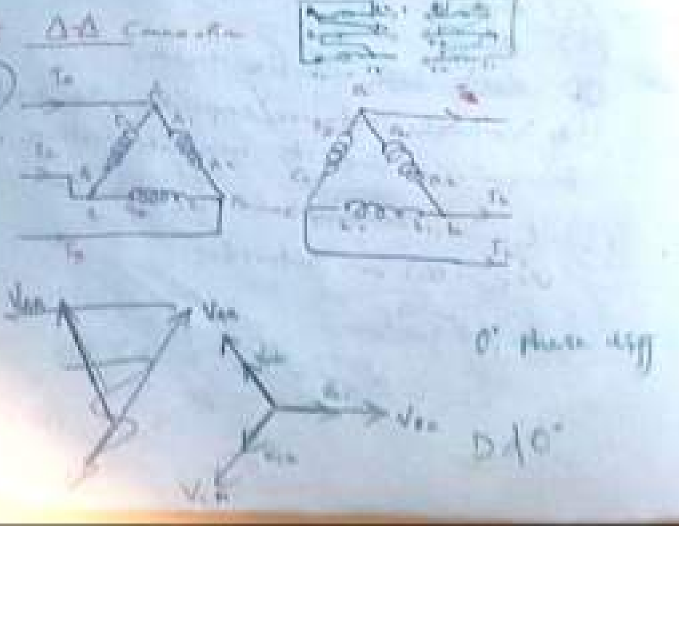
1. Grp - I : No phase displacement Yy0 , Dd0
2. Grp - II : 180° — do — Yy6 , Dd6
3. Grp - III : (-30°) — do — Yd1 , Dy1
4. Grp - IV : (+30°) — do — Yd11 , Dy11



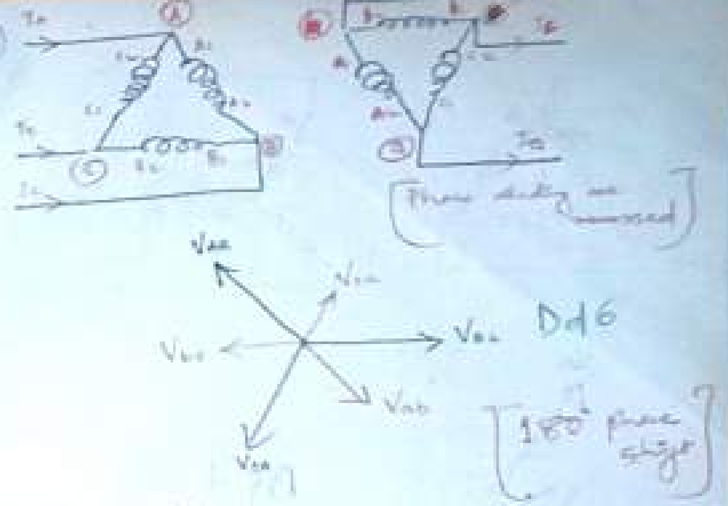
Yd11

* Δ-Δ connection

(I)

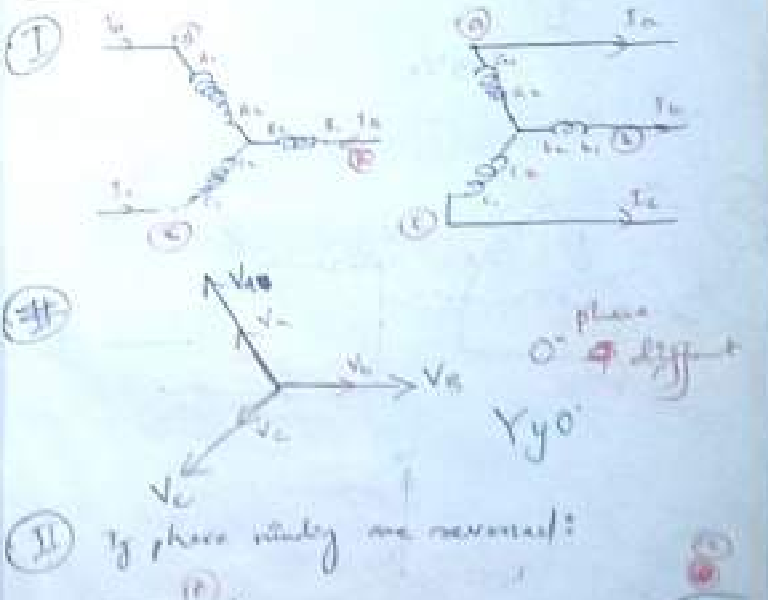


(II)

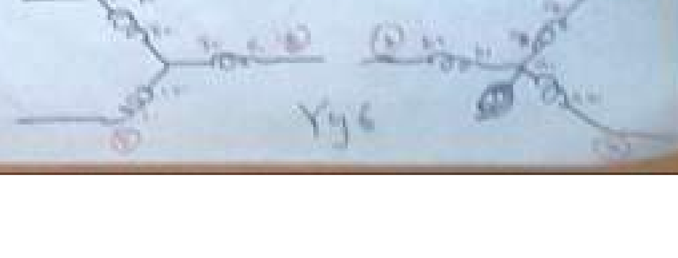


Y-Y connection

(I)

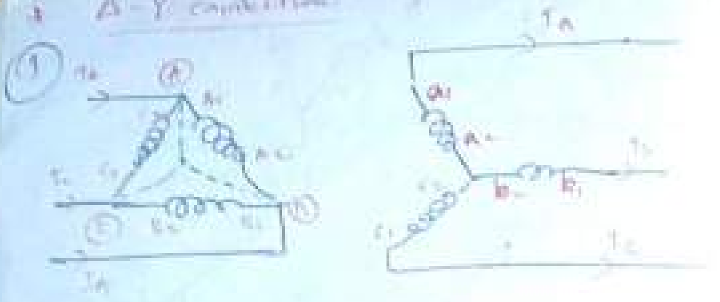


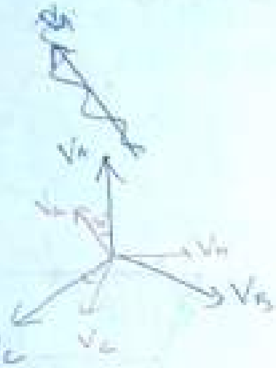
(II) If phase winding are reversed:



Δ-Y connection

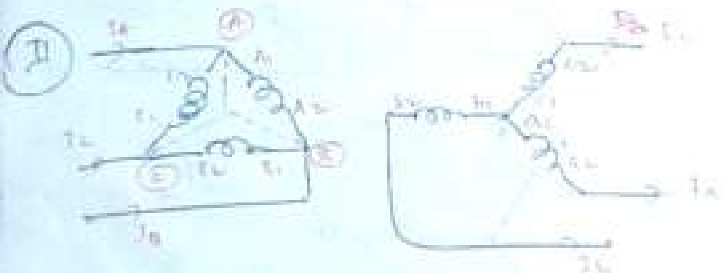
(I)

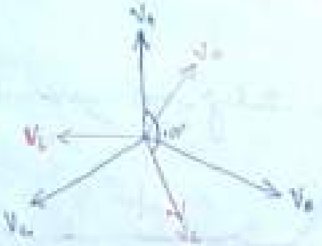




Dy 11

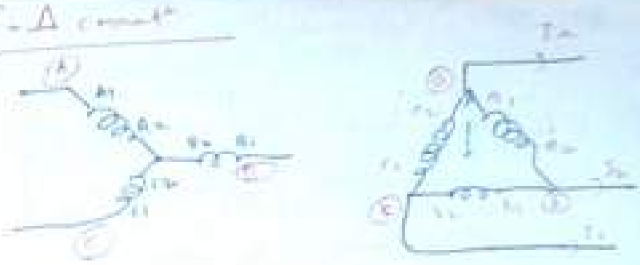
(II)

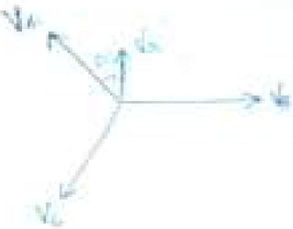




Dy 5

Y-Δ connec^n

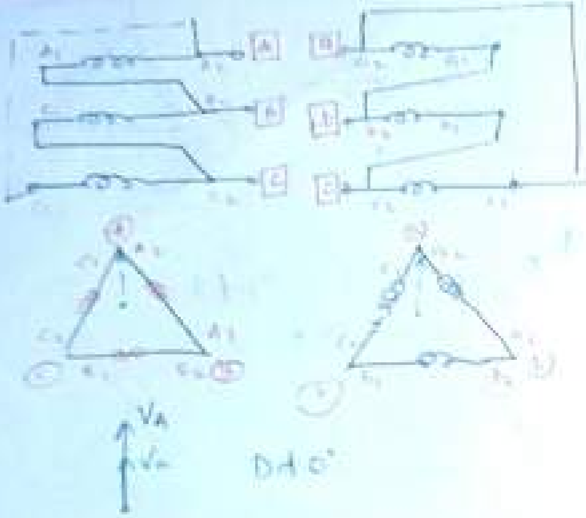




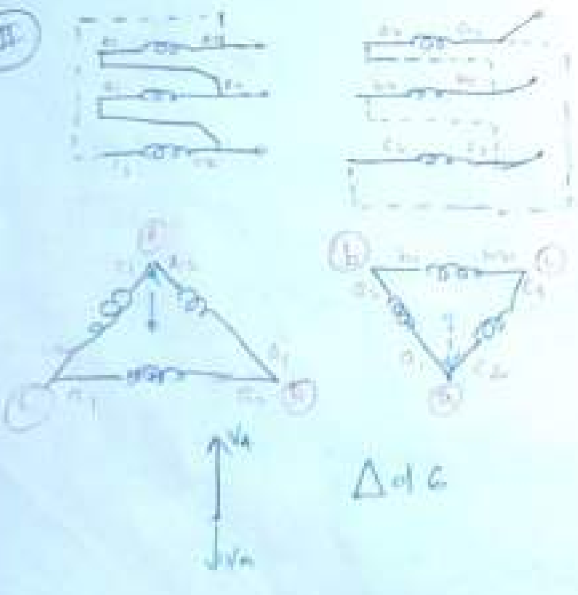
Yd 1

* ~~Δ-Δ~~ Δ-Δ connect.

(I)

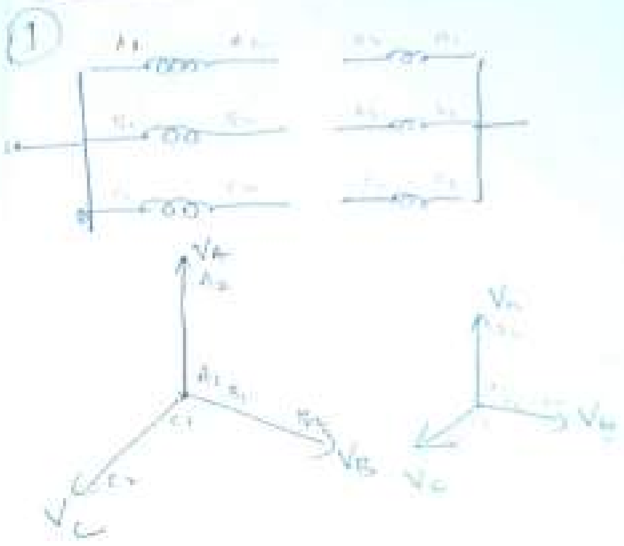


(II)

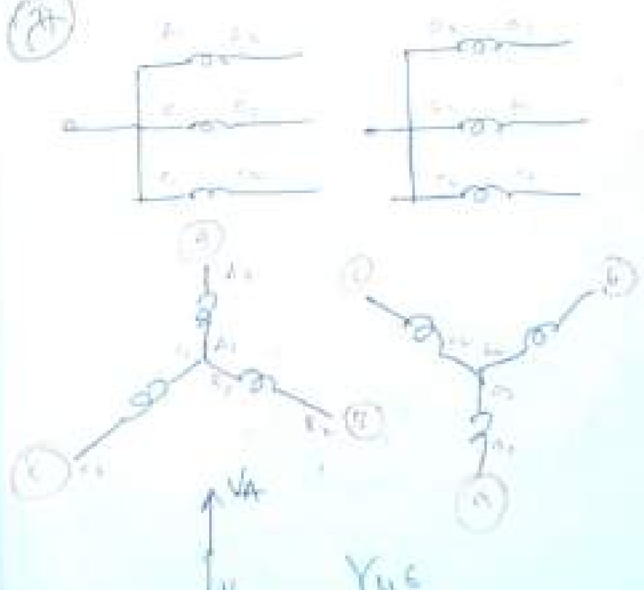


* Y-Y connect (Teach first)

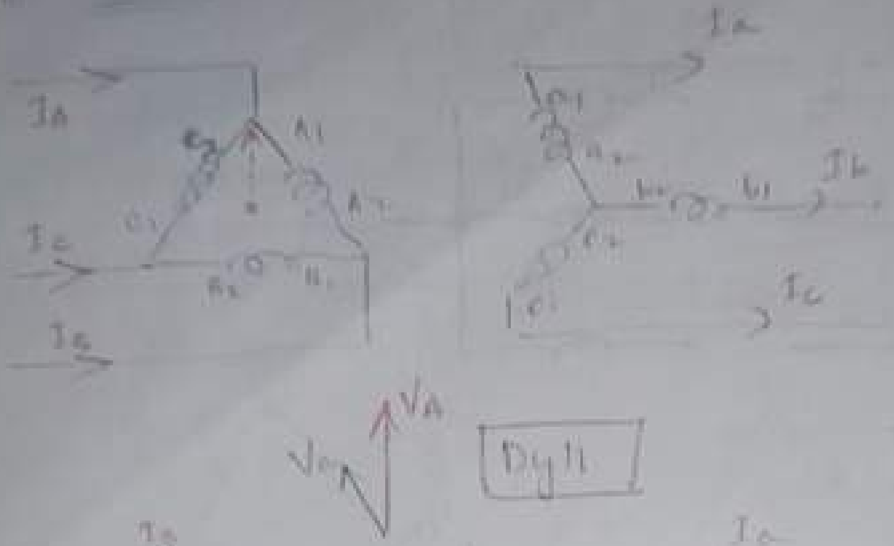
(I)

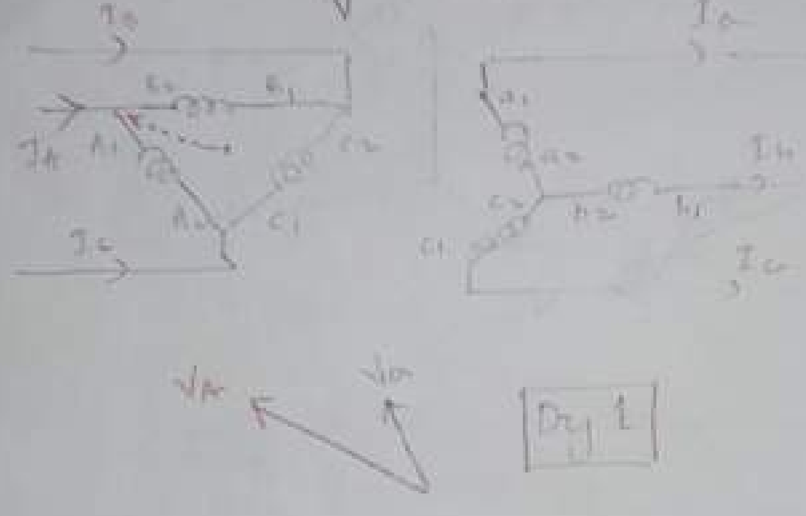


(II)

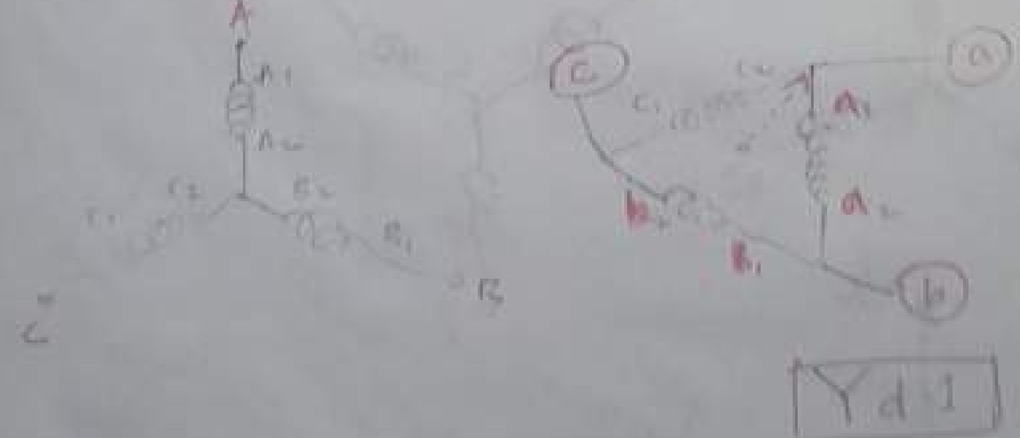


* Δ-Y





* Y-Δ



0° → Yy0, Dd0

180° → Yy6, Dd6

−30° (lag) → Yd1, Δy1

30° (lead) → Yd11, Δy11

* Parallel operation of 3φ t/f

14/ ① Polarities of t/f must be same
✓ (Dot convention) → (+ve polarity) I' entre dot in primary & leave dot for 2°. (φ'' oppose φ')

I' entre dot, I'' entre dot, φ' & φ'' are additive

✓ ② Identical 1° & 2° voltage rating

~~③ $Z_{pu} \propto \frac{1}{(KVA)\,rating}$~~

→ load sharing acc. to their rating (Same PF operation)

④ Identical $\frac{X}{R}$ ratio in the TF impedance.

⑤ Same pu impedance for load sharing (desirable) (Z_{pu})

3φ/

✓ (A) Phase sequence must be the same (R-Y-B)

✓ (B) The phase shift b/w 1° & 2° voltage must be same for all tf which are connected in ||.

(Phase group)

ΔΔ ΔY

YY YΔ

ΔY

Dd0° Dy1 Yd11

Yy0° Dy1 Dy11

Yd1

* Reason for ||el operation

① Uneconomical to have a [illegible]

② Capacity of spare to [illegible]

③ Scope for future expansion

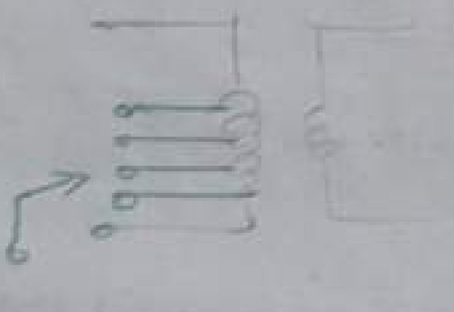
④ Reliability & [illegible]

[illegible]

Spare TR [illegible]

(I) Off load Tap changer (After Tap changer)

It regulates the output voltage through changes of Tap in the transformer. ← NEXT



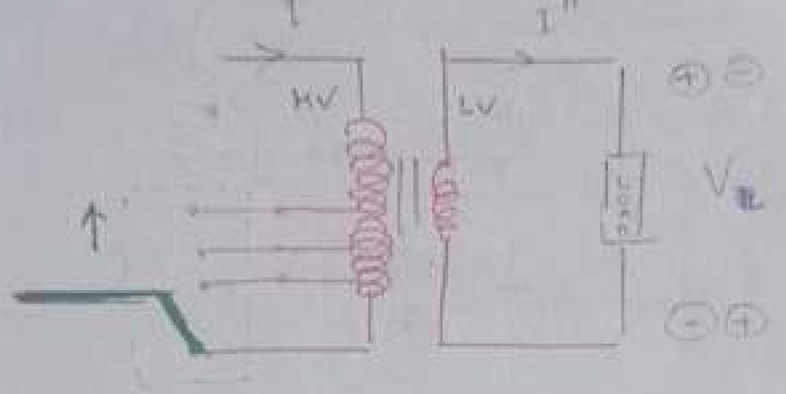
→ The TR is disconnected [illegible] when tap changing is required.

* Tap changer (First)

- Due to change the load: V_R varies.

  ↑ load → ↓ V_L (drop ↑)

- To keep the V_L constant: tapping from HV winding are taken

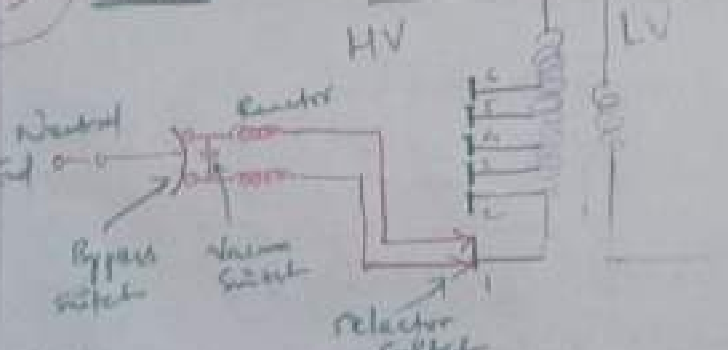


HV turn ↓
LV voltage ↑

→ • Why on HV winding?

1. HV winding are on & outside the LV; so easier to get tapping connection
2. Current is low on HV side; tap changing contact/lead can be smaller size. (~~Late~~ spacing)

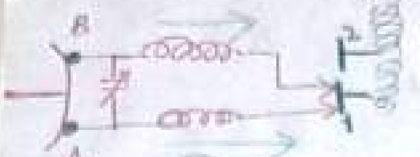
(II) OLTC



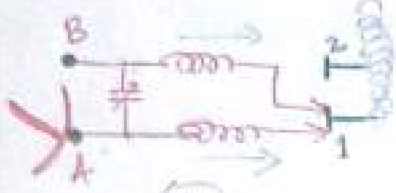
→ Load act should not be broken to avoid arcing which may damage [illegible]

Parts

1. Selector switch (Select tap position of the winding)
2. Reactor (During tap change the circulating current is limited by it)
3. Vacuum switch (Duty of the make & break current during tap changing sequence)
4. Bypass switch

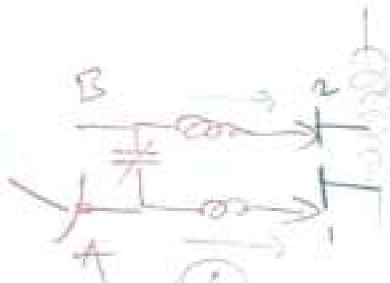


(1)



(2)

(3)



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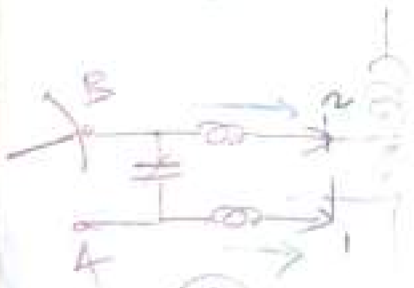

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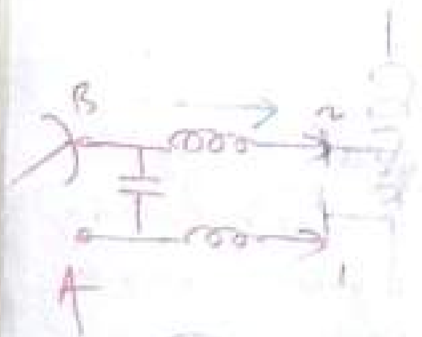

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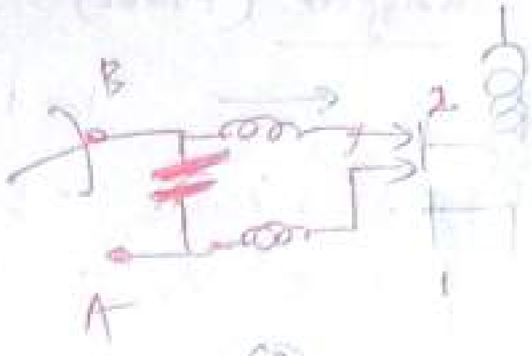

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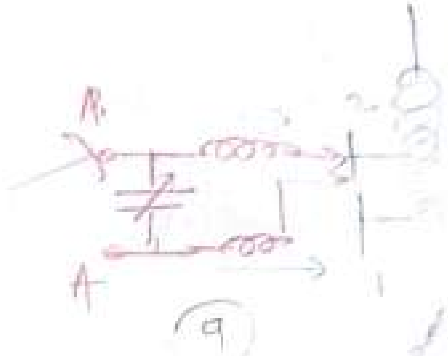

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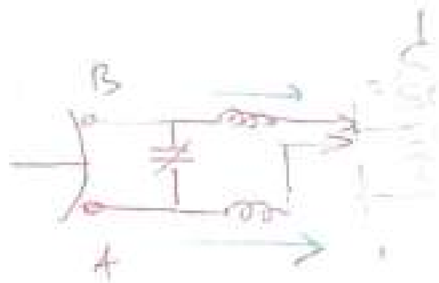


* Maintenance of 3ϕ TF

(I) Daily

(i) Ambient Temperature

(ii) Winding Temperature & Oil temp

If above normal level then; shutdown TF.

(iii) Load & Voltage

Check against rated figure.

(II) Weekly

(i) Oil level

if low then & check than the minimum level then checkout for leakages.

(ii) Oil level in bushing

if low then; dry the oil & examine for leakage

(III) Monthly

(I) Relief diaphragm

Replace if crack or broken.

→ Mechanical pressure relief valve.

→ Gas pressure will lift the diaphragm & gas escape quickly

(II) Dehydration (breather)

Check for the color of silica gel. If pink then ~~~ change with new & dehydrate the pink silica gel to get back to ~~~ normal color

(III) Quarterly

(I) Bushing

Examine for crack & dirt.

Acutely; clean or replace.

(IV) Half yearly

(I) Oil

Check for dielectric strength & water content in it.

(II) Cooler fan, bearings & control ...

Lubricate bearing, check gears, examine contacts, control

Replace burnt or worned ~~contact~~ p...

(III) Oil in cooler

Test for pressure.

Examine if any leakage.

(V) Yearly

(I) Oil in transformer / & Oil filled bushing

Check for sludge.

Filter or replace.

(II) Cable box

Examine the connection & cracks.

3ϕ INDUCTION MOTOR

* Advantages \

① Cheap ② Robust ③ Efficient
④ Reliable ⑤ Overload capacity
⑥ Good speed regulation
⑦ High τ starting. ⑧ Little maintenance

* Construction ⇓

(I) STATOR

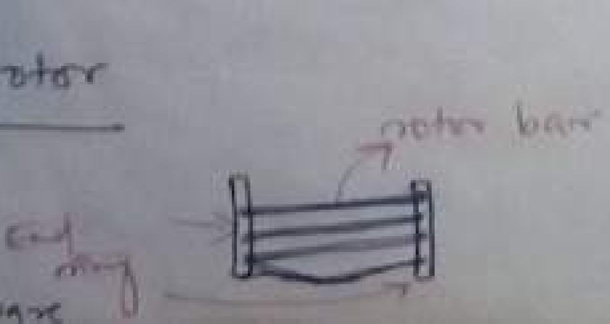
→ High grade alloy steel lamination.
→ Lamination are supported on stator frame of cast iron.
→ ~~Stator~~ insulated conductor are placed on the slots present in inner periphery of the stator frame.
→ Stator conductor are connected to form 3ϕ winding.

(II) Rotor

→ Laminated alloy of steel.
→ Mounted on the shaft
→ Lamination are slotted on the outer periphery to receive rotor conductor.

(A) Cage rotor

→ Copper/Al
→ Skewed slots/bars



* Skewed because

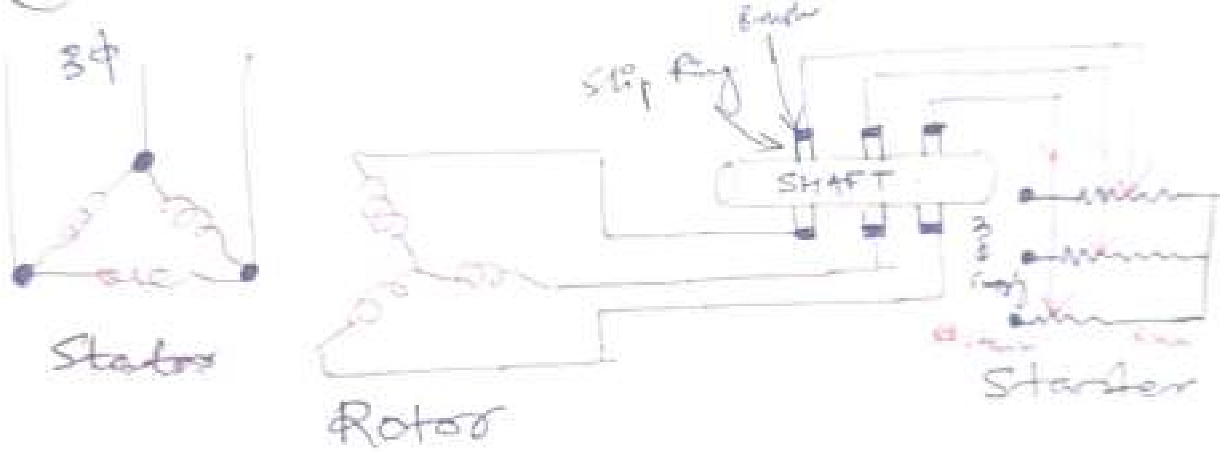
(i) More uniform torque & less noise during operation

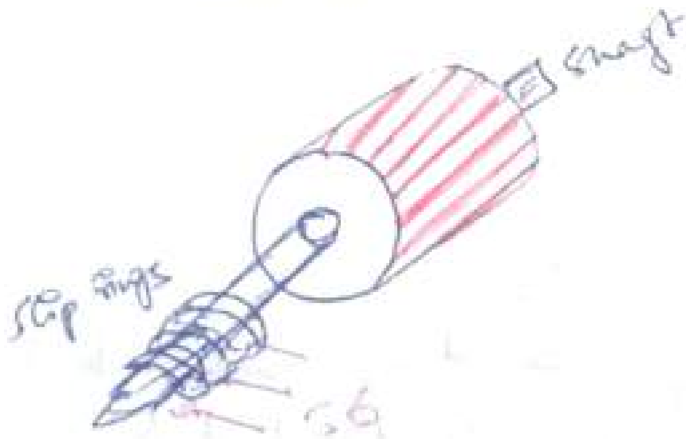
(ii) Locking tendency of rotor is reduced;

Locking

rotor & stator teeth attract each other due to magnetic action

(B) Wound rotor / Slip ring rotor





→ Insulated conductor are put in slots of a rotor to form 3φ distributed winding

→ Slip rings are mounted on the shaft & brushes resting on them.

→ This set up provide connection to external resistance

Why Rext connected

(I) To increase T_{st} & I_{st} decrea..

(II) To control speed of motor.

* ~~Operating~~ Working Principle III

According to Faraday's law of EMI EMF is induced in rotor bar due to change in magnetic flux (3ϕ rotat.. magnetic field) linkage thigh it.

As rotor bars are short circuit.. current flows thigh the rotor ba..

As per Lenz's law, the rotor will rotate ~~to~~ to reduce the relative speed ~~rate~~ between magnetic flux & ~~stator~~ rotor conductor.

(to reduce its cause).

If rotor speed up to N_s, then there shall be no relative speed. ~~It~~ It results in no flux change ~~in~~ ~~coo~~ experienced by rotor bar. Hence no emf is induced & no curr.. flows in rotor conductor.

Therefore, ~~rotor decelerate~~ no ~~torq~~ torque ~~will~~ would be generated.

∴ Rotor decelerate & can't run at N_s.

It always run @ ~~at~~ below N_s

As the motor operation depends upon the induced voltage in rotor conductors, it is called induction motor.

SLIP

The difference in speed between the N_s & rotor speed is called 'Slip Speed'.

$$\% S = \frac{N_s - N_r}{N_s} \times 100$$ | Percent Slip.

"Speed Slip" $= N_s - N_r$

It is around 5% at full load
2% at Large motor.

* Frequency of Rotor voltage & current

At stator; $f = \frac{PN_s}{120}$

At rotor; $f_r = \frac{P(N_s - N_r)}{120}$

$$\frac{f_r}{f} = \frac{N_s - N_r}{N_s} = S$$

$$\Rightarrow \boxed{f_r = sf}$$

@ standstill; $N_r = 0$; $s = 1$; $f_r = f$

@ $N_r = N_s$; $s = 0$; $f_r = 0$

(Q) Frequency of emf in stator of 4 pole IM is 50Hz, and that in rotor is 1.5Hz what is the slip, and speed of motor.

$$f_r = s f$$

$f = 50Hz$; $f_r = 1.5 Hz$; $s = \frac{1.5}{50} = 3\%$

$$N_s = \frac{120 f}{P} = \frac{120 \times 50}{4} = 1500 \text{ rpm}$$

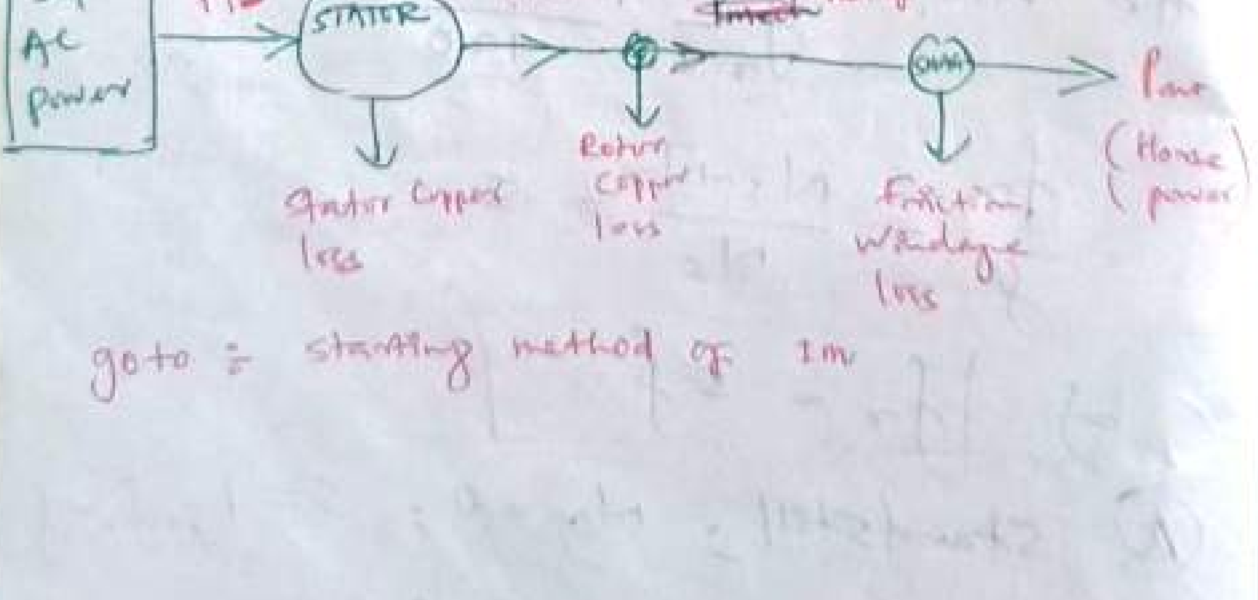
$$S = \frac{N_s - N_r}{N_s} \times 100 = 3$$

$$\Rightarrow 1500 - N_r = \frac{3 \times 1500}{100}$$

$$\Rightarrow N_r = 1500 - 45$$

$$N_r = 1455 \text{ rpm}$$

Power flow in IM (Before Rotor losses)



goto : starting method of IM

* ROTOR Current

(A) At standstill

{0 → standstill, r → rotor} {subscript}

Let;
- E_{r0} = emf induced/phase of rotor @ standstill
- R_r = Resistance per phase
- X_{r0} = reactance/phase
- Z_{r0} = impedance/phase

Then

$$I_{r0} = \frac{E_{r0}}{Z_{r0}}$$

$$\cos\phi_{r0} = \frac{R_r}{Z_{r0}} = \frac{R_r}{\sqrt{R_r^2 + X_{r0}^2}}$$

(B) At Running

{s → slip {subscript}

$E_{rs} = s E_{r0}$ induced emf/phase at slip "s".

R_r → constant

$$X_{rs} = 2\pi(s f_0)L = s.X_{r0}$$

$$Z_{rs} = R_r + j X_{rs} = R_r + j s.X_{r0}$$

$$I_{rs} = \frac{E_{rs}}{Z_{rs}}$$

$$\cos\phi_{rs} = \frac{R_r}{\sqrt{R_r^2 + j(s X_{r0})^2}}$$

[NOT REQUIRED]

Power generated at rotor :- → I^2R copper loss

$$P_{rs} = 3 E_{rs} I_{rs} \cos\phi_{rs} = 3 E_{rs} \frac{E_{rs}}{Z_{rs}} \frac{R_r}{Z_{rs}}$$

$$\Rightarrow P_{rs} = 3\frac{E_{rs}^2 R_r}{(Z_{rs})^2} = 3\frac{s^2 E_{r0}^2 R_r}{R_r^2 + (s X_{r0})^2}$$

$[S. 2\pi n T_d] = P_{rs}$ (∵ All power will be I^2R loss)

↑ rotor input

GOTO TORQUE →

Q) Example 4.4 (Page 319) "Asfaq Hussain"

3Φ, 50Hz, 4-pole IM
Slip = 4%

Calculate (a) Speed of motor
(b) frequency of rotor emf

$R_2 = 1\,\Omega$
$X_{20} = 4\,\Omega$

ϕ_{20} (a) start
(b) @ 1400 rpm

Ans (i)

(a) $N_s = \frac{120}{P} f = 1500$ rpm

$s = \frac{N_s - N_r}{N_s} \times 100$ $N_r = (1-s)$

$\Rightarrow \frac{4 \times 1500}{100} = 1500 - N_r$

$\Rightarrow \boxed{N_r = 1440 \text{ rpm}}$

(b) $f_r = sf = \frac{(4)}{100}(50)$

$\Rightarrow \boxed{f_r = 2\,Hz}$

(ii) (a) $\phi_{20} = \frac{R_2}{\sqrt{R_2^2 + X_{20}^2}} = \frac{1}{\sqrt{1+16}} = 4.12$

$\cos \phi_{20} = \cos(75) = 0.24$ (lag)

(b) @ 1400 rpm

$S = \frac{1500 - 1400}{1500} \times 100 = \frac{100}{15}\ \%$

$Z_{2s} = R_2 + jsX_{20} = 1 + j\frac{1}{15}(4)$

$\Rightarrow Z_{2s} = 1.034 \angle 14.93°$

$\cos \phi_{2s} = 0.9662$ (lag)

* Relationship between rotor copper loss & rotor input (After Power flow in IM)

τ_d = developed torque on the rotor.

n_s = synch speed (rps) = $\frac{N_s}{60}$

n_r = rotor speed (rps) = $(1-s)n_s$

P_{ir} = Power input to rotor from stator.

$$P_{ir} = \omega_s \tau_d = 2\pi n_s \tau_d$$

P_m = mechanical power developed by rotor

$$P_m = \omega_r \tau_d = 2\pi (n_r) \tau_d$$

"I^2R" loss in rotor = $P_{ir} - P_m$

$$\Rightarrow P_{rc} = 2\pi (n_s - n_r) \tau_d$$

$$\frac{P_{rc}}{P_{ir}} = \frac{2\pi (n_s - n_r) \tau_d}{2\pi n_s \tau_d} = \frac{n_s - n_r}{n_s}$$

$$\Rightarrow \boxed{P_{rc} = s \cdot P_{ir}} \leftarrow \text{Slip power (loss)}$$

~~$P_{ir} = P_m + P_{rc}$~~

~~$P_{rc} = s(P_m + P_{rc})$~~

~~$\Rightarrow \boxed{P_{rc} = \left(\frac{s}{1-s}\right) P_m}$~~

$P_{ir} = P_m + sP_{ir}$

$\Rightarrow P_{ir}(1-s) = P_m$

$$P_{ir} : P_{rc} : P_m = 1 : s : (1-s)$$

$$n_s : n_{\text{slip speed}} : n_r = 1 : s : (1-s)$$

$P_{rc} = s \cdot P_{ir}$

$P_m = (1-s) \cdot P_{ir}$

$\tau_d = \frac{P_{ir}}{W_s}$

(Q) Ex 4.6 (322)

$P_{is} = 60\,KW$ $\quad s = 0.03 = \frac{3}{100}$

$P_{loss\text{-}stator} = 1\,KW$

$P_{ir} = 60 - 1 = 59\,KW$

~~rotor~~ $P_{rc} = s P_{ir} = \frac{3}{100} \times 59 = 1.77\,KW$

$P_M = P_{ir} - P_{rc}$

$\Rightarrow P_m = 59 - 1.77 = 57.23\,KW$

(Q) Ex 4.8 (323)

440V, 50Hz, 6 pole, 3-ϕ, $P_{is} = 80$...

rotor emf → 100 alternati-/min $= \frac{100}{60}$ Hz

$f_r = \frac{100}{60}$ Hz.

(a) Slip

$f_r = s \cdot f$

~~$\Rightarrow s = \frac{50}{100} \times 60 =$~~

$\Rightarrow s = \frac{100}{60 \times 50} = \frac{1}{30}$

(b) Rotor Speed $\quad \left(N_s = \frac{120(50)}{(6)} = 1000 \right)$

$N_r = (1-s) N_s = \left(1 - \frac{1}{30}\right)(1000)$

$\Rightarrow N_r = 966.7$ rpm

(c) $P_{mech-develop} = P_{ir} - P_{rc} = (1-s)P_{ir}$

~~$P_{rc} = \left(\frac{1}{30}\right)(80) * 1000\ W \quad (s \cdot P_{ir})$~~

~~$= 2667\ W$~~

$P_m = (1-s)P_{ir}$

$= 77333\ W$

(d) Rotor copper loss / phase

$P_{rc} = (s)P_{ir}$

$\Rightarrow P_{rc} = \left(\frac{1}{30}\right)(80000)$

$\Rightarrow P_{rc} =$ ~~267~~ $2667\ W$

$P_{rc}/phase = \frac{2667}{3} = 889\ W$

(e) R_r ; $I_r = 65$

$P_{rc} = I_r^2 R_r$

$\Rightarrow \frac{889}{65^2} = R_r \Rightarrow R_r = \underline{0.21\ \Omega}$

Torque in an IM

Power gain in rotor:

$= 3 E_{r s} I_{r s} \cos\phi_r = 3 E_{r s} \frac{E_{rs}}{Z_{rs}} \cdot \frac{R_r}{Z_{rs}}$

$= 3 \frac{E_{rs}^2}{Z_{rs}^2} R_r$

$= 3 \frac{[s^2] E_{r0}^2 R_r}{R_r^2 + (sX_{r0})^2}$

$P_{rc} = 3 I_{rs}^2 R_r$ (rotor copper loss)

$\Rightarrow P_{rc} = 3 \left(\frac{s E_{r0}^2}{Z_{rs}^2} \right) R_r$

$\Rightarrow P_{rc} = 3 \left(\frac{s^2 E_{r0}^2}{R_r^2 + (sX_{r0})^2} \right) R_r = s P_{ir} = s \cdot \tau_d \cdot 2\pi n_s$

$\Rightarrow \frac{3 s E_{r0}^2 R_r}{R_r^2 + (sX_{r0})^2} = \tau_d \cdot 2\pi n_s$

$\Rightarrow \tau_d = \frac{3}{2\pi n_s} \left[\frac{E_{r0}^2 \cdot R_r \cdot s}{R_r^2 + (sX_{r0})^2} \right]$

$\Rightarrow \tau_d = K \cdot \left[\frac{s E_{r0}^2 R_r}{R_r^2 + (sX_{r0})^2} \right]$ → Torque developed

① Starting torque

$s = 1$

$\tau_{st} = K \left[\frac{E_{r0}^2 \cdot R_r}{R_r^2 + (X_{r0})^2} \right]$

$K = \left(\frac{3}{2\pi n_s} \right)$

$\tau_{st} \propto E_{r0}^2 \ (\propto E_{st})$

Starting torque is proportional to the sq. of input voltage to stator

Developed Torque (τ_d)

$\tau_d = \frac{P_{m}}{\omega_r}$ — mech power developed / mech angular velocity of rotor

But; $P_m = (1-s) P_{ir}$

$\omega_r = (1-s) \omega_s$

So; $\tau_d = \frac{P_{ir}}{\omega_s}$ → constant $\Rightarrow$ $\tau_d \propto P_{ir}$

(X) $\tau_{sh} = \frac{P_o}{\omega_r} = \frac{P_m - P_{rot}}{\omega_r}$ (torque developed; mechanical loss)

② Max torque

$\frac{d[\tau_d]}{ds} = 0 \Rightarrow \tau_d = \frac{K E_{r0}^2}{(?)} \left[\frac{s R_r}{R_r^2 + s^2 X_{r0}^2} \right]$

$\frac{d\tau_d}{ds} = K' \left[\frac{(R_r)[R_r^2 + s^2 X_{r0}^2] - 2 s X_{r0}^2 s R_r}{R_r^2 + s^2 X_{r0}^2} \right]$

$\Rightarrow 0 = R_r^3 + s^2 R_r X_{r0}^2 - 2 s^2 R_r X_{r0}^2$

$\Rightarrow s^2 R_r X_{r0}^2 = R_r^3$

$\Rightarrow R_r = s X_{r0}$

$R_r = X_{rs}$

$\tau_{d\,max} = \frac{K'}{2 X_{r0}}$

@ τ_{max} @ starting

$R_r = s X_{r0} = X_{r0}$ ($\because s = 1$)

$R_r = X_{r0}$

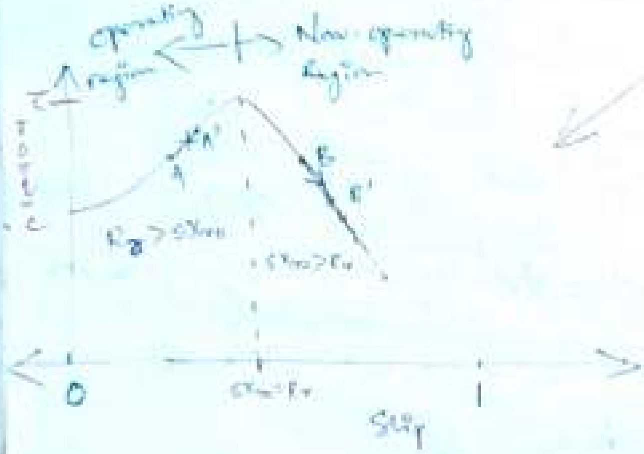
So; $\tau_{max} = K' \left[\frac{s \cdot R_r}{2 R_r^2} \right] = \frac{K' s}{2 s X_{r0}}$

$$T_{max} = \frac{K (E_{r0})^2}{2 X_{r0}}$$

Conclusion :-

(i) T_{max} is independent of the "R_r"

(ii) $T_{max} \propto \frac{1}{X_{r0}}$



Slip ↑ → Speed ↓ → motor slows down

@ "A"

If load increases → slip increases,
operating point moves to A'
As a result, ~~torque~~ increase
Load ↑ → Slip ↑ → Speed ↓ → Torque ↑
~~equilibrium~~ come back to A ← Speed ↑ ←

@ "B"

If load ↑ → slip ↑ → move to B'
Breakdown ← slip ↑ ← ~~slip~~ speed ↓ ← torque ↓

* Torque - slip & Torque - Speed

We have;

$$T = \frac{K s R_r E_{r0}^2}{R_r^2 + s^2 X_{r0}^2}$$

If R_r & X_{r0} are constant
then T varies with "s"
T-s curve has three region
(i) Low - slip (iii) High - slip
(ii) Medium - slip

(i) **Low - slip** ($s \approx 0$) ($R_r >> s X_{r0}$)

$$T = \frac{K s R_r E_{r0}^2}{R_r^2} = \frac{K' s}{R_r}$$

$\Rightarrow T = K'' s$ (∵ R_r is constant)

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

straight line curve (Linear operation)

(ii) **~~Medium~~ High slip** ($s \approx 1$) ($R_r << s X_{r0}$)

$$T = \frac{K' s R_r}{s^2 X_{r0}} = \frac{K''}{s}$$

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

inversely proportional

(iii) **Medium slip**

The ~~graph~~ shape curve change
this occurs @ $R_r = s X_{r0}$ | T_{max}
Also called pull-out torque / breakdown torque

Ex-4.13

$R_r = 0.05\,\Omega$

$X_{r0} = 0.2\,\Omega$

Find :- 'R_{ext}' for τ_{max} starting

Sol

τ_{max} condition

$R_r = s X_{r0}$

$\Rightarrow 0.05 + R_{ext} = 0.2$ @ starting ; $s = 1$

$\Rightarrow R_{ext} = 0.2 - 0.05 = \underline{0.15\,\Omega}$

Full load Torque & maximum Torque

$$\tau_{FL} = \frac{K s R_r E_{r0}^2}{R_r^2 + (s X_{r0})^2}$$

$$\tau_{max} = \frac{K E_{r0}^2}{2 X_{r0}}$$

At starting, $s = 1$

$$\tau_{st} = \frac{K R_r E_{r0}^2}{R_r^2 + X_{r0}^2}$$ (Next page derivation)

$$\boxed{\frac{\tau_{FL}}{\tau_{max}} = \frac{2 s s_m}{s^2 + s_m^2}}$$

$$\frac{\tau_{st}}{\tau_{max}} = \frac{2 s_m}{1 + s_m^2}$$

$$\frac{\tau_{st}}{\tau_{FL}} = \frac{s^2 + s_m^2}{s(1 + s_m^2)}$$

$$\frac{\tau_{FL}}{\tau_{max}} = \frac{2 s X_{r0} R_r}{R_r^2 + (s X_{r0})^2}$$

But : $R_r = s_m X_{r0}$

$$\frac{\tau_{FL}}{\tau_{max}} = \frac{2 s X_{r0}\, s_m X_{r0}}{s_m^2 X_{r0}^2 + s^2 X_{r0}^2} = \frac{2 s s_m}{s_m^2 + s^2}$$

$$\boxed{\frac{\tau_{FL}}{\tau_{max}} = \frac{2 s s_m}{s_m^2 + s^2}}$$

$$\boxed{\frac{\tau_{st}}{\tau_{max}} = \frac{2 s_m}{s_m^2 + 1}}$$

Ex-4.14 6 pole, 3φ, 50 Hz

$s = 4\% = 0.04$

$Z_{r0} = (0.01 + j0.05)\,\Omega$

To find $\tau_m = f(\tau_{FL})$?

Speed (N_m) = ?

Sol

$N_s = \frac{120(50)}{6} = 1000$ rpm

$s = \frac{N_s - N_m}{N_s} = \frac{1000 - N_m}{1000}$

$\Rightarrow (0.04)(1000) = 1000 - N_m$

$\Rightarrow N_m = 960$ rpm

@ τ_{max} :

$R_r = s_m X_{r0}$

$\Rightarrow \frac{0.01}{0.05} = s_m$

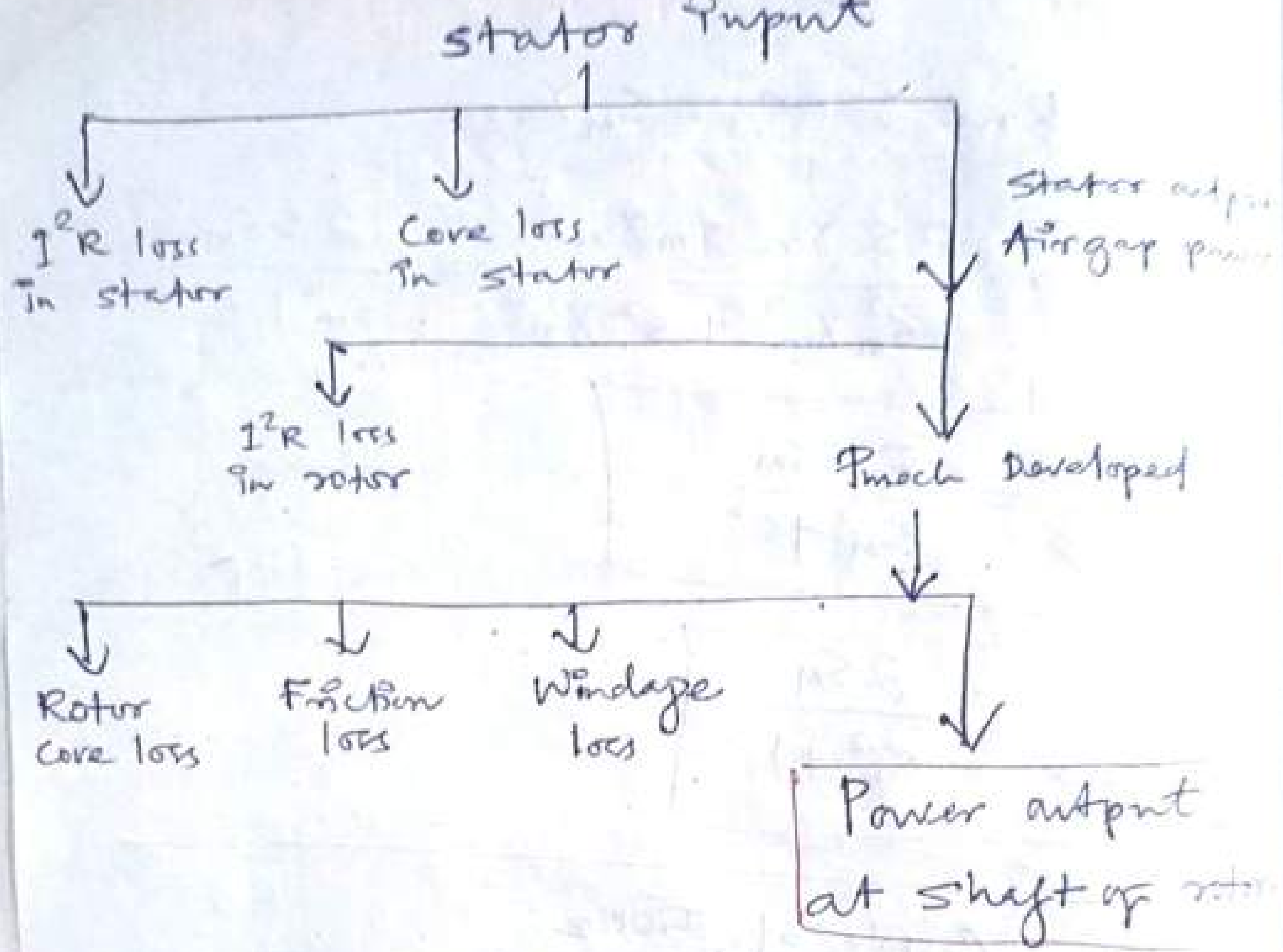
$\Rightarrow \underline{s_m = 0.2}$

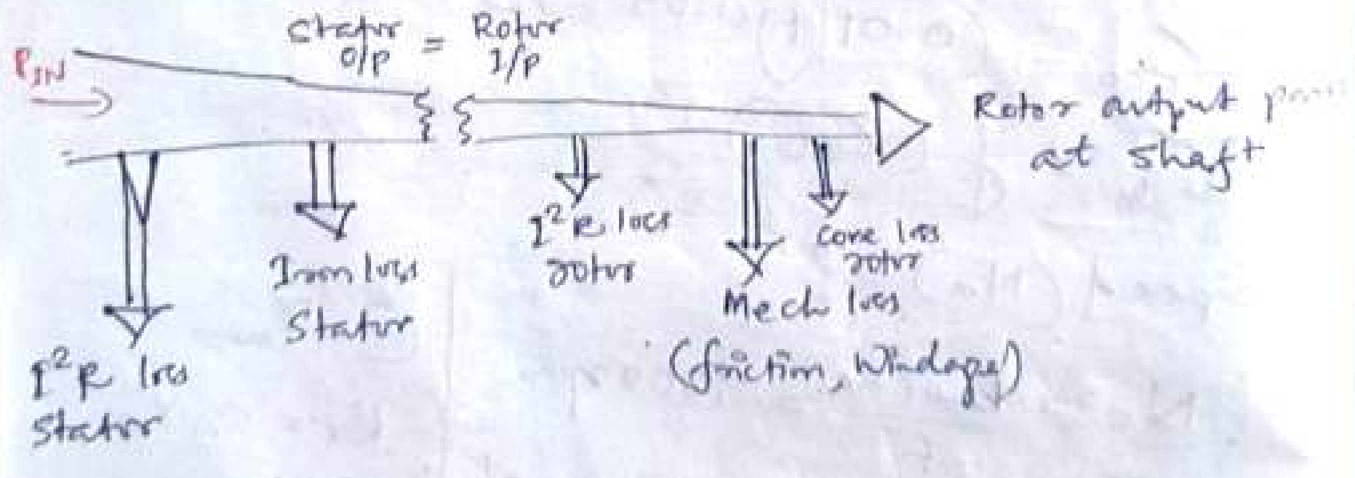
$$\frac{\tau_{FL}}{\tau_{max}} = \frac{2 s s_m}{s^2 + s_m^2}$$

$$\tau_{FL} = \frac{2(0.2)(0.04)}{0.04 + 0.0016}\, \tau_{max}$$

$\Rightarrow \boxed{\tau_{max} = 2.6\, \tau_{FL}}$

* Power flow in IM





Starting of IM

@ $N_r = 0$; $s = 1$

EMF ↑ → rotor current ↑ → stator current ↑

Voltage dip in T° ← Voltage drop ↑

(V_e ↓↓)

That's why to limit I_{st} ; different means are adopted ..

① DOL starting

→ Direct on line

→ For small IM upto 5kw.

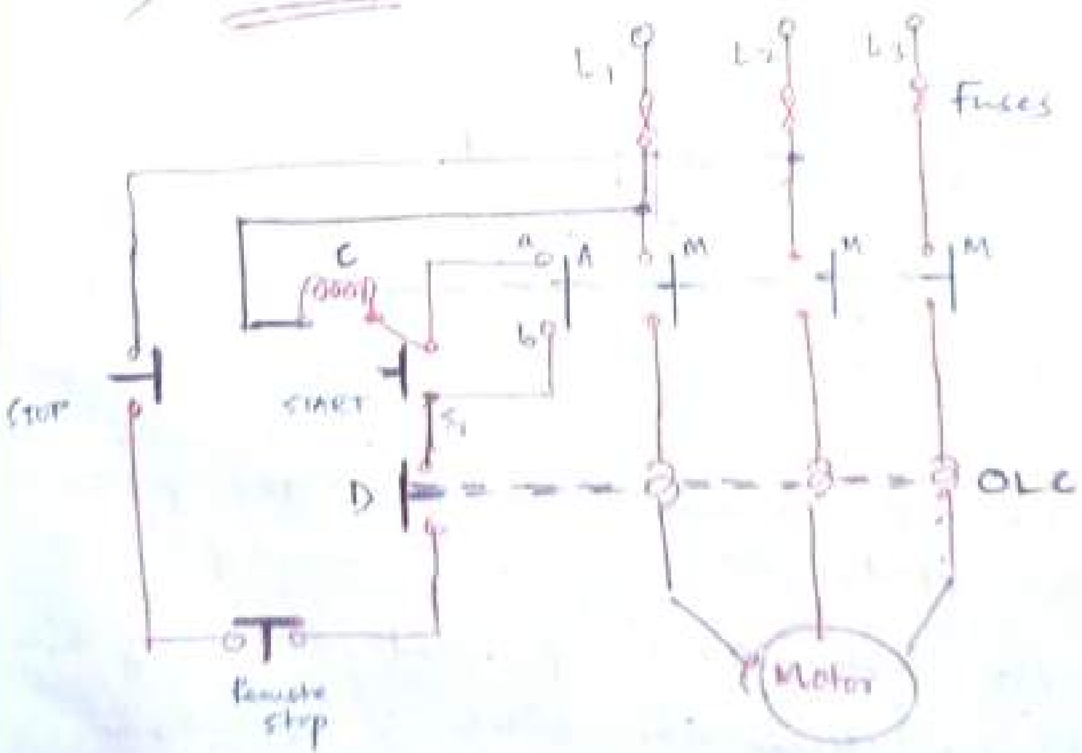
Push ON/OFF

Overload → Bimetallic strip (thermal element)

Underload → when power is not present stop

why It doesn't reduce voltage @ in starting

why Inrush current flows @ starting .

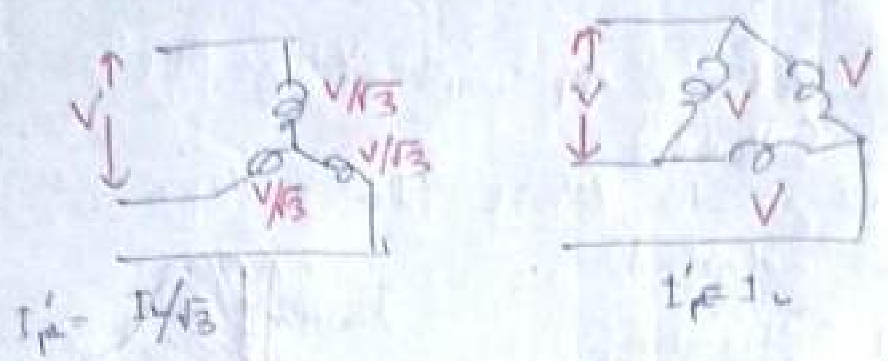


* Undervoltage protection — Below a certain voltage "C" coil is demergized & motor disconnect

* Overload protection — OLC are energized during OL, and NC contact D is open & C de-energized Motor stop

(II) Y-Δ starter (Reduced voltage ...)

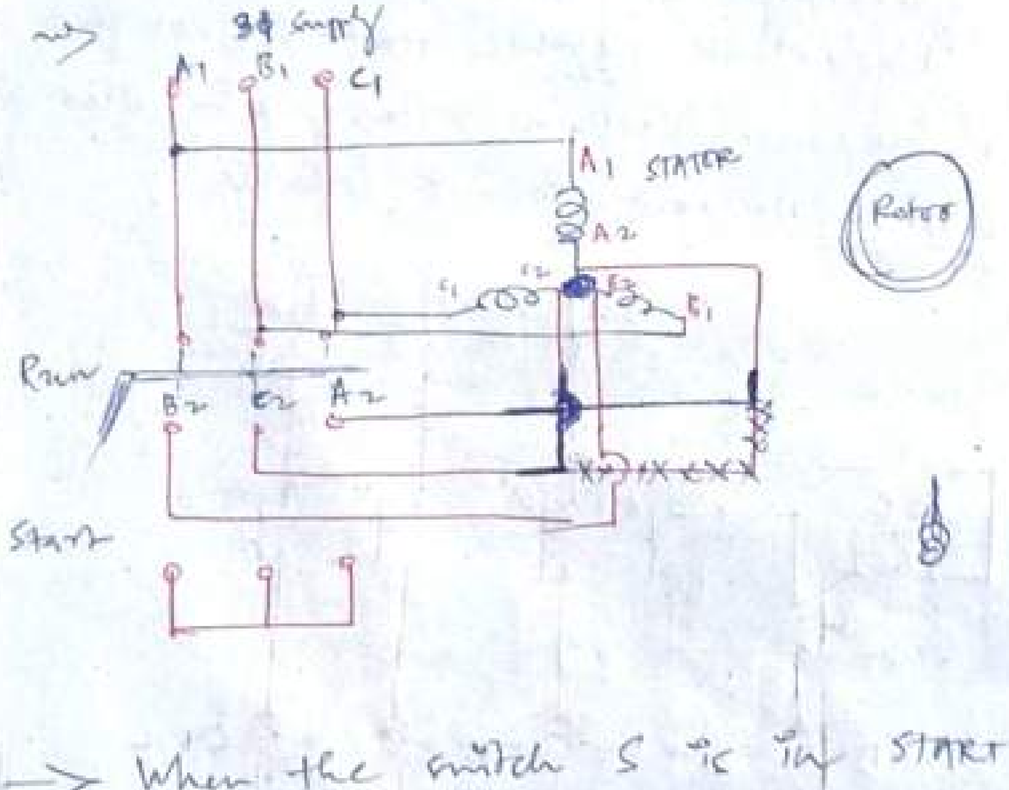
↓I ∝ V ↓



→ Start as STAR & run as Δ

→ At Y connection; V & I are reduced 57.7 % . ($V_{ph} = V_L/\sqrt{3}$)

→

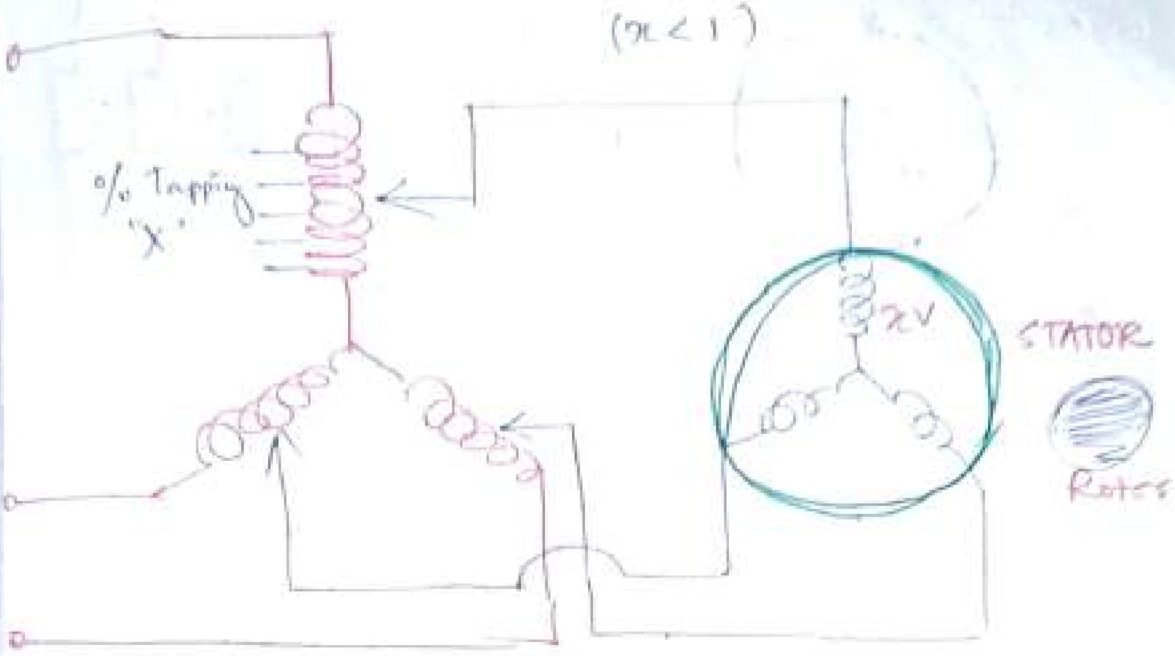


→ When the switch S is in START position the stator windings are connected in ...

→ When motor picks up speed; 80% of ... speed; change over switch S is thrown quickly to the RUN posn; which connects stator winding in Δ.

$$\frac{\tau_{st}}{\tau_{FL}} = \left(\frac{1}{3}\right)\left(\frac{I_{st}}{I_{FL}}\right)^2$$

(III) Auto Transformer



→ For large IM,
→ It is efficient but expensive.
→ It required suitable 3φ Auto Tf.
→ The starting current & Torque is dependent on tapping.

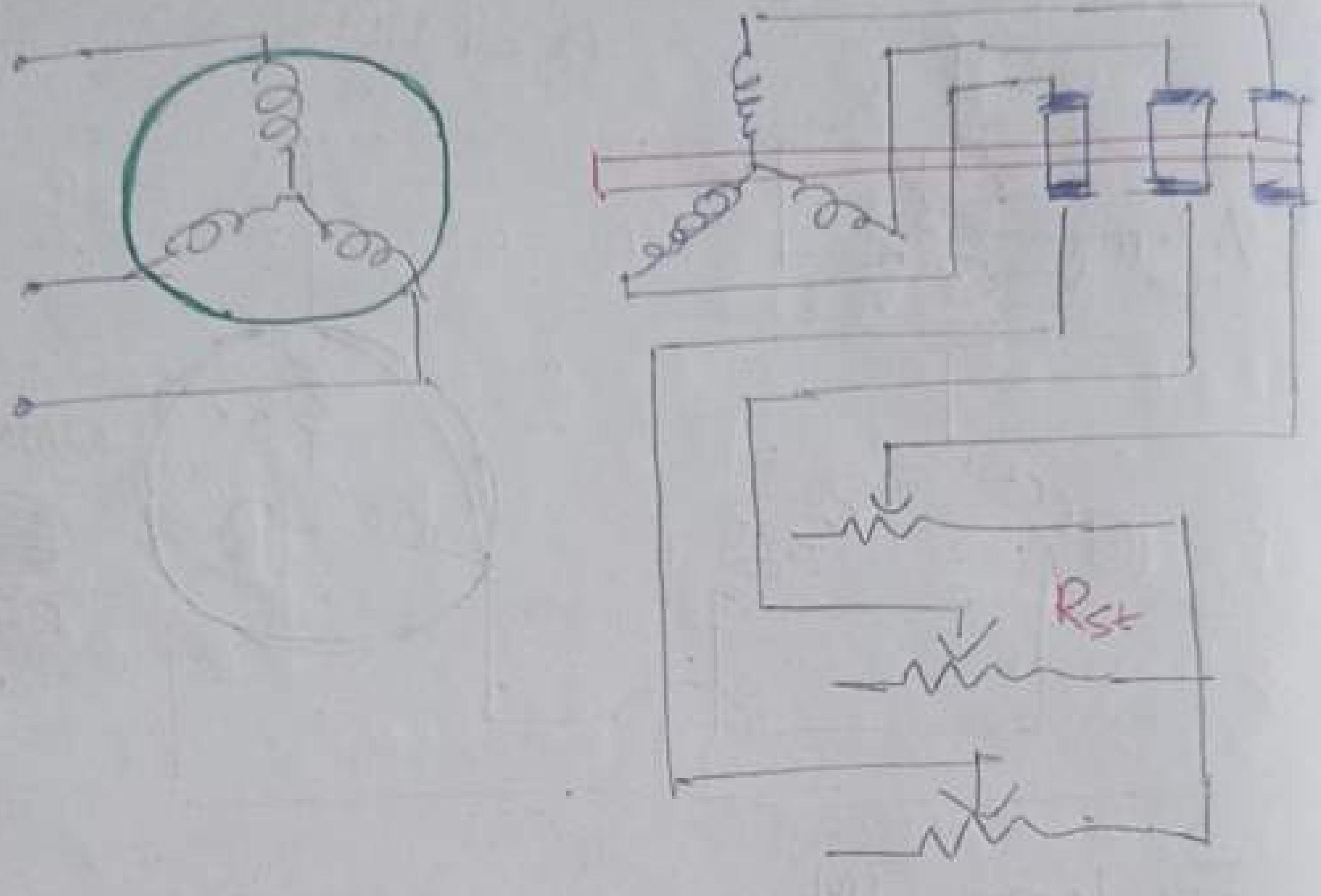
$$\frac{\tau_{st}}{\tau_{FL}} = x^2 \left(\frac{I_{st}}{I_{FL}}\right)^2 S_{fL}$$

(IV) ~~Rotor~~ Stator resistance for starting

↑R → ↓I_{st} → φ↓ → E_{st}↓ IR↑ ; E_{st}↓

→ low η ; voltage drop ↑↑

✱ Rotor resistance starting



→ Rst limits the Irotor.

→ T_{st} is increased ($\because R_{st} + R_r = X_r$

→ High starting torque application like TRACTION.

Speed control of IM

$$N_r = (1-s)\frac{120f}{P} = f(s, P, f)$$

1 Pole changing

A Multiple stator winding

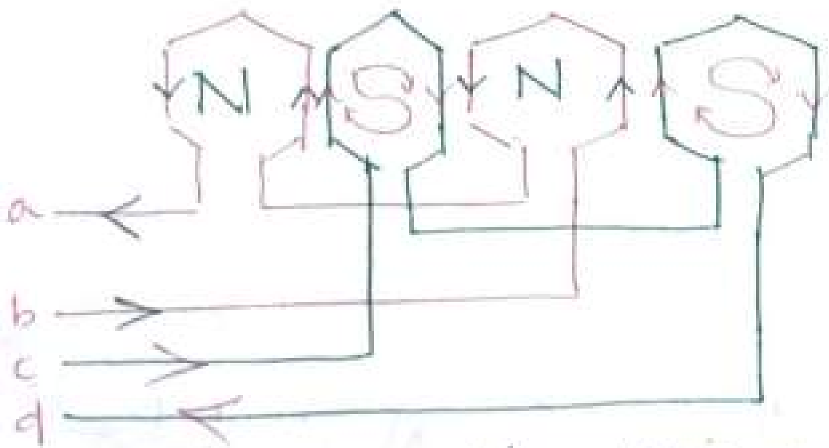
Two separate windings are provided on stator for two diff pole numbers.

One winding is energized at a time.

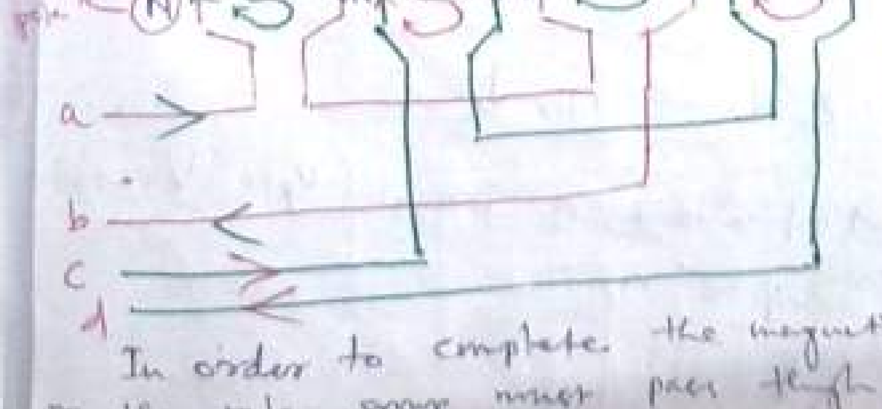
Ex - 6 pole & 4 pole.
@ 5% slip.
950 rpm, 1425 rpm.

→ This method is less η & costly.

B Method of consequent pole.



4 pole → N_s = 1500 rpm.



Reversing "a-b"

In order to complete the magnetic path, the flux of the pole group must pass through the space between the groups, thus inducing magnetic

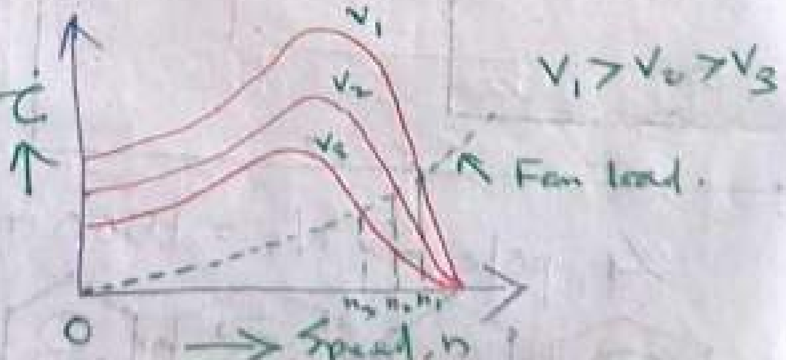
pole of opposite polarity (i.e. S).
These induced poles are called consequent pole.

$N_s' = \frac{120 \times 50}{8} = 750$ rpm (Half speed)
2:1 speed ratio is possible

(c) Pole Amplitude Modulation -
Speed ratio other than 2:1.

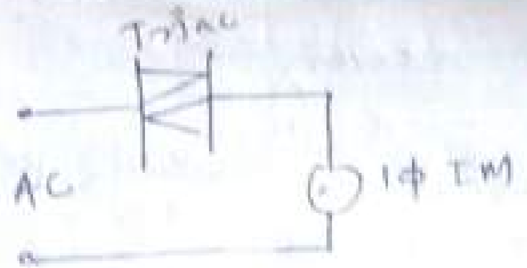
(II) Stator voltage control

$\tau_d \propto E_{20}^2 \propto V_s^2$



$V \downarrow \rightarrow \tau \downarrow \rightarrow n_r \downarrow$

Speed control within a range (upto V rated)
"Δn_r" upto "n_s"



Household ckt

Speed control is obtained by varying firing angle of the triac.

(III) Variable frequency control

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

$\frac{V(ac)}{f}$ ratio is maintained constant

$E = 4.44 \phi f T$.

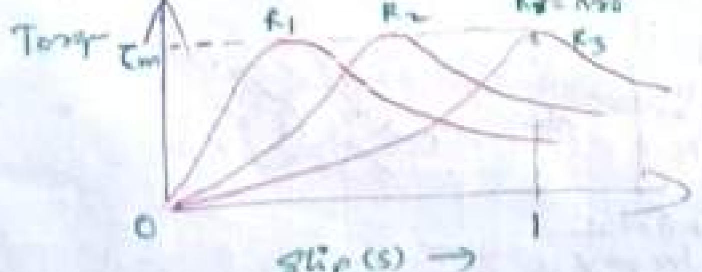
* Variable voltage & Variable frequency source is required.

(A) Voltage Source Inverter } DC to AC (df, dv)
(B) Current — do — } Fix Var

(C) Cyclo converter } AC to AC (df)
Fix Var

(IV) Rotor resistance control

→ For only wound IM
→ Rext is connected to rotor through slip ring.



$R_1 < R_2 < R_3$

$\uparrow R_r = \uparrow S X_{r0}$ | @ T_{max}

Speed ↑
(Upto Nrated)

V Slip-power recovery

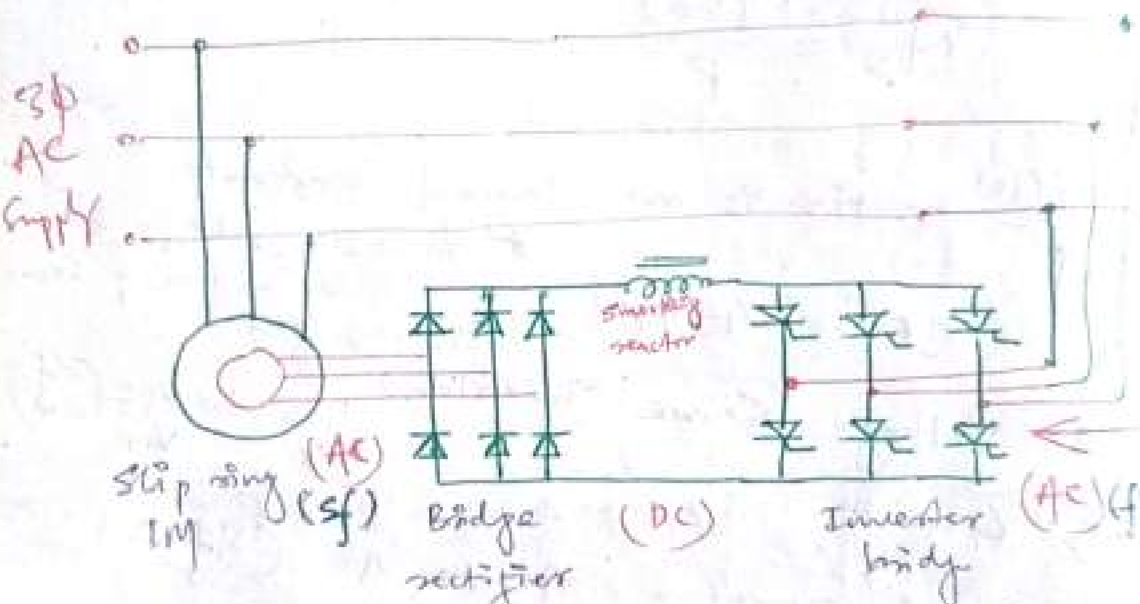
→ ~~In rotor resistance method power is wasted as I^2R loss~~

Injecting emf in rotor
(i) Additive (z ?
(ii) Subtractive (z

→ efficiency decreased.

→ If slip power is recovered from rotor ckt; η ↑

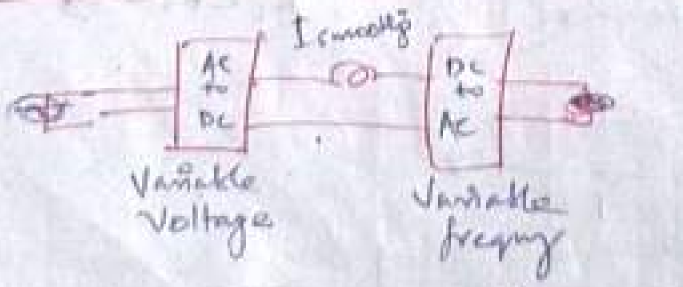
"SCHERBIUR drive";



→ Why not rotor power is direct connected to supply.

→ Bcz it has "sf" frequency

Variable frequency drives



→ CSI (constant)

→ VSI (constant)

Plugging

→ It is a method of braking IM.

→ Reversing the phase sequence of 2 phase terminals across stator in running motor.

→ The rotor want to rotate in opposite direction due to which it come near 0 speed where an adequate mechanical braking is applied otherwise there is a possibility that motor rotate in reverse direction.

→ Relative speed = $N_s + N_r$

High induced emf → ↑↑ I_{rotor}

→ Temperature rise ↑↑ → need to be withstand by IM.

* Type of motor - Enclosure

① Open drip proof (ODP)

→ Allow air to circulate through [illegible] for cooling.

→ Prevent drop of liquid / dirt falling into motor within 15 K° angle [illegible] vertical.

→ Indoor application
[Clean, dry location]

③ Total enclosed fan cooled (TEFC)

→ Air ventilation is prevented from [illegible] b/w inside & outside of frame.

→ A fan is attached to the shaft it pushes air over the frame during its operation.

Ex - pump, fan, compressor, Industrial drive
(Most versatile)

⑤ Total enclosed non-ventilated (TENV)

→ No cooling fan is provided.

→ No opening vent, tightly enclosed but not air tight

Ex - Suitable for dirt & dampness, Atmosphere [illegible] location [illegible]

④ Total enclosed Air over (TEAO)

→ Dust tight frame & Blower duty motor [illegible] must be mounted below the airflow of the fan [illegible]

→ Air flow over the fan

⑥ Explosion proof enclosure (EXPL)

→ Totally enclosed machine

→ Design to withstand explosion of gas [illegible] of vapour inside machine

Ex - location containing hazardous gas or dust.

⑦ Hazardous location (HAZ)

Class I :- Chemical like, Acetylene, Acetone, Benzene, ethanol, butane.

Class II :- Al, mg - dust
Carbon, coal - dust
Flour dust

Induction Generator

condition of operation of IG;

(i) Slip becomes negative
∴ $N_r > N_s$

(ii) Prime mover torque is opposite to the electric torque

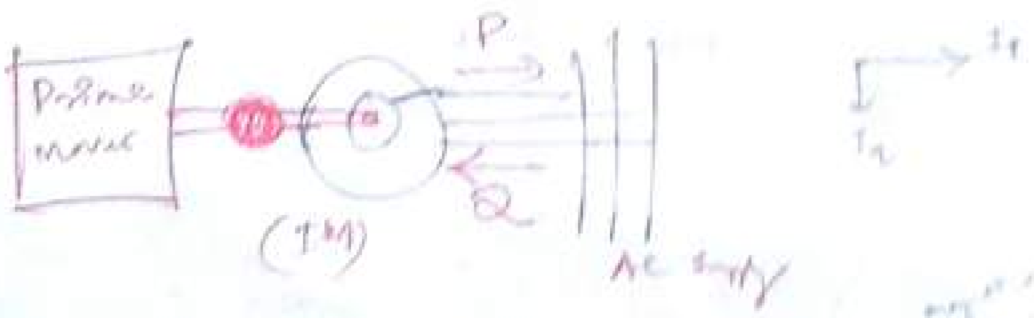
→ With external source, prime mover speed becomes greater than N_s ∴ $\underset{(-ve)}{S} = N_s - N_r$

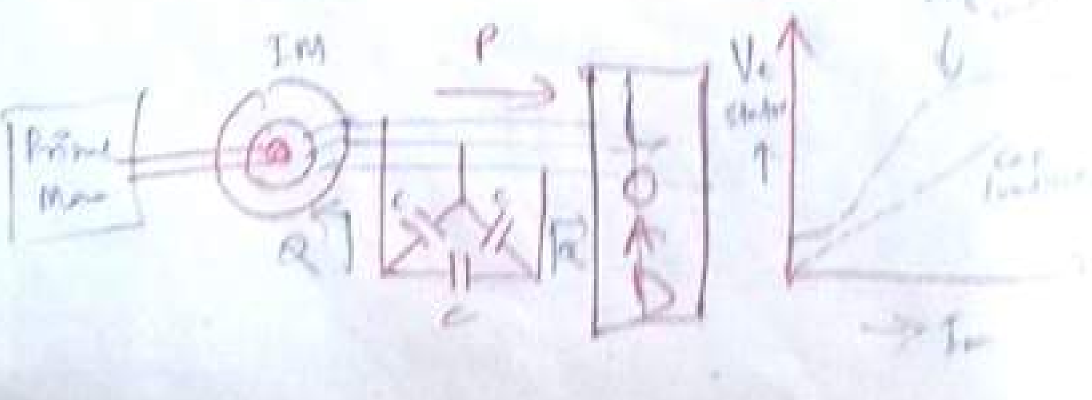
→ It is also called asynchronous generator

→ It is not self excited machine.

→ It require (Reactive power Q) to magnetise the stator

→ It continuously required Q for it so, to make it self excited capacitor bank is used.





Application

(I) Wind turbine (Variable wind speed)

(II) Hoist

Advantage

(1) No commutator, No brush arrangement

(2) Cheaper, (3) No ~~[illegible]~~ or synchronization is required.

Disadvantage

It requires large Q from the supply

Q. Why Overexcited Alternator is called Synchronous condensor?

. Mech Energy $\xrightarrow[\text{Mag flux}]{}$ Electrical Energy

→ The flux ~~is~~ nothing but reactive power (Q).

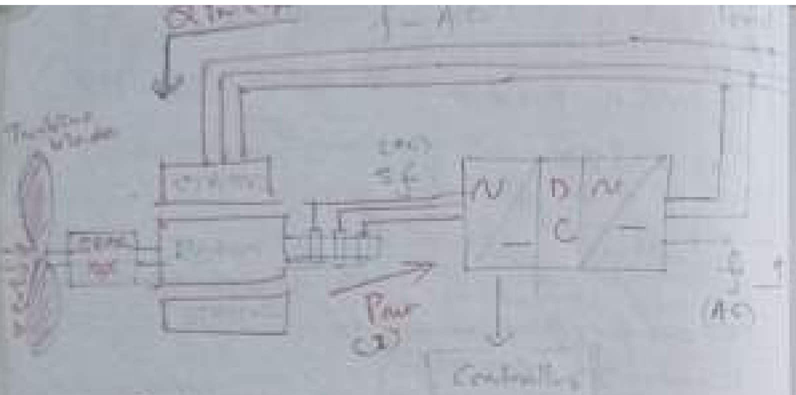
→ It comes from the alternator field.

→ If less ~~reactive~~ power Excitation is given the M/c draws reactive power from the system.

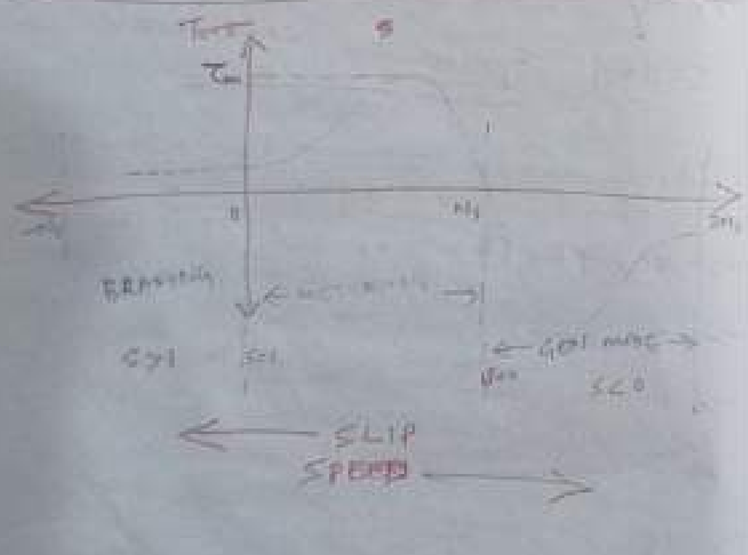
→ If Large excitation is giving the excess reactive power is supplied to system.

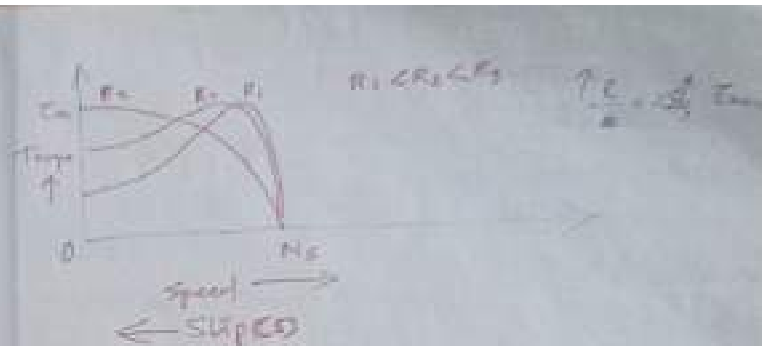
$$(Q \propto I_\mu)$$

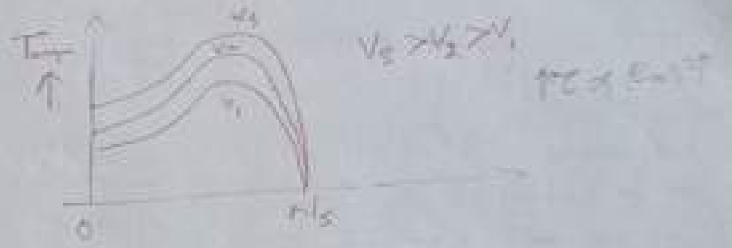
(I_μ → magnetizing current)

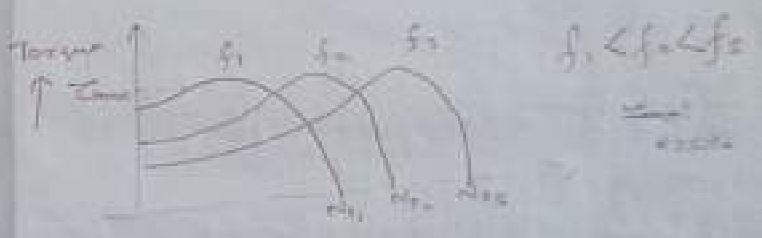


(Wind Turbine)









Torque-Slip C/S

SINGLE - PHASE IM

① Working principle

→ When the stator of a 1ϕ IM is f...
1ϕ supply it produces alternating fl...
in the stator winding.

→ This chang alternating flux prod...
an emf in rotor bars according to
Faraday's law of EMI.

→ Alternating flux unable to start ...
motor.

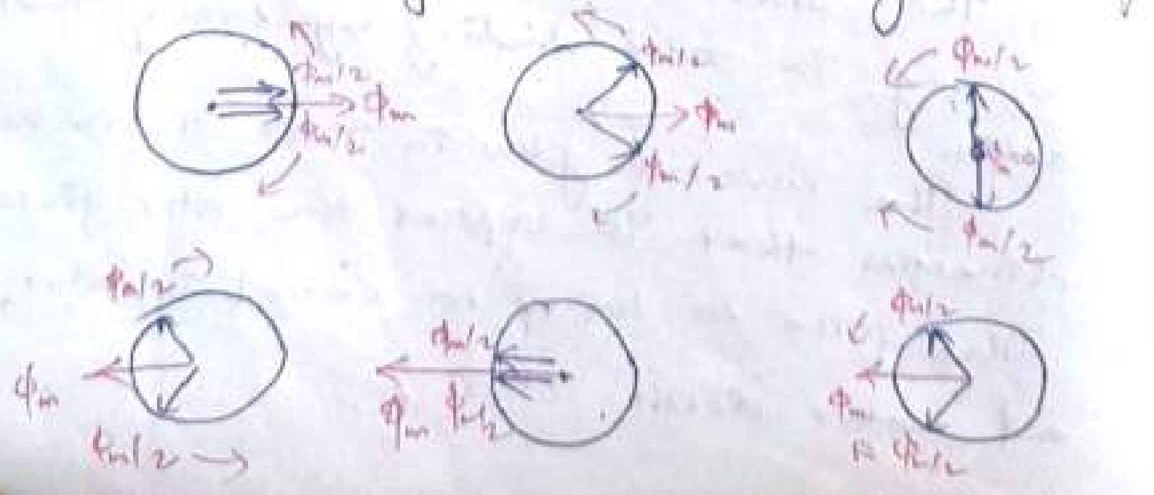
→ However; if rotor is given initial
start by external force; then the
motor accelerate to its rated speed

④ Constructin

Stator : 1ϕ supply → Starting / Running
Rotor : squirrel cage.

② Double field Revolution theory

Any alternating quantity can be resolved into two component having magnitude half of the maximum ~~value~~ of the alternating quantity

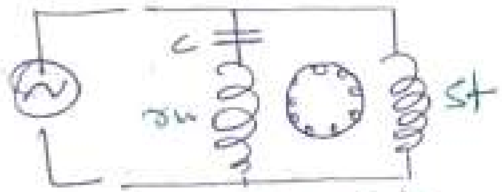


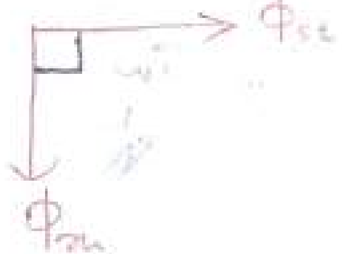
(4) Why 1φ IM is not self starting?

Alternating flux acting on the sq rotor can't produce rotation; only rotating flux can.

(5) * How to make 1φ IM self starting

→ At starting: it is converted into 2 phase motor, by introducing additional "starting winding".





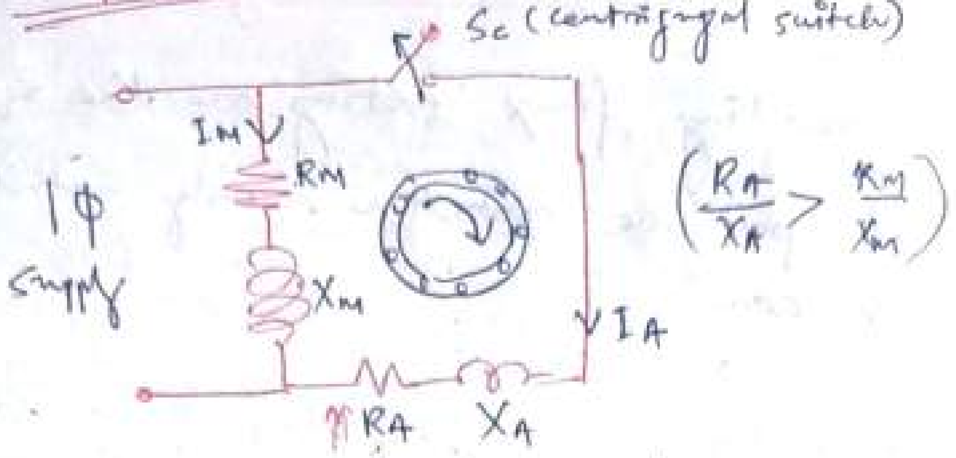
* Ferrari's Principle

→ The two windings are connected in parallel across a 1φ supply. and are spaced 90° electrical degree apart.

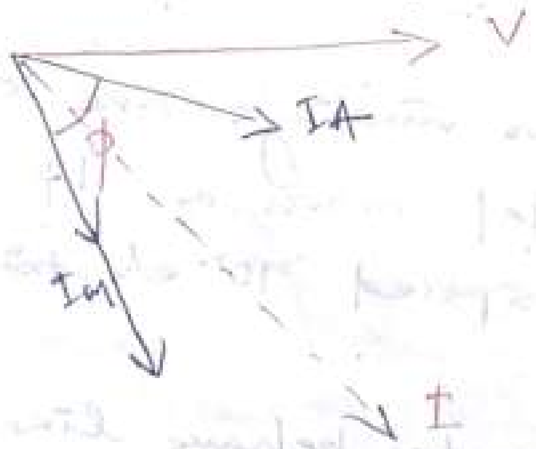
→ Hence motor behave like a 2φ IM and stator produces ~~revolving~~ rotating magnetic field.

→ Once the motor gathers speed upto 80-90%; the starting winding is disconnected by the mean of a centrifugal switch.

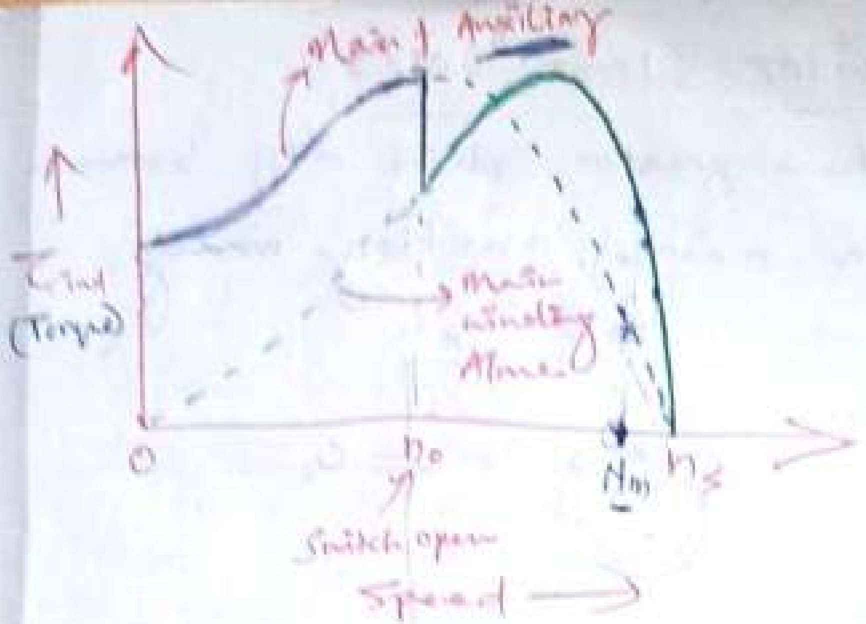
① Split - phase IM



→ Resistance start motor
→ Main & Auxiliary winding .
Main $R_M << R_A$
Main = Thicker .
Auxiliary = Thin .
I_A in phase with V_s ($\because R_A >> X_A$)
→ I_M has phase lag ($\because X_M >> R_M$)



→ The phase diff betn two winding is 30° (not 90°)
→ Unequal current → unequal torque
$\tau_{st} = 1.5$ to $2\ \tau_{FL}$
→ At 80% speed "Sc" disconnect 1st and motor rotate with main winding.



* Reversal of Direction

→ It can be reversed by reversing the connection of either main or starting winding.

→ The motor must be brought to rest for this purpose.

* Motor CS

$\tau_{st} = 1.5\ \tau_{FL}$

$\tau_{max} = 2.5\ \tau_{FL}\ |_{@\ N = 0.75 N_s}$

$I_{st} = (7 \text{ to } 8)\ I_{FL}$

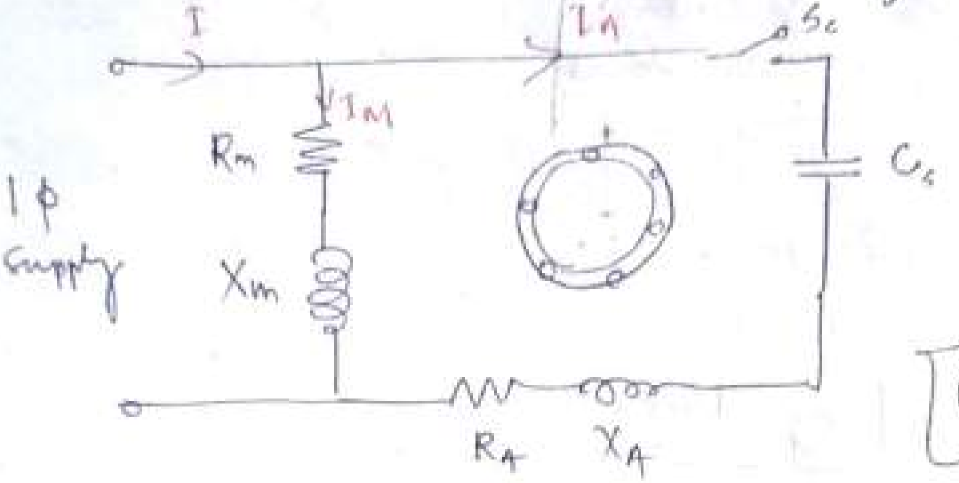
* Application

→ Washing m/c, AC fan, food mixture, floor polisher, blower, etc.

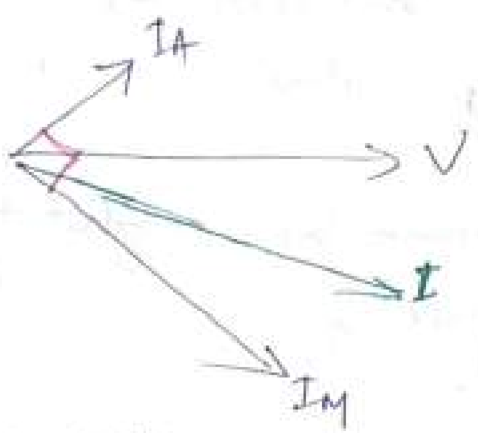
→ Low starting τ; so used for load upto 1 KW.

(2) Capacitor-start motor.

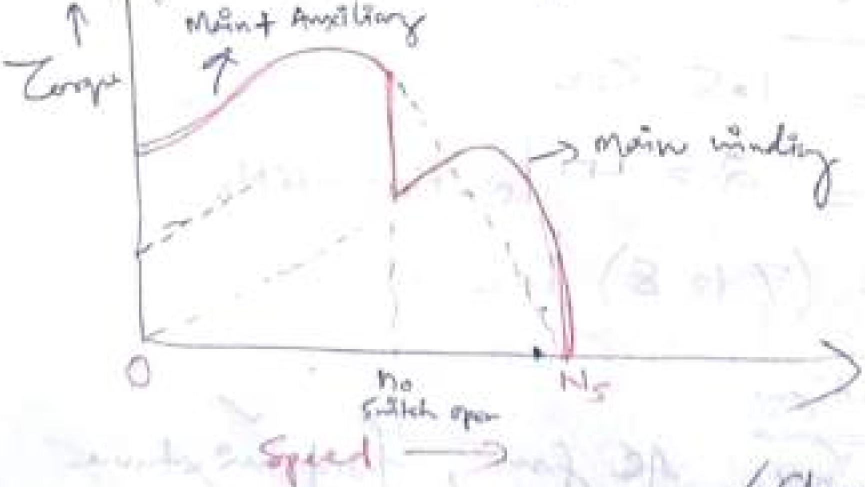
-> To produce greater phase diff b/w current in main & auxiliary winding



[CKT]



(Phasor)



(Characteristic)

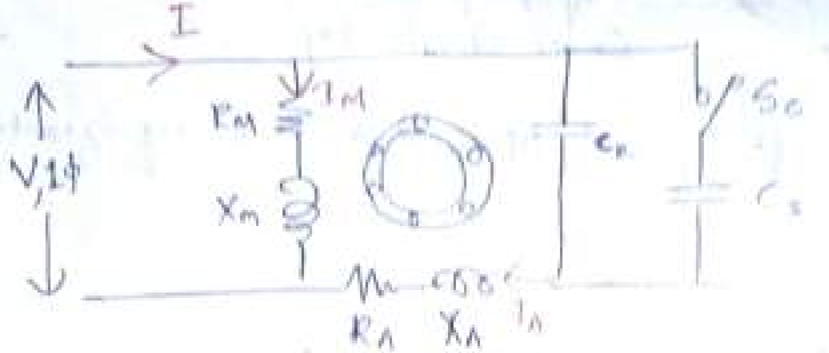
* Reversal of direction

⊙ Either one of the winding connection is reversed to get it done

Before that the motor brought to rest

* High inertia load where frequent starts are required. Refrigerator, AC-compressor,

③ Capacitor Start – Run IM



→ For $T_{st}\uparrow \rightarrow I_{st}\uparrow$ is required.

↓

$$X_c \downarrow = \frac{1}{\omega C_s \uparrow}$$

Short time rated capacitor

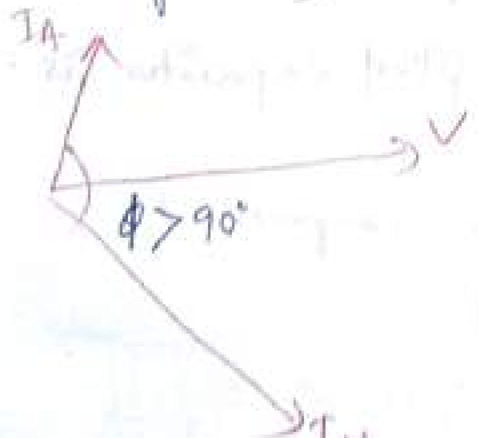
Electrolytic cap

→ During normal operation

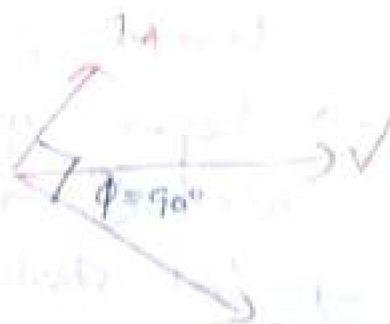
$I_{rated} < I_{st}$;

↳ $\uparrow X_c = \dfrac{1}{\omega C_r \downarrow}$ → long time rated (oil filled paper) capacitor

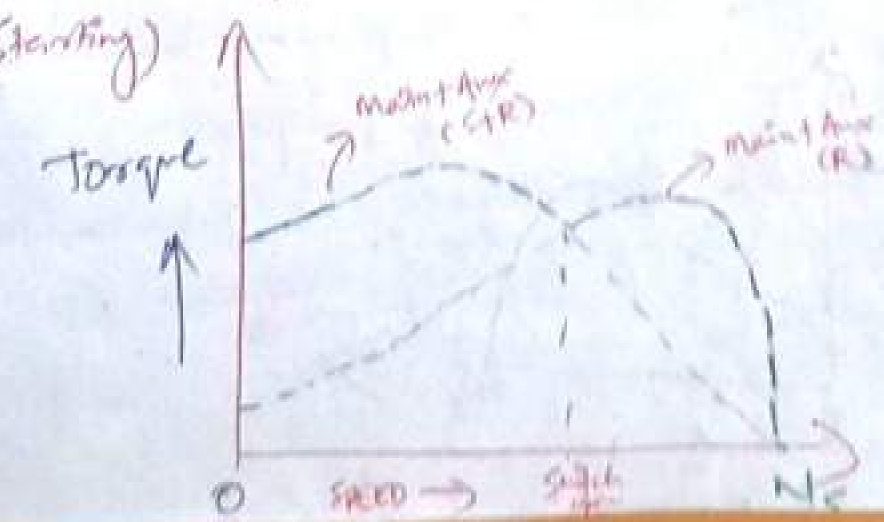
→ As motor approaches 90% N_s ; S_c is open & C_s is disconnected.



(Starting)



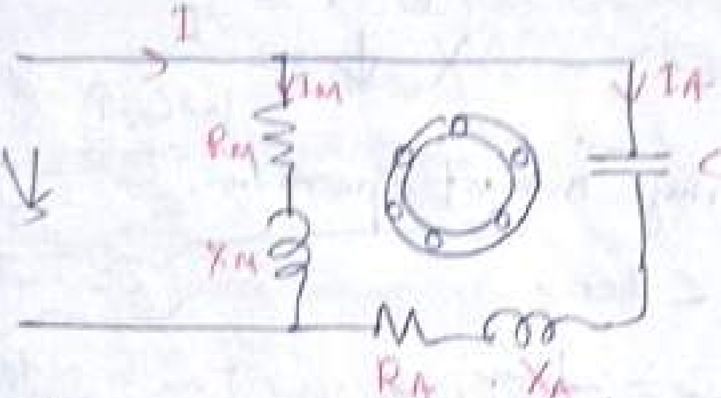
(Running)



→ Quiet & smooth running.
→ ↑η than ~~split phase or IM~~ cap-start IM.

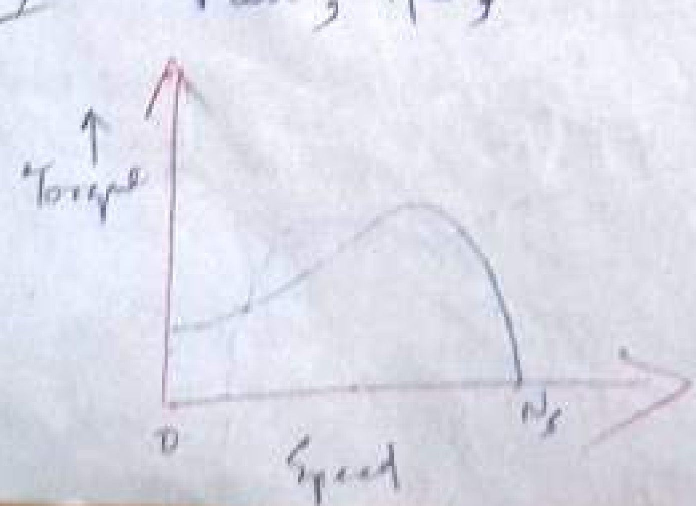
EX:- Pump, ~~Air~~ compressor, refrig...

(4) Capacitor - Run IM
(Permanent split capacitor)

→


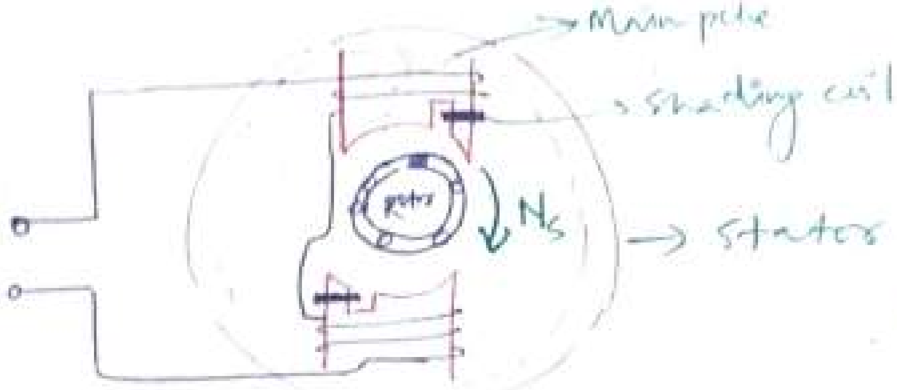
→ No switch is required.
→ Uniform torque.
→ Less noisy during operation.
→ Paper - spaced oil filled capacitor is used (costly)
→ Low starting torque compared to (2-capacitor IM)

Ex - Fan, AC,

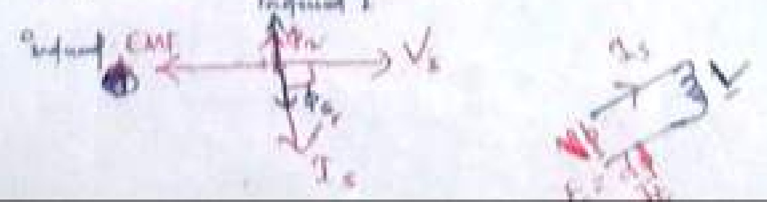


* Shaded pole IM

→ Self starting 1ϕ IM.
→ Salient pole stator.
→ Copper ring is fitted on the smaller part "a", called shaded pole.
Shading coil – single turn coil of copper



→ Alternating flux produced in the stator core.
→ A portion linked with shading coil & emf is induced, induced current flows and produces a flux which is opposite to the main field flux.
→ There is space & time displacement between the main pole & shading pole results in rotating magnetic field.
→ As a result; starting torque is ~~produced~~ developed on the rotor.
→ The direction of rotation is from Non shaded to shaded pole directi.

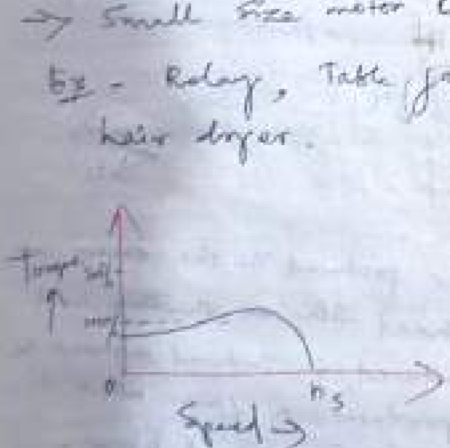


→ reversal is not possible in shading pole.

Application

→ cheap
→ τ_{st} is low
→ Losses are high ; ∴ $\eta \downarrow$.
→ Small size motor upto "40KW"

Ex - Relay, Table fan, exhaust fan, hair dryer.



START

→ High current for $\tau_{st} \uparrow\uparrow$
$\uparrow C = \frac{Q}{V}\uparrow\uparrow$
→ (430 - 516) μF
→ voltage rating
→ Larger size ($\uparrow C = \frac{\epsilon_0 A \uparrow\uparrow}{d}$)

RUN

→ medium current
$C = \frac{Q}{V}$
→ 5μF - 45 μF
→ ϕ $V_{rating} = 1.5\, V_{line}$ (phase voltage)
→ maintain 90° phase delay.

SPECIAL ELECTRICAL MACHINE

→ For control of speed & precise positioning. — → Robotics, → 3-D printing, → Printing press } Appli.

* Principle of stepper motor

→ It has movement in discrete steps.

→ The angular rotation depends upon the nos of pulses fed into the control circuit.

→ Each input pulse initiate the drive circuit which produces one step of angular movement.

→ Solid state switch (~~FET~~ MOSFET, BJT) are used to energised & deenergised appropriate winding in required sequential manner.

* Classification of stepper motor

- Variable reluctance
- Permanent magnet
- Hybrid (VR+PM)

* Variable Reluctance motor

It operate on the principle that, flux line occupy low reluctance path. The stator and rotor get aligned in such a way that, the magnetic reluctance is low.

→ Soft Iron is used for magnetic core of rotor

* Step Angle

The angle by which a stepper motor moves when one pulse is applied to the (input) stator.

Resolution = $\frac{\text{Nos of Steps}}{\text{Nos of Revolution of rotor}}$

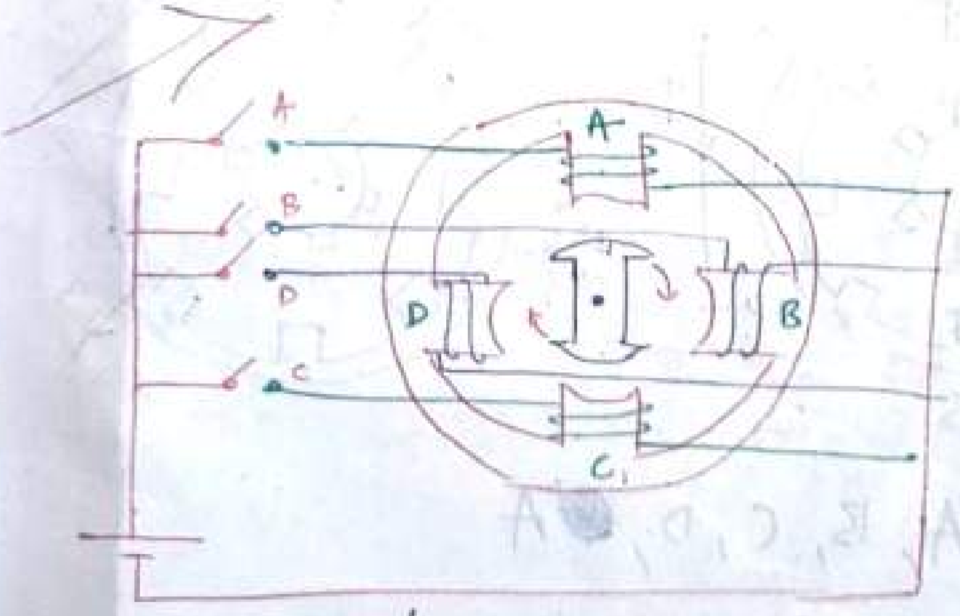
Ex

High precision motor
1000 Step per revolution
i.e. – 0.36° step angle

Standard motor
200 step per revolution
i.e. – 1.8° step angle

~~$\alpha = \frac{360°}{M_s N_r}$~~

N_r → Nos of ~~rotor~~ ~~teeth~~ pole
M_s → Nos of Stator phase.



[4/2 - pole]

* Four phase - 2 pole VR Stepper motor

~~$\alpha = \frac{360°}{m_s N_r} = \frac{360°}{4 \times 2} = 45°$~~

A, B, C, D, A → 90° steps clockwise rotati.

A, A+B, B, B+C, C, C+D, D, D+A, A → 45° st. clockwise

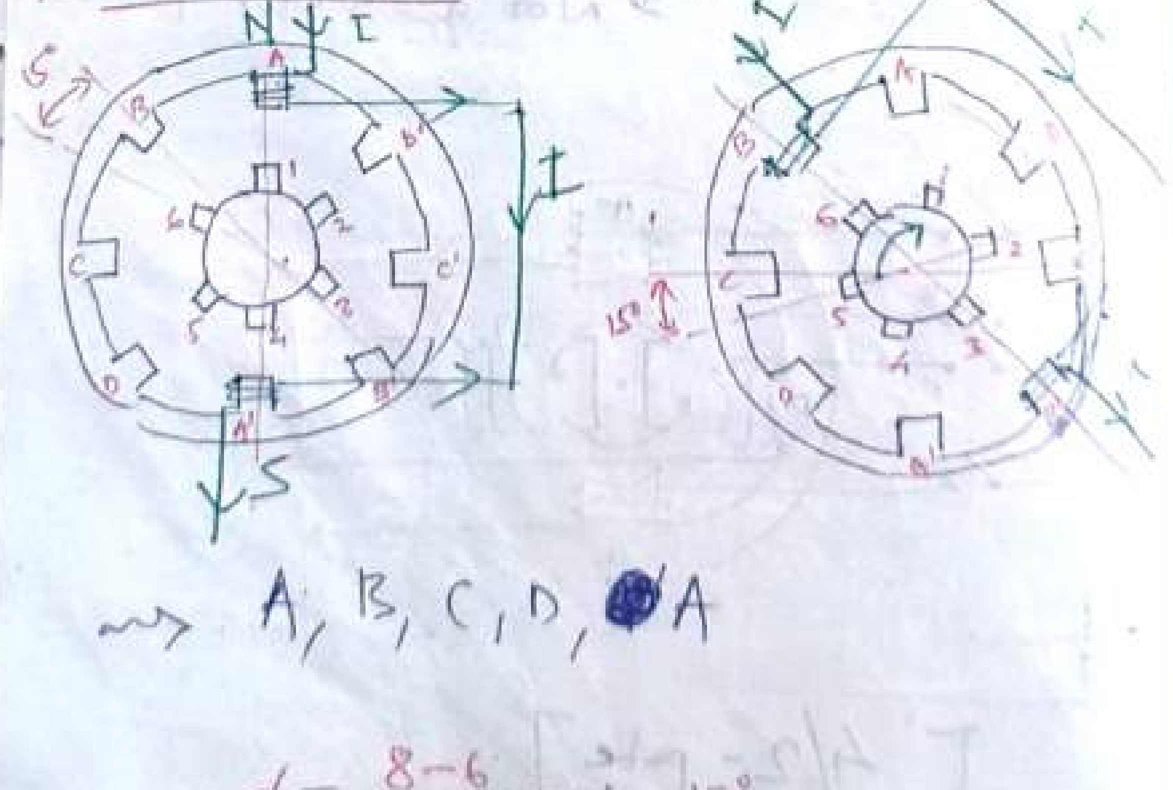
$$\alpha = \frac{N_s - N_r}{N_s N_r} \times 360°$$ → 45

N_s → Nos Stator pole
N_r → Nos of rotor pole

~~$$\alpha = \frac{360°}{m_s N_r}$$~~ → 90°

m_s → nos of stator phases

* 8phase 6 pole



→ A, B, C, D, A

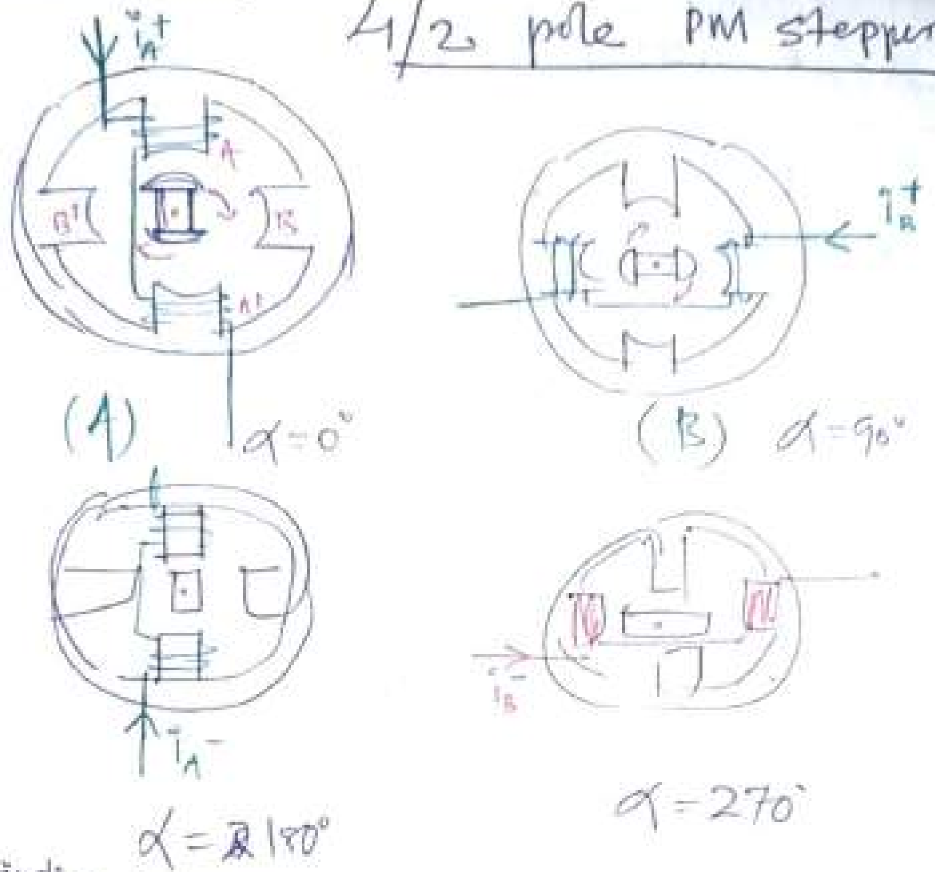
$$\alpha = \frac{8-6}{8 \times 6} \times 360° = 15°$$

Disadvantage
→ Motor may drift from final position after supply is cut-off due to inertia.

Permanent Magnet / stepper motor

→ Detent torque (next page)

4/2 pole PM stepper motor



Phase winding sequence

↘ $i_A^+ \; i_B^+ \; i_A^- \; i_B^+ \; i_A^+$ → clockwise rotation

$i_A^+ \; i_B^- \; i_A^- \; i_B^+ \; i_A^+$ → Anti-clockwise rotation

Comparison

→ PM has higher inertia & lower acceleration than VR.

→ Pulse rate is 300 pulse/second – PM

1200 pulse/sec – VR.

→ PM produce more torque compared to VR.

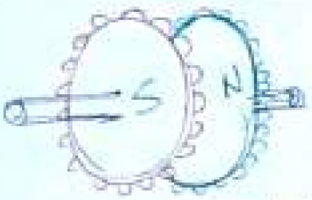
Advantage	Disadvantage
→ Detent torque	→ Low acceleration
→ High torque	→ Work efficiently for step angle 30°–90°
→ Better operation for start, stop & reverse	
→ More reliable.	

Hybrid stepper motor

Detent Torque

In permanent magnet type rotor; it prevent the rotor from drifting when machine supply is turned off.

→ PM & Hybrid stepper motor produce detent torque.



Stator
pole 1, 3, 5, 7 → A phase
pole 2, 4, 6, 8 → B phase

A⁺ → 1, 5 → North
3, 7 → South
5 align with S-disc

B⁺ → 2, 6 → North
4, 8 → South
6 align with S-disc

A⁻ → 3, 7 → North

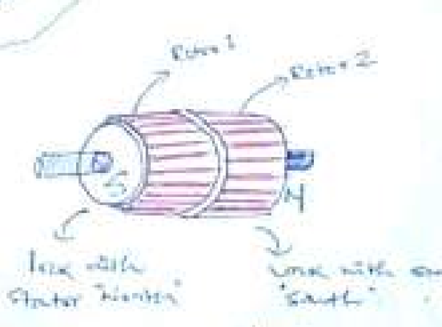
→ Hybrid motor is combination of variable reluctance & permanent type motor.

→ Rotor is axially magnetised like permanent magnet stepper motor & stator is electro-magnetically magnetised like variable reluctance stepper motor.

→ Both stator & rotor are multi toothed.

→ One end is magnetised as North pole & other end — " — as South pole.

→ Toothed rotor cup are placed on each end of the magnet, and the cup are offset by half of the tooth pitch.



A⁺ supply :- 1, 5 North
3, 7 South

So, 1-5 align with the rotor teeth of South polarity & 3, 7 align with the rotor teeth of North polarity.

B⁺ supply :- 2, 6 – North & 4-8 South
Rotor 1 (South) align with 2-6 pole & Rotor-2 align with 4-8 pole.

Comparison

	Permanent	Reluctance	Hybrid
Step Angle	7.5° or large	1.8° or small	1.8° or small
Torque output	Moderate	Low	High
Detent torque	Yes	No	Yes
Pulse Rate / Speed	Low	High	High
Noise	Quiet	Loud	Quiet
~~Micro step~~	~~Yes~~	~~No~~	~~Yes~~
Design	Simple	moderate	Complex

COMMUTATOR MOTOR

→ AC commutator motors has higher torque & higher speed than induction motor.

→ But not maintenance free as IM.

* Commutation

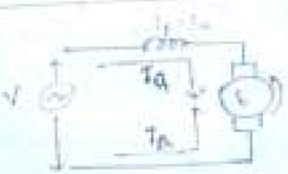
→ It is the process of converting AC current in armature winding into DC current after going through ~~[illegible]~~ (Split ring & Brush) (In DC Generator)

→ It is a rotating switch.

Classification

- 1ϕ Series motor
- Universal motor
  - Repulsion Induction motor
- Repulsion motor

① Single phase Series motor / Universal motor



$\tau = \phi I_a$

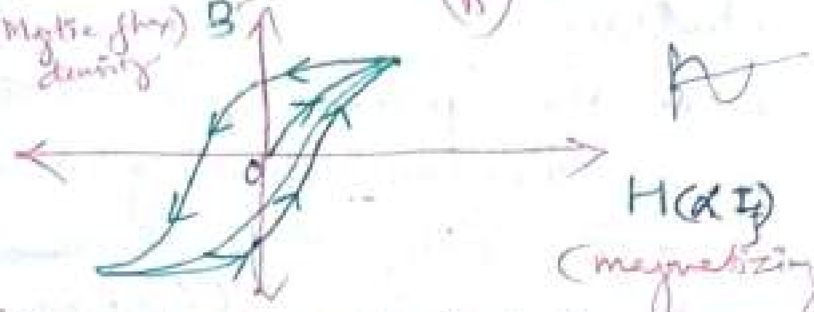
→ By changing polarity, (I_a) & (ϕ) are reversed.
So, Torque develop in same direction.

→ Motor continue to run in same direction.

• So; series motor can operate on both AC & DC.

Drawback when it is used with AC

(1) $\eta \downarrow$ due to hysteresis loss & eddy current loss.



→ Using steel material in core.

• Eddy current

It produce due to relative motion between core & the magnetic flux

Thin lamination of core stack together to reduce it.

(2) Power factor is low due to large reactance of the field & armature winding.

(3) Sparking at brush is maximum (excessive)

Overcome these difficulties

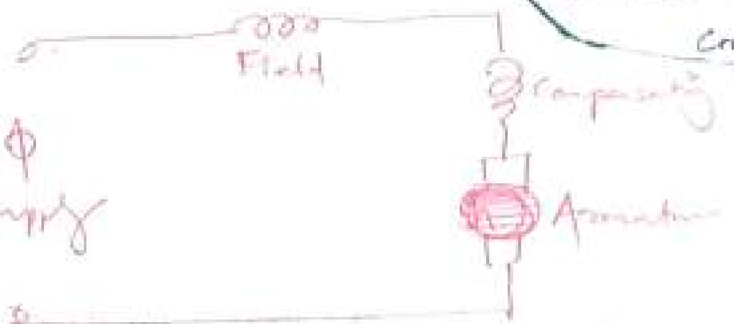
(1) Core constructed of magnetic material having low hysteresis loss and laminated to reduce eddy current loss.

② Field winding of small number of turns (∴ Flux reduces)

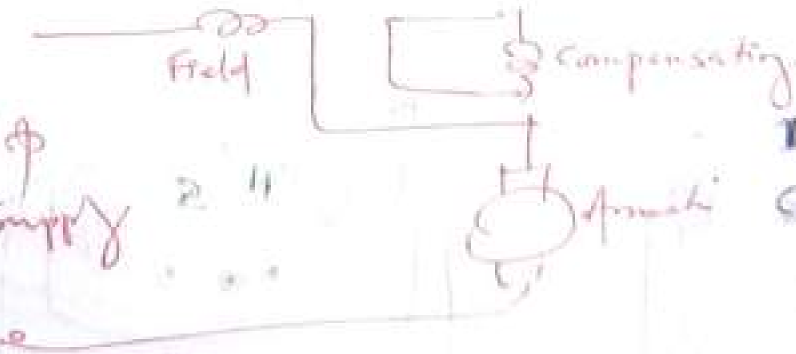
In order to get desired torque ($\phi \downarrow I_a \uparrow$) ∴ number of armature conductors are increased.

③ To counter effect of armature reaction (→ poor commutation), a **compensating winding** is used.

Placed in series with armature winding and it is 90° electrical with the main field axis.

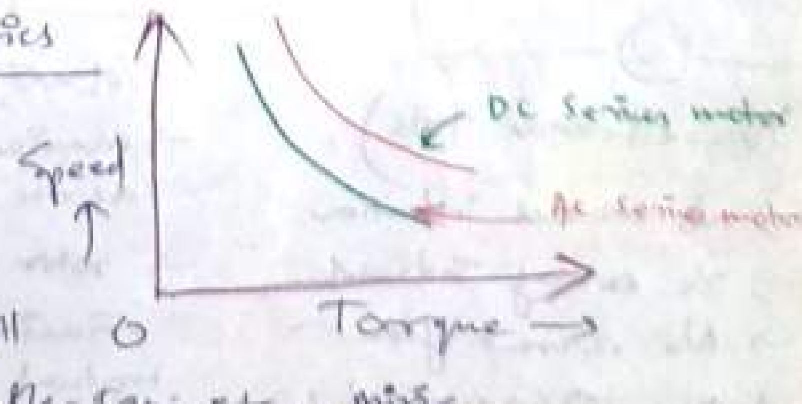


Conductively compensated



Infuctively compensated.

Characteristics



Application

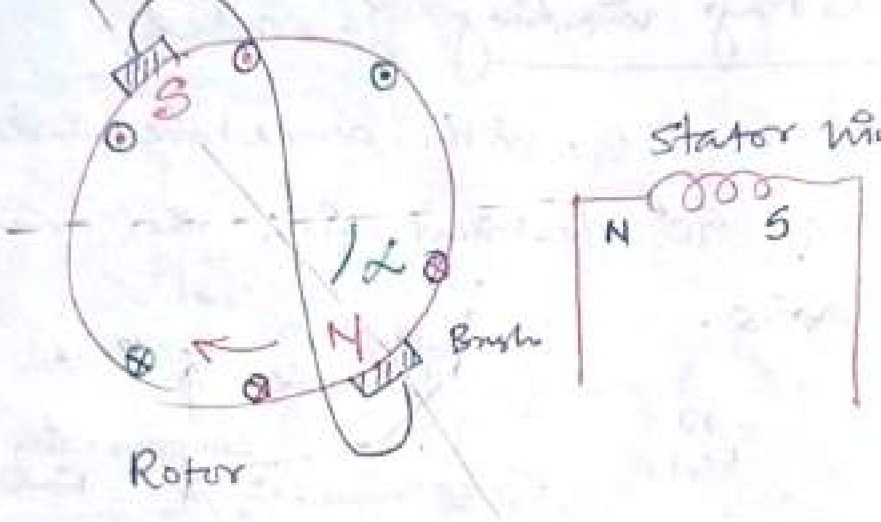
Hair dryer, Drill blower, Table-fan, etc., Mixie

II Repulsion motor { To facilitate starting of 1ϕ ...

Construction

→ Stator is supplied with 1ϕ AC

→ Rotor end ckt is short circuited through carbon brush.



Working principle

→ Similar pole repel each other i.e. North pole repels North pole.

Case II

(Quadrature Axis)

→ No mutual induction

→ No emf induced

→ No current flow

→ No torque develop

First Case I

($\alpha = 0°$)

→ Maximum emf is induced across brushes.

→ rotor & stator flux coincide & perfect mutual coupling betn them.

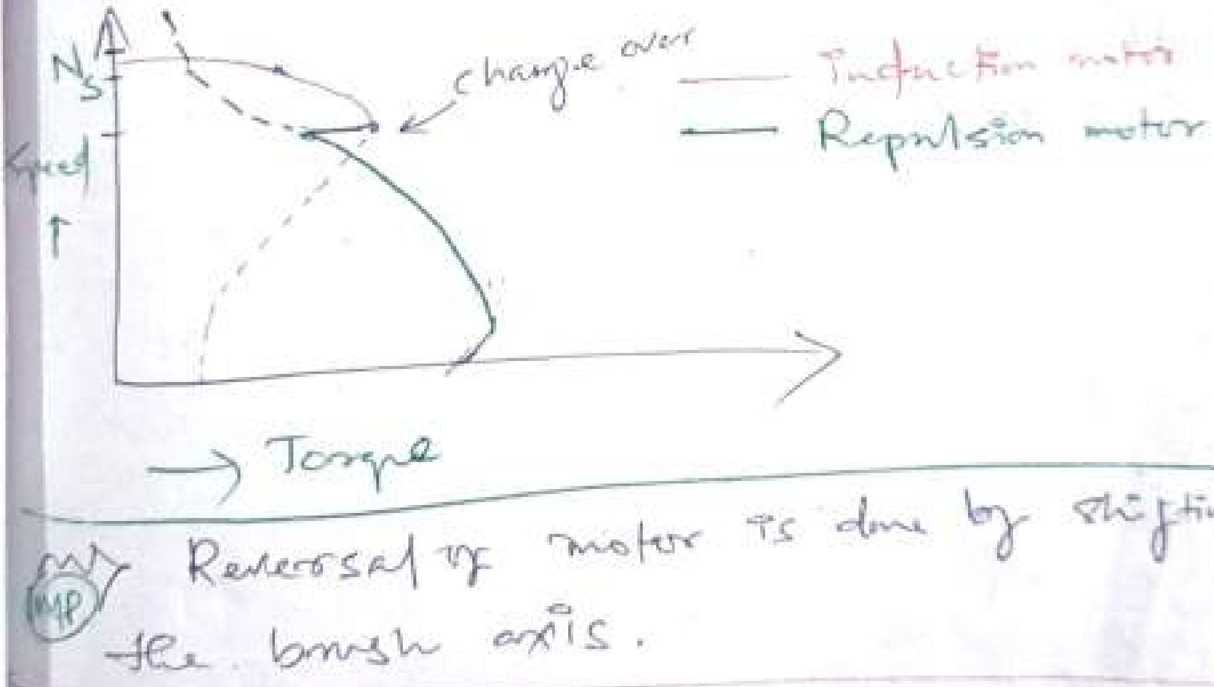
→ No Tem.

→ Repulsion motor:
High starting torque & no speed regulation (may go beyond Ns)

→ Induction motor (1ϕ)
Low starting torque & good (0) speed regulation (constant speed with normal load)

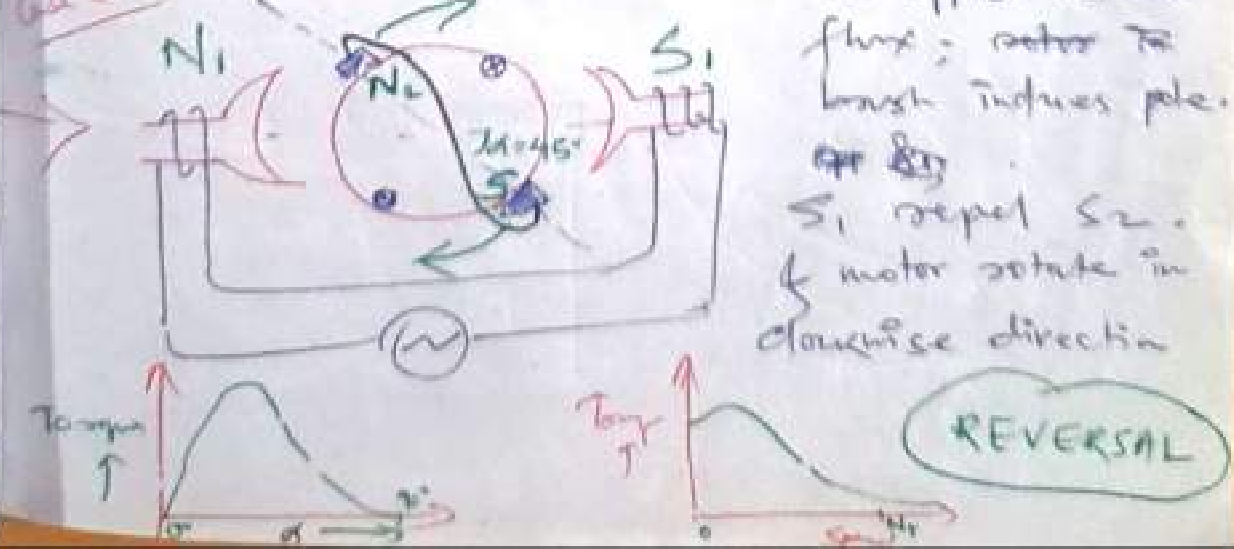
→ Repulsion start - Induction run motor

At about 80% transition from the repulsion motor to induction motor is done. (or At $\tau_{rep} \geq \tau_{ind}$) → Shortcircuiting the commutator



→ Torque

→ Reversal of motor is done by shifting the brush axis. (MP)



To oppose stator flux; rotor brush induces pole. S1 repel S2. & motor rotate in clockwise direction

Advantage of repulsion motor

1. Self starting (
2. High T_{st}
3.

Disadvantage

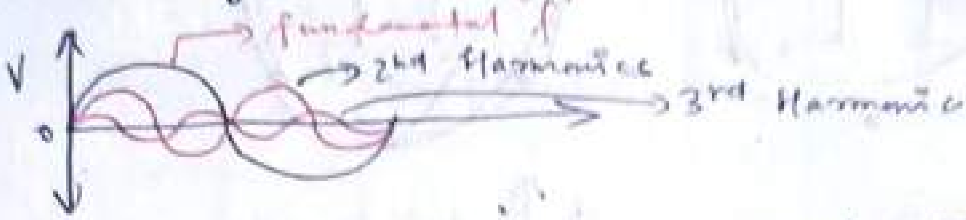
1. May spark at brush.
2. Commutator of brush wear out qu...
3. Very high no load speed

Application

1. Hoist, ... mining equipment

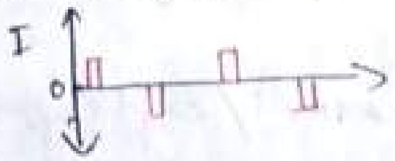
HARMONICS

In Electrical System, a harmonics of a voltage/current waveform is a sinusoidal wave whose frequency is an integer multiple of the fundamental frequency (i.e. 50Hz).



Causes of Harmonic production

(i) Non-linear load, draw current in abrupt short pulses.
This short pulse cause distortion in current waveform.



(ii) Power electronics devices causes Harmonics.

(iii) Magnetic saturation of transformer core.

(iv) CFL, Arc welders

(v) ~~Slot harmonics~~

Motor (vi) Non-sinusoidal flux distribution in the air gap. ~~(v∝φ)~~ $[V \propto \frac{d\phi}{dt}]$

$$E \leftarrow \phi = \frac{mmf}{R} = \frac{NI}{R}$$

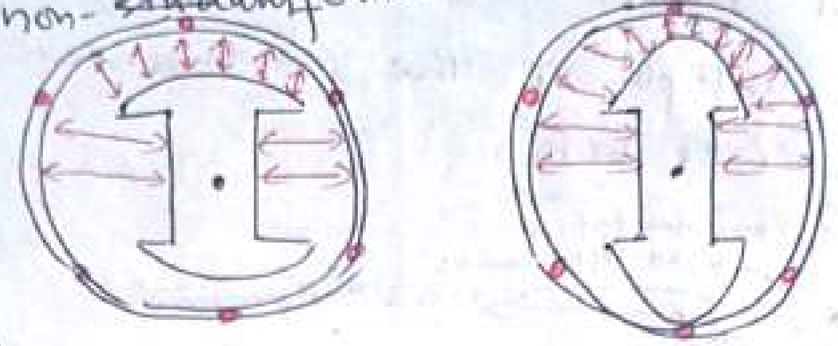
E: $\sin(\theta)$, ϕ: $\cos(\theta)$

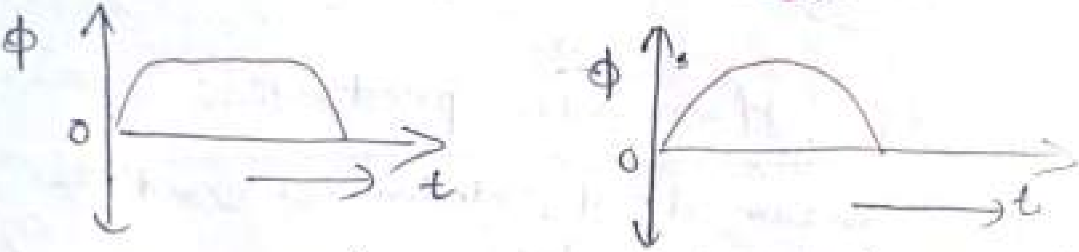
NI → constant

R → variable → $\sec(\theta)$

* Why non-sinusoidal flux distri... in air-gap?

(1) In salient pole ; the air gap ... non-~~sinu~~uniform.

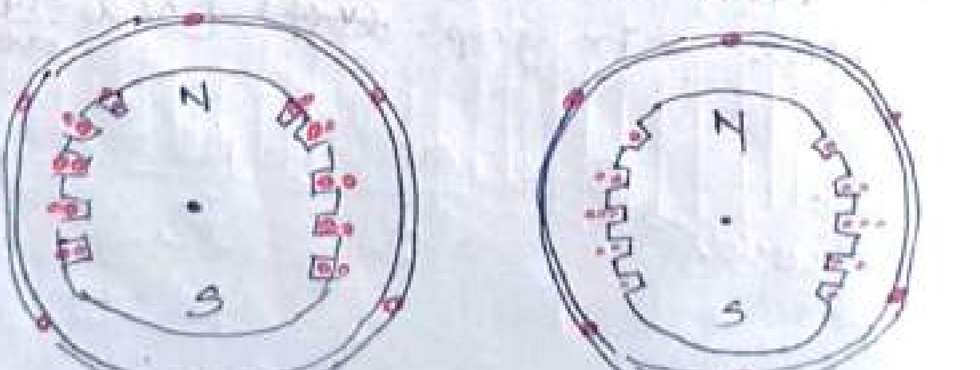




Solution :- "Chamfered pole" shoes ... used to provide uniform f... distribution.

(2) In turbo-alternator / cylindrical ... synchronous machine ; the air ... is uniform.

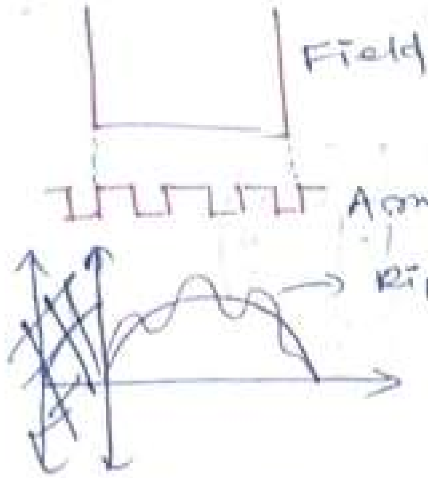
Solution :- To adjust the above factor the distribution of field windings sh... be done in such a way that ... it produces sinusoidal flux distri...



③ Slot Harmonics

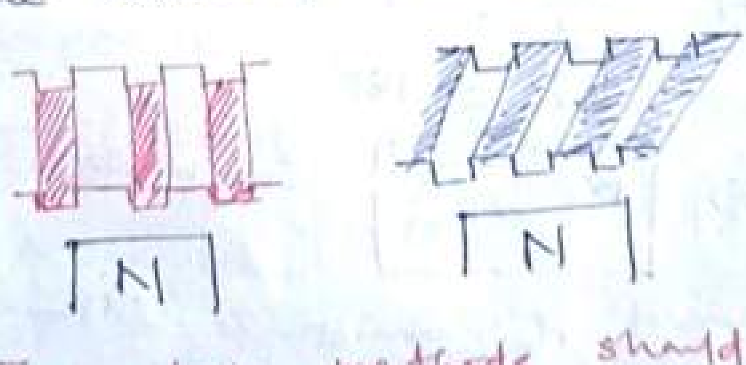
The stator where armature windings are mounted ~~a~~ is not smooth rather it is slotted.

It causes in non-uniform flux distribution.



<u>Solution:</u> To reduce the ripple in generated emf the pole face ~~slot~~ should be skewed.

"OR" skewing of armature slot. the harmonics can be ~~removed~~ reduced.

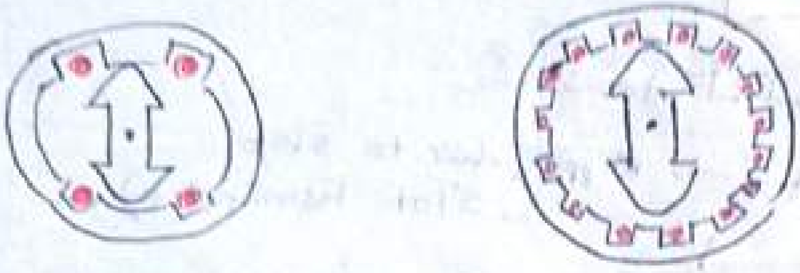


\# The above methods should be followed to make the flux sinusoidal but still it is not purely sinusoidal.

* Other solution at generated emf end : [Armature End]

① Distributed armature winding

The distributed winding along air-gap periphery tends to make generated emf waveform sinusoidal.



② Short pitch / Chorded coil

The nth harmonic can be eliminated if

$$K_p = \cos\left(\frac{n\alpha}{2}\right) = 0$$

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

$$\Rightarrow n\alpha = 180^\circ$$

$$\Rightarrow \boxed{\alpha = \frac{180^\circ}{n}}$$ Short pitch angle

→ The 3rd Harmonic is eliminated in line (∵ Star connection)

→ 5th & 7th Harmonics are present in emf generated. So, "α = 30°" should be made to reduce 5th & 7th Harmonics.

→ Higher order Harmonics are insignificant

$\alpha_5 = \frac{180^\circ}{5} = 36^\circ \rightarrow$ For 5^{th} Harmonics

$\alpha_7 = \frac{180^\circ}{7} = 25^\circ \rightarrow$ For 7^{th} Harmonics

$\alpha_{5,7} = \frac{36+25}{2} \simeq 30^\circ \rightarrow$ For 5^{th} & 7^{th} Harmonics

* Conclusion (How to remove Harmonics)

- First we tried to make flux sinusoidal
  1. Chamfered pole
  2. Skewing pole in order to vary conductor length sinusoidally

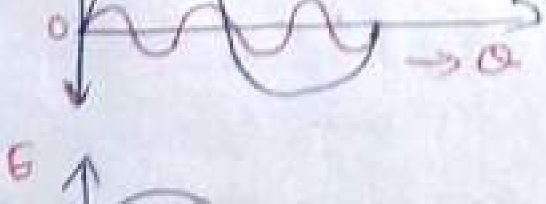
  } Modification on field side

  3. By increasing air gap → ↑ reluctance → Harmonics flux ↓ (Improve stability of machine)

- On Armature side
  1. Short pitching the winding
  2. Distributed winding
  3. fractional slot
  4. By skewing armature slot.

→ flux harmonics → [Space Harmonics]

Emf harmonics → [Time Harmonics]



$B = B_1 \sin\theta + B_3 \sin 3\theta$

$E = E_1 \sin wt + E_3 \sin 3wt$