DATE-04/12/24

By Murli Sir

Induction m/c

* These are the most commonly used motors because of there 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 genr but not prefered 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 dispalacement 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 perticular dirn depanding on φ seq.

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

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

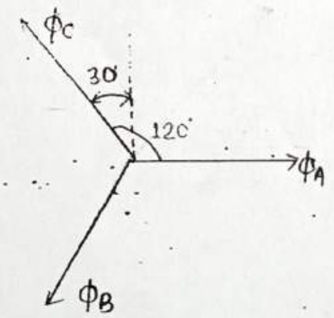
$$\phi_C = \phi_C \sin(\omega t - 240)$$

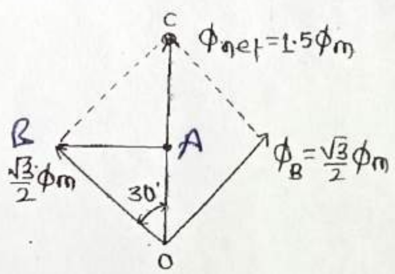
at $\omega t = 0$

$\phi_A = 0$

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

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





From Δ OAB

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

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

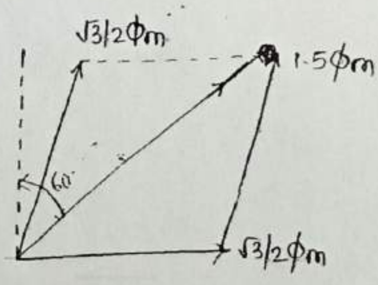
$$OC = \frac{3}{2}\phi_m = 1.5\phi_m$$

at $\omega t = 60$

$\phi_A = \sqrt{3}/2\,\phi_m$

$\phi_B = -\sqrt{3}/2\,\phi_m$

$\phi_C = 0$

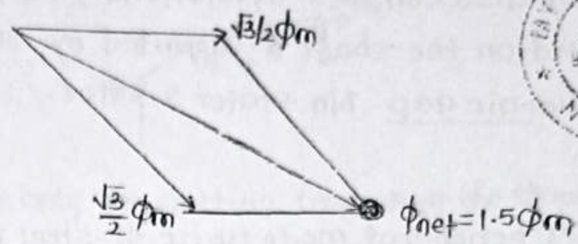


at $\omega t = 120^\circ$

$\phi_A = \sqrt{3}/2\,\phi_m$

$\phi_B = 0$

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

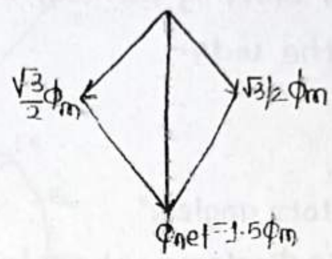


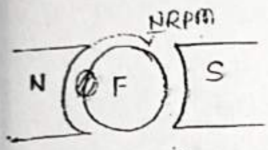
at $\omega t = 180^\circ$

$\phi_A = 0$

$\phi_B = \sqrt{3}/2\,\phi_m$

$\phi_C = -\sqrt{3}/2\,\phi_m$





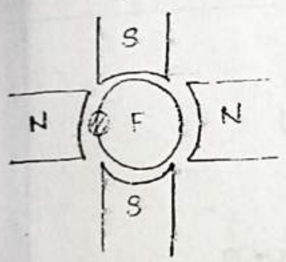
$N/60$ RPS

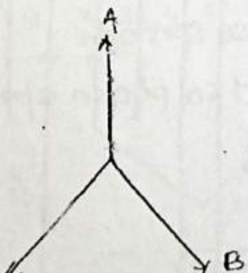
cycles/rotation $= P/2$

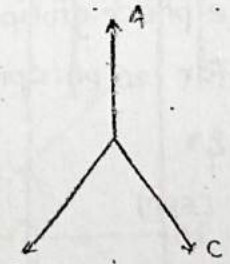
rot/sec × cycles/rot $= \frac{PN}{120}$

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

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







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(1) Integral slot wdg (2.) fractional slot wdg

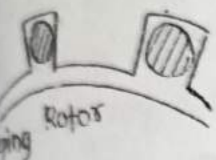
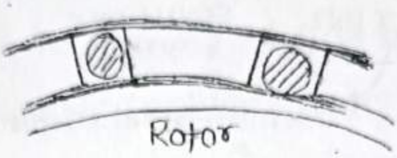
$\downarrow$ n= spp (integer) — eg:- 12/2/3 , 18/2/3

$\downarrow$ n= non integer (Fraction) — Eg:- 18/4/3

Fractional slot wdgs practicaly offer short pitched wdg specialy more suitable in double layer wdg cases.

Fractionaly $\rightarrow$ Automaticaly short pitched

Type of slots $\rightarrow$

Open	Closed	Semi-open/closed
		
wdg design, routine main-tainance, repairs is easy	Difficult	quite difficult
less expensive.		
offer high reluctance to leakage flux, less leakage reactance.	High leakage flux, high leakage reactance	moderate.
Net air gap is more which requirs more magnetising current to maintain flux & the operating PF will be low wrt Ef.	Net air gap is less, so magnetising current less PF more.	moderate.

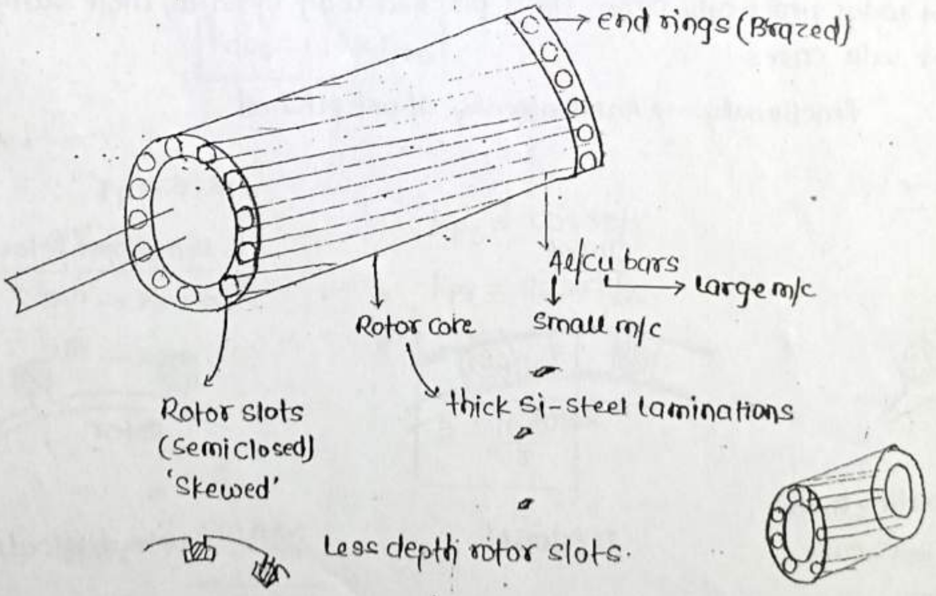
* Wrt leakage reactance its Operating pF is better comparitively.	wrt leakage reactance Operating pF is low	moderate.
* Non uniform air gap will produce space harmonics by distorting flux waveform. also called as slot/tooth harmonics.	No slot/tooth harmonics	moderate

* Generaly prefered slots in IM in stator (OR) rotor are semiclosed type.
* Large rating m/c eg. power plant genᵣ (OR) large rating IM prefered open type because they produce less leakage reactance & also offers easy, maintaince repair works.

*Rotor →

(1) Squirral cage (OR) Cage rotors.

(2) Wound/slip Ring rotors.



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

* This bars are solidaly closed (or) sc with 2 end rings (Brazed)
* Rotor slots are skeyed (twisted or inclined) wrt shaft axis or stator slots to avoid locking tendancy during starting.
* Under the running cond^n rotor Freq. is negligible & the rotor core losses are very low.

Therefore no need of thin laminations.

* It requires least maintaince repairs, mech. strong, simple design, less cost & excellent running c/s.
* The drawback is due to its low starting torque .
* As the rotor is permanantly closed its resistance can't be varied for starting (or) controlling purpose.

"Poles are automaticaly formed on the rotor equal to the no. of poles on stator."

* Due to mutual ind^n the poles are induced in the rotor.

Therefore it reacts to any no. of poles on the stator.

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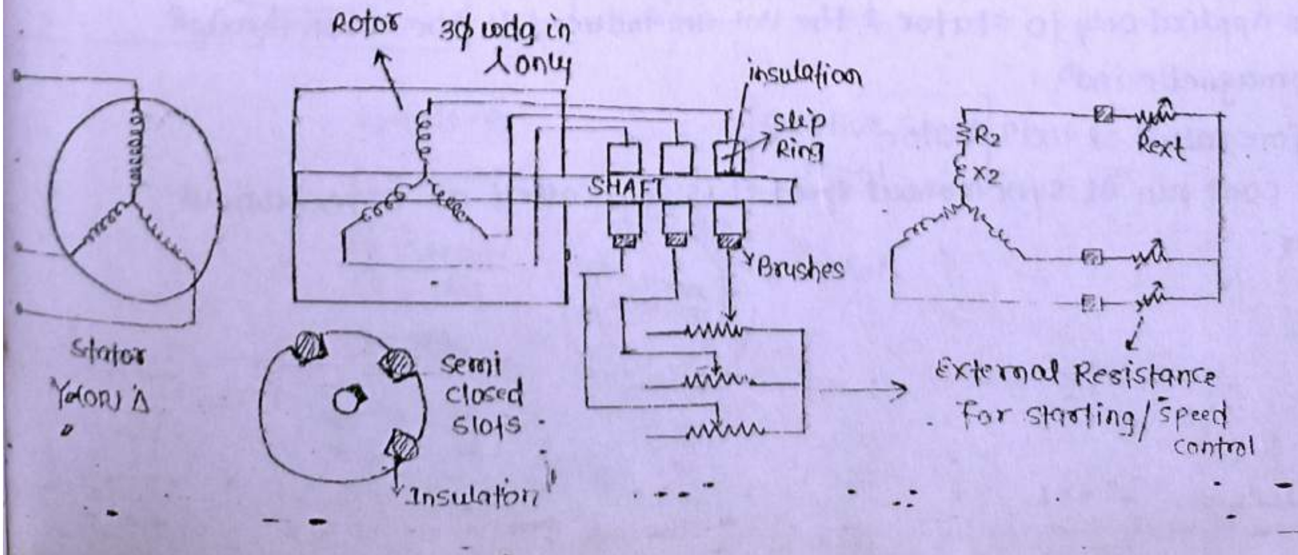
(2) Slip Ring/wound → * The rotor is a cylindrical drum shaped st. punched into slots (semiclosed) on the outer peripheral which contain a 3ϕ wdg similar to stator wdg but essentialy star connected.

* Rotor is designed for the same no of poles as on the stator. but preferabely 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 ⅄ connected wdg will be brought out & connected to 3 slip rings mounted on the same shaft with suitable insulation.



* The starting torque is ∝ to rotor resistance but the rotors are naturaly designed for least possible resistance. In order to have high starting torque an external resistance is inserted in each phase equaly through slip ring & brushes.
* Under running condn the resistance is disconnected using a METAL COLLAR arrangement the brushes are slight down & 3 slip rings are SC to form a closed rotor.
* This is only used for high starting torque appn. Around 90% of motors are squarral cage type only.
* Slip motors are expensive, compleated design, high maintaince repairs, running c/s are not good comparitevely.

* Principle:- (How rotor run)?
* when a 3ϕ supply is given to stator RMF is produced at Ns. As the flux sweeps fast the rotor cuts it & cuts it & induces EMF due to relative speed Ns. & the rotor freq. at stand still is supply freq.
* As the rotor is essentialy closed it produces current & the current carrying condr placed in the magnetic field will experienced a force which is torque & the rotor rotates.
* According to Lenz law it rotates in the dirn of magnetic field to oppose the cause i.e. relative speed.
* Actualy 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 Ns.
* The rotor slips back RMF by a speed Ns-N known as steep slip speed.
* The principle of operation is mutual indn 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 indn.
Therefore called as indn 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.

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

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

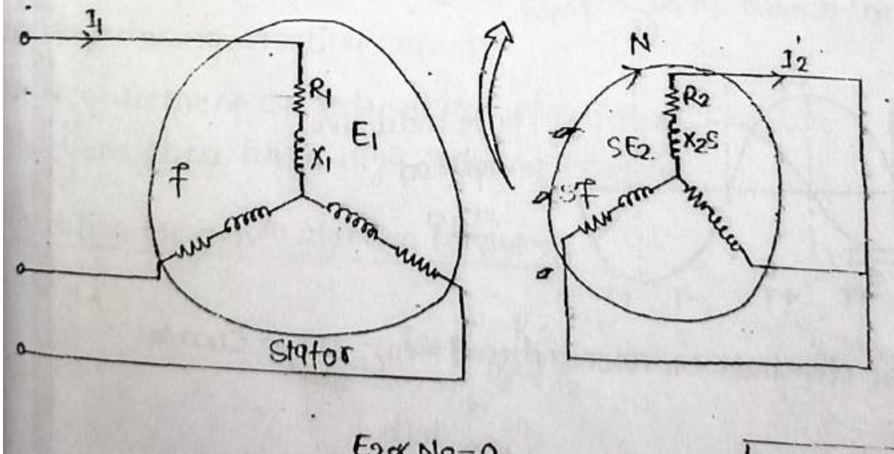
$$N_S - N = SN_S$$

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

* During starting at N=0, S=1.0
* A well designed indn 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 Ns, then no relative speed, no E_2, $I_2=0$, $T=0$.
* The operating region of indn 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→



$E_2 \propto N_S - 0$

$E_2' \propto N_S - N$

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

$E_2' = SE_2$

Relative Speed
$N_S - N$

$f \propto N_s - 0$

$f' \propto N_s - N$

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

$\boxed{f' = sf}$

$f = \frac{120(N_s - 0)}{120}$

$f' = \frac{P(N_s - N)}{120}$

$f' = \frac{P \cdot N_s \cdot S}{120}$

$\boxed{f' = sf}$

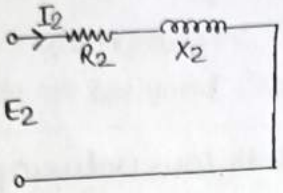
$X_2 = 2\pi f l_2$

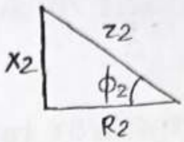
$X_2' = 2\pi s f l_2$

$\boxed{\therefore X_2' = sX_2}$

* Rotor resistance approximately remains same.

Rotor PF →





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

$\cos\phi_2' = \frac{R_2}{R_2 + jsX_2}$

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

$I_2' = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}}$ (running)

$e_2 (B\, l\, v)$.

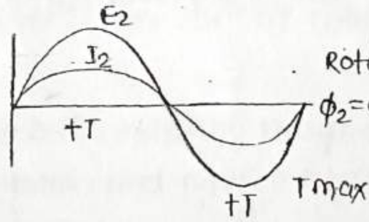
$F = i(B \times l)$

* Torque →

$F = BIl$

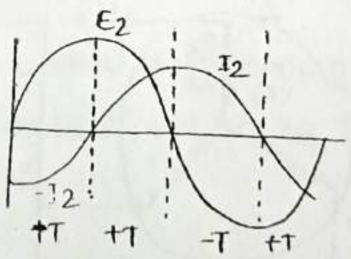
$T \propto \phi I_a$ (dc)

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



Rotor pure resistance

$\phi_2 = 0$



pure inductive

$\phi_2 = 90$

$T = 0$

* The torque developed in the rotor depends on rotor induced emf, rotor current & also significantly on rotor PF.
* If the rotor is b/c pure inductive the torque developed be 0.

Starting Torque →

$$T_{st} \propto E_2 I_2 \cos\phi_2$$

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

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

$$\boxed{T_{st} = k \times \frac{E_2^2 R_2}{R_2^2+X_2^2} \quad N\text{-}m} \qquad \because \boxed{k = \frac{3\times 60}{2\pi N_S}} \text{ (Refer power torque relations)}$$

* The starting torque is significantly depanding on supply vol. & very sensitive to the vol. variation.

$$T_{st} \propto E_2^2 \propto V^2 \qquad V \to \phi \to E_2$$

* Starting torque is also directly proportional to rotor resistance.

It increases with rotor resistance upto a suitable value & decrease if the resistance is increasing further.

In squirrel cage motor the rotor resistance is a least possible value & they will be started using reduced vol. starting methodology.

Therefore they have low starting torques.

In slip ring rotor resistance can be increased which increases starting torque while reducing starting current

No requirement of reduced vol. starting.

Therefore they have high starting torque.

Condition for max^m starting torque →

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

$$\left[\frac{dT_{st}}{dR_2} = 0\right]$$

$$\left[\frac{1}{(R_2^2+X_2^2)} - \frac{(2R_2)\cdot R_2}{[R_2^2+X_2^2]^2}\right] = 0$$

$$\frac{1}{R_2^2+X_2^2} = \frac{2R_2^2}{(R_2+X_2)^2}$$

$$\boxed{R_2 = X_2}$$

* 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 ~~th~~ its max^m torque.

* Under such $cond^n$ the rotor PF will be 0.707 lagging

* Running torque → Consider a motor running at rated load with slips 'S' speed 'Ns'

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

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

$$T_f \propto (K_1\phi) \times \frac{SE_2}{\sqrt{R_2^2+(SX_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2+(SX_2)^2}}$$

$$T \propto \frac{(K_1\phi)\, SE_2 R_2}{[R_2^2+(SX_2)^2]}$$

$$T = K \cdot \boxed{\frac{SE_2^2 R_2}{R_2^2+(SX_2)^2}} \qquad \left(K = \frac{3\times 60}{2\pi N_S}\right)$$

* For a given (or) const. supply vol. $T_f \propto \dfrac{SR_2}{R_2^2+(SX_2)^2}$

* Under normal running $cond^n$ at low values of slip;

$$S\downarrow;\ (SX_2)^2 << R_2$$

$$T_f \propto \frac{S\cancel{R_2}}{R_2^{\cancel{2}}}$$

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

& at the high values of slip

$$S\uparrow \quad (SX_2)^2 >> R_2$$

$$T_f \propto \frac{SR_2}{(SX_2)^2} \propto \frac{R_2}{SX_2^2}$$

$$\boxed{T_f \propto \frac{R_2}{SX_2^2}}$$

* 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.

Condn for maxm running torque →

$$T_F = \frac{SR_2}{R_2^2+(SX_2)^2}$$

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 maxm running torque.

maxm starting torque $\boxed{R_2 = X_2}$

maxm running torque $\boxed{R_2 = SX_2}$

Starting	Running torque
$T_{st\,max} \propto \frac{R_2}{R_2^2+X_2^2}$	$T_{f(running)} \propto \frac{SR_2}{R_2^2+(SX_2)^2}$
$T_{st\,max} \propto \frac{1}{2X_2}$	$T_{f(max)} \propto \frac{1}{2X_2}$

$$\boxed{T_{max} \propto \frac{1}{2X_2}}$$

$$K_1 = \frac{3\times 60 E_2^2}{2\pi N_S}$$ (Refer $\frac{V}{f}$ speed control)

$$\boxed{S_m = \frac{R_2}{X_2}}$$ (Also a condn for maxm value)

$$\frac{T_{st}}{T_{max}} = \frac{R_2}{R_2^2+X_2^2} \times 2X_2$$

$$= \frac{2R_2X_2/X_2^2}{R_2^2/X_2^2 + X_2^2/X_2^2}$$

$$\boxed{\frac{T_{st}}{T_{max}} = \frac{2S_m}{S_m^2+1}}$$

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

$$\boxed{\frac{T_f}{T_{max}} = \frac{2SS_m}{S_m^2+S^2}}$$

$$T = \frac{3\times 60}{2\pi N_S}\left(\frac{SE_2^2 R_2}{R_2^2+(SX_2)^2}\right)$$

$$T \propto \frac{SR_2}{R_2^2+(SX_2)^2}$$

Speed decrease

for low slip so $(S x_2)^2 << R_2^2$

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

for high slip $(S x_2)^2 >> R_2^2$

$T \propto \frac{S R_2}{S^2 x_2^2} \propto \frac{R_2}{S x_2^2}$

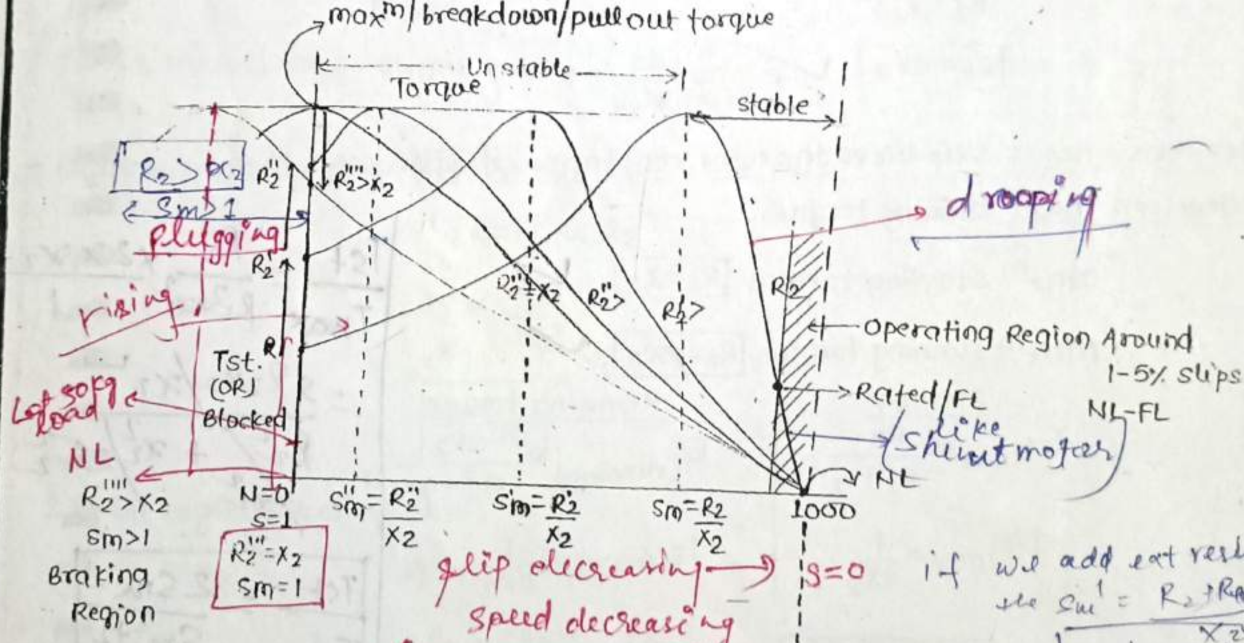
for a given R_2, x_2 value $\boxed{T \propto \frac{1}{S}}$

S = 1 High — Low → S = 0 NS

* The motor rotates at any slip b/n 0 & 1 but it delivers its max^m torque only at a particular slip $S_m = R_2/X_2$.
* Generaly 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^m torque because slip at which max^m torque occurs $S_m = 1$
* max^m torque magnitude is indepandant of rotor resistance but the slip at which it occurs depends on R_2.
* max^m torque is inversaly proportional to leakage reactance of rotor at stand still.

Therefore it will be designed as min^m as possible with less depth slots.

* Torque-slip c/s →



if we add ext resistance the $S_m' = \frac{R_2 + R_{ext}}{X_2}$

$\boxed{S_m' = \frac{R_2'}{X_2}}$ which ↑

Generally;

$T_{max} >> T_F$

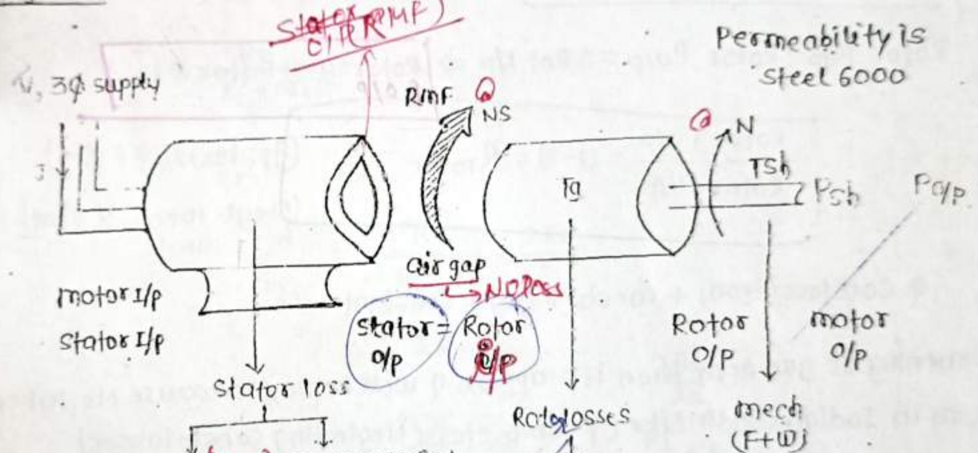
$(T_{max} \simeq 2\text{-}3\, T_F)$

& $(T_{st} \simeq 1.5\, T_F)$

Const ← $\boxed{T} \propto \frac{S \uparrow\uparrow}{R_2 \uparrow\uparrow}$

* T-s c/s are essentialy straight line in the operating region (Low slip).
* Every motor will have its max^m capacity or capability to develop torque which occurs only at slip s_m if the load increases beyond it it can't deliver torque & its stops which is unstable region.
* Im have 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 η consideration.
* The max^m torque is independant of rotor resistance but the slip & speed where it occurs depands on rotor resistance.
* If $R_2 >> X_2$ max^m torque occurs in the braking region.

* Power stages →



Stator losses —→ core loss / → cu loss

Rotor Losses —→ Only cu losses (we neglect Rotor core loss) bcz of less freq(sf)

mech. losses —→ Frictional / → windage

In airgap NO loss

* There are no losses in the air gap.

Reluctance don't produce any drop like Resistance

But (losses are stopping the rotor Not to catch N_s)

$$\boxed{\text{Total loss} = + \begin{cases} \text{Iron} \to \text{Friction} + \text{Windage} = \text{Const (Blocked rotor Test)} \\ \text{Cu loss} \to \text{Variable loss (N L Test)} \end{cases}}$$

Stator I/p - stator loss = stator o/p = $\boxed{\text{Rotor I/p = Air gap power}}$

Rotor I/p - Rotor cu loss = Rot. o/p

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

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

$$\frac{2\pi N_s T_g}{60}$$

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

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

Rotor Pi/p = $\frac{2\pi N_s T_g}{60}$ watts | Rot Po/p = $\frac{2\pi N T_g}{60}$ watts

$$\text{Rotor Pi/p} - \text{Rotor Po/p} = \text{Rot cu loss} = \frac{2\pi T_g}{60}(N_s - N) = \frac{2\pi T_g}{60} \cdot S\, N_s = \underbrace{\frac{2\pi T_g N_s}{60}}_{\text{Ri/p}} \cdot S$$

Ri/p×S

$$\boxed{\text{Rotor cu loss} = S \cdot \text{Rot Pi/p}}$$

Rotor Pi/p - Rotor Po/p = S Rot I/p ⇒ $\boxed{\text{Rotor P o/p} = (1-S)\text{ Rotor Pi/p}}$

$$\boxed{\frac{\text{Rotor Po/p}}{\text{Rotor Pi/p}} = (1-S) = \eta_{rotor} = \frac{N}{N_s}}$$

(Approx η of IM.)
(Negl. mech. & stat)

* Core loss (iron) + mech (F+W) = constant loss.

* If IM is running at 950 RPM then its approx. η will be 90% because Ns taken as 1000 RPM in Indian condⁿ like (F→50Hz etc). (Neglecting const. losses)

* T developed →

$$T_g = \frac{60}{2\pi N_S} \times \begin{array}{c}\text{Rotor power I/p} \\ \text{(OR)} \\ \text{Air gap power}\end{array}$$

$$T_g = \frac{60}{2\pi N_S} \cdot \frac{\text{Rot. cu loss}}{\text{slip}} \longrightarrow 3I_2'^2R_2'$$

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

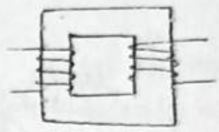
$$= \frac{60}{2\pi N_s} \cdot 3 \times \left[\frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}\right]^2 \times \frac{R_2}{S} \qquad I_2' = \frac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$$

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

$$\boxed{T_g = \frac{3\times 60}{2\pi N_s} \frac{S E_2^2 R_2}{R_2^2 + (SX_2)^2}} \quad N\text{-}m$$

$$T_g = \frac{3\times 60}{2\pi N_s} \times \frac{S(KE_1)^2 \cdot R_2}{R_2^2 + (SX_2)^2} \quad N\text{-}m$$

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



$E_1 = N_1 \frac{d\phi}{dt}$ $\quad E_2 = N_2 \frac{d\phi}{dt}$

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

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

* Torque Rating in terms of 'Sm' →

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

$$T_f \propto \frac{SR_2}{R_2^2 + (SX_2)^2}$$

$$T_m \propto \frac{1}{2X_2}$$

$$\text{Now; } \frac{T_{st}}{T_{max}} = \frac{R_2}{R_2^2 + X_2^2} \times \frac{2X_2}{1}$$

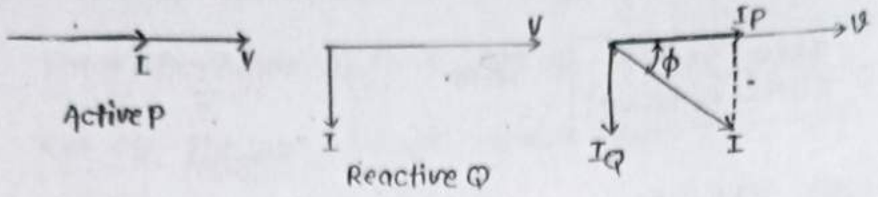
$$= \frac{2R_2 \cdot \frac{X_2}{X_2^2}}{\frac{R_2^2}{X_2^2} + \frac{X_2^2}{X_2^2}} = \frac{\frac{2R_2}{X_2}}{\frac{R_2^2}{X_2^2} + 1}$$

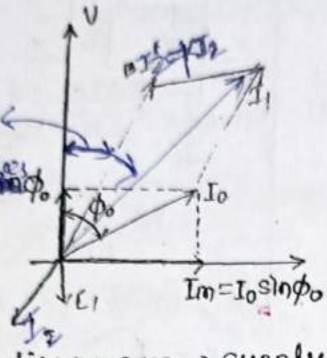
$$\boxed{\frac{T_{st}}{T_{max}} = \frac{2S_m}{S_m^2 + 1}}$$

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

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

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

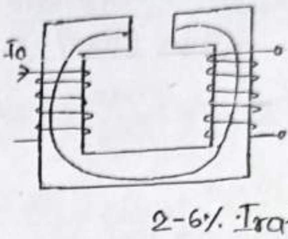




Angle reduced P.f. improves (after loading)

$I_m >> I_c$

No Load



* draw more current to maintain flux in air gap because of high reluctance in the air

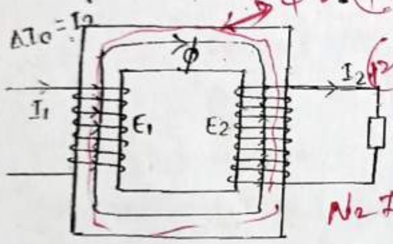
2-6% I rated

Highly lagging

* Active power → supply some losses
* Reactive power → To maitain flux

$\left.\begin{matrix}\Delta I \\ + \\ \uparrow I_0\end{matrix}\right\} = \dfrac{V_1 - E_1 \downarrow}{Z_1}$ (due to flux reduction)

ϕ_2 (oppose ϕ)



$N_2 I_2$ (De magn. armature reaction mmf)

$I_2' \Rightarrow \phi_2' \rightarrow (\phi_2' - \phi_2) = \phi$

$I_2' \propto I_2$

$I_2' = K I_2$

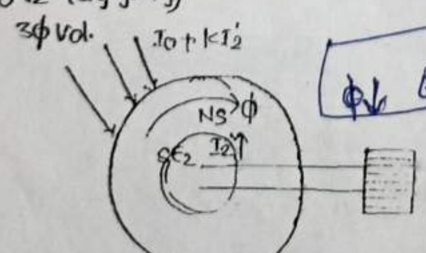
(I_2' → load component in primary)

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

$\phi_2' = \phi_2$

$\frac{I_2' N_1}{\phi_2'} = \frac{I_2 N_2}{\phi_2}$

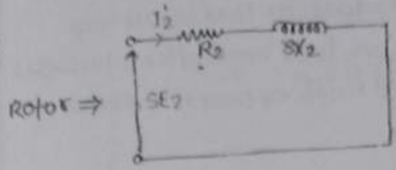
* IM on NL → * It draws a large magnetising current around 30% of rated to establish flux (RMF) in the air gap of high reluctance.
* Only ZPF lagging current will supply flux (magnetising current).
* Im draws reactive power to establish flux in the air gap.
* It draws active power for supplying its losses & load torque if loaded.
* on NL as the magnetising current is very high it operates at low lagging PF (less than 0.2 lagging)



$\boxed{\phi \downarrow \; E_1 \downarrow \; I_2' \uparrow \; \frac{I_2}{K} \uparrow} \Rightarrow \left(I_0 + \frac{I_2}{K}\right)$ when loaded

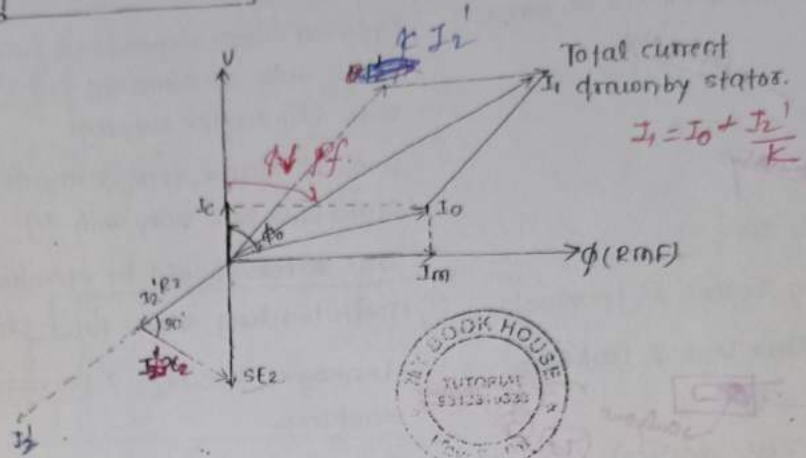
When load ↑ $I_2 \uparrow$ $N \downarrow$ $S \uparrow$

$sE_2 \uparrow$



$SE_2 - I_2'(R_2 + jSX_2) = 0$ (V)

$I_2' = \frac{SE_2}{R_2 + jSX_2}$



* On load rotor current increase proportionaly to produce its own flux in the air gap which is stationary wrt stator RMF. but opposes it acc to Lenz law & reduce it.
* Therefore stator draws more current proportionaly to maintain the flux const in the air gap. $\frac{I_2}{K}$
* Whenever rotor is loaded it will immediately call current from stator. (I_2') with load PF improves but operate at low PF comparitive to an eq. Xmer.

Transformer	Induction motor
(1) Ele to ele. energy conversion through magnetic medium in high permeability core	Ele to mech. energy conversion. through magnetic medium in the air gap of high reluctance.
(2) Require less magnetising current	Requires large magnetising current.
(3) NL current 2-6% of rated	Around 30-40% of rated.
(4) Low lagging PF on NL	Very much low lagging PF.
(5) PF improves with load.	PF improves with load. but compare low.
(6) Concentrated wdg. No R.M.F.	Distributed wdg produce RMF.

* draw more current ... flux in air gap because of ... reluctance in air

6% Irated

Highly lagging

$V_1 - E_1$ (due to the reduction)

$(\phi_2' - \phi_2)$

$I_2' \propto I_2$

$I_2' = \frac{N_2}{N_1} I_2 \Rightarrow I_2' = \frac{I}{K}$

$\phi_2' = \phi_2$

$I_2' N_1 = I_2 N_2$

nd 30% of rated to ... reluctance.

nt).

que if loaded.

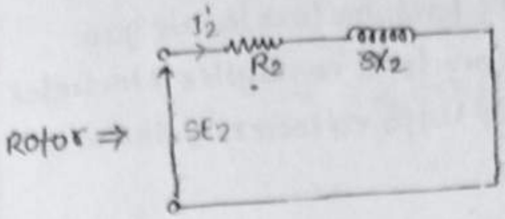
low lagging PF

$I_0 + \frac{I_2}{K}$ when loaded

$I_2 \uparrow$ $N\downarrow$ $S\uparrow$

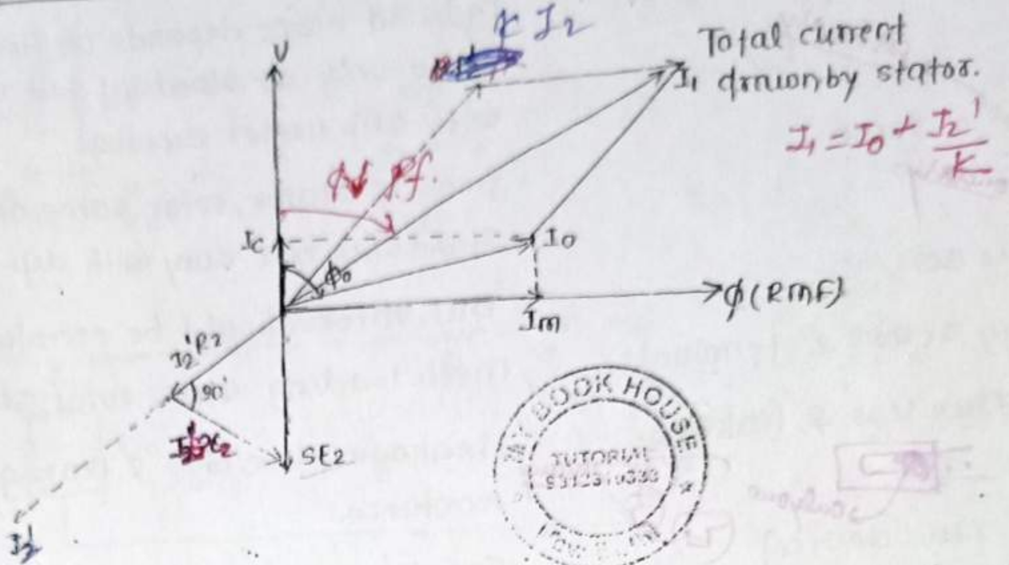
$SE_2 \uparrow$

255



$SE_2 - I_2'(R_2 + jX_2) = 0$ (V)

$I_2' = \frac{SE_2}{R_2 + jSX_2}$



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(5) PF improves with load.	PF improves with load. but compare low.
(6) Concentrated wdg. No RMF	Distributed wdg produce RMF

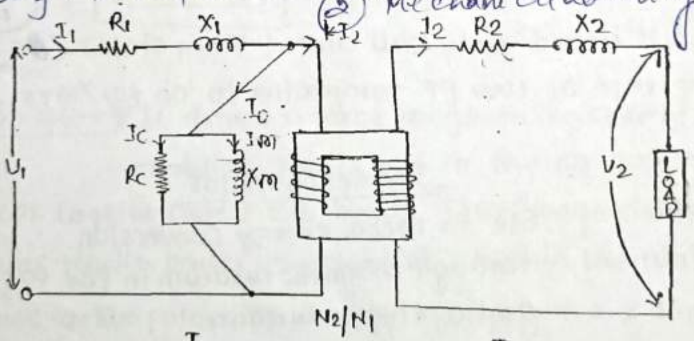
(7.) Contain core loss & Cu loss only	Stator core loss, no loss in air gap & rotor core loss negligible & includes mech. loss with Cu losses of stator & rotor.
(8.) Induced emfs depends on turns ratio.	Induced emfs depends on turns ratio only at standstill but vary with slip under running.
(9.) Freq. of 1°, 2° same (→ primary, → secondary)	Freq. of stator, rotor same only at stand still but vary with slip.
(10) 2° is never SC	But rotor should be essentialy SC.
(11) Ele. loading across 2° terminals	Mech. loading across rotor shaft.
(12) Leakage flux less & leakage reactances (only one)	Leakage flux high & leakage reactance. (many)
(13) Constant flux device	Constant flux m/c.
(14) Mutual ind^n.	Mutual ind^n.

from NO Load → Full load operation is same. For analysing I. M. mathematically T/Fs equivalent ckt is used but there

~~Both Tr~~

* T/F eq. Ckt Representation →

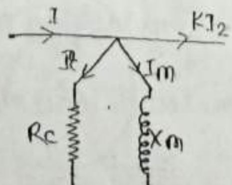
are two difficulties (1) f is not same in stator and rotor (2) Mechanical loading.



I_2

$I_1 \to I_0,\ KI_2$

$I_0 \to I_C,\ I_m$



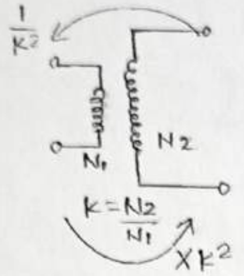
$R_C = \frac{V_1}{I_C} \Rightarrow X_m = \frac{V_1}{I_m}$ [Ficticious/Imag. value]

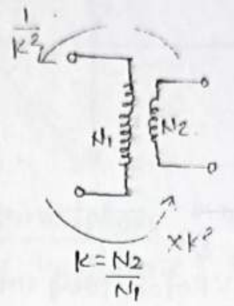
$I_C < I_m$

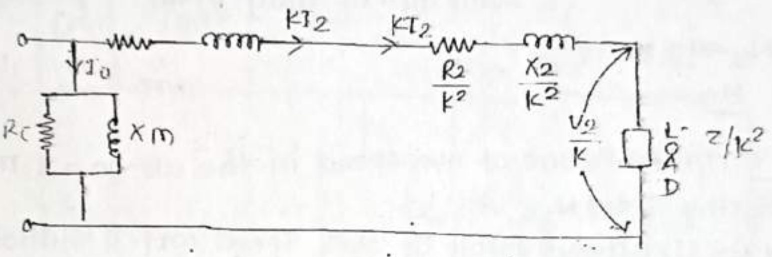
R_C, X_m depends on I_C & I_m.

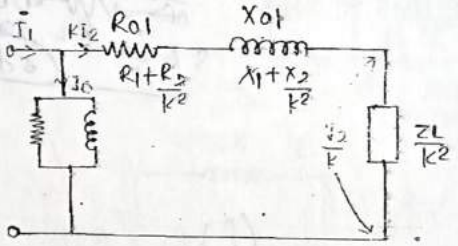
$$I_1^2 R_2' \Longrightarrow I_2^2 R_2$$

$$R_2' \Longrightarrow \left(\frac{I_2}{I_1}\right)^2 R_2$$

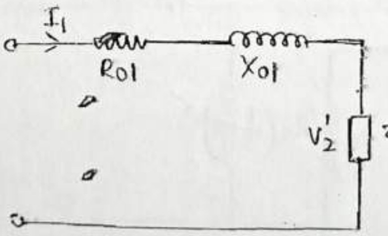








approx eq. ckt Neglecting shunt branch
Ref to 1°



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.

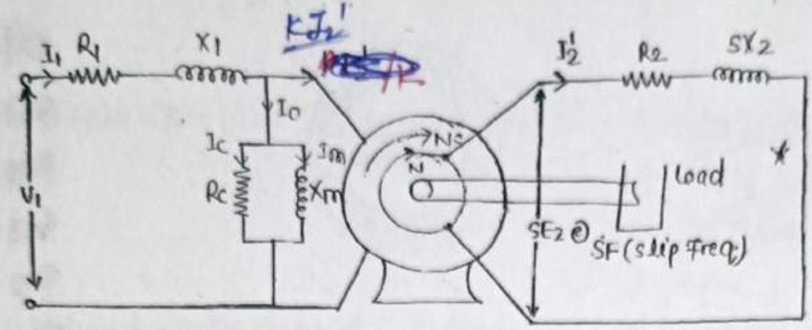
However there are 2 major diff which need to be resolved:-

(i) freq. of rotor is slip freq.

(ii) Loading is mech. across the shaft.

$R_c >> X_m$ $\quad I_c = \frac{V}{R_0}$. $\quad I_m = \frac{V}{X_m}$ and $I_c << I_m$

so i- $R_c >> X_m$



Stator $\qquad$ Rotor

S_{RMF} wrt stator @ N_S

R_{RMF} wrt stator @ $SN_S + N$

$\downarrow$

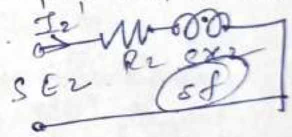
$\because$ Rotor itself rotate @ N in the same dir^n of mag. Field

$N_S - N + N$

$\underline{N_S}$

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

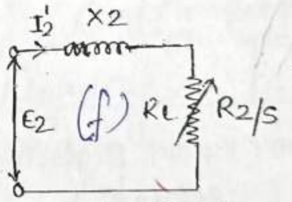
*The absolute flux in space will always rotate at syn. speed wrt. a stationary point in space of stator but wrt. rotor it is at SN_S.



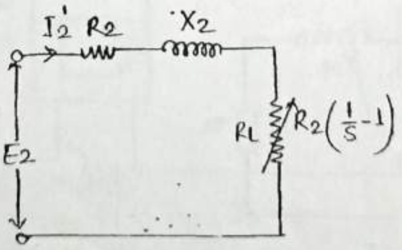
*

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

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



(at rotor freq)



* If $I_m \to$ open (NL)

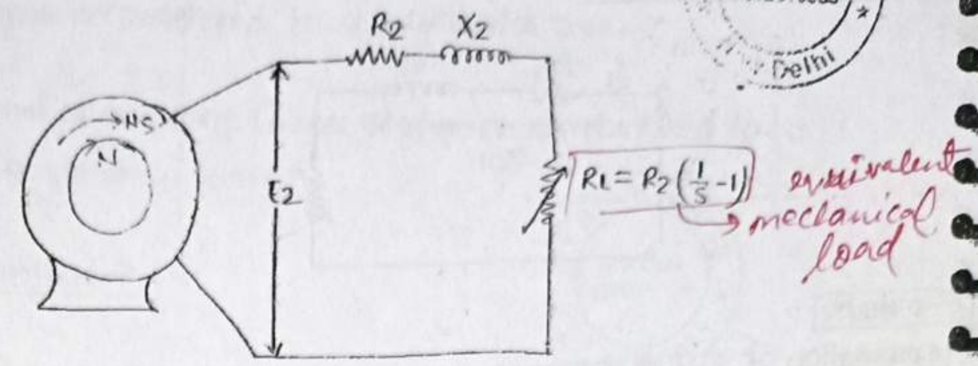
$S \to 0$

$R_L \to \infty$ (OC) like TF

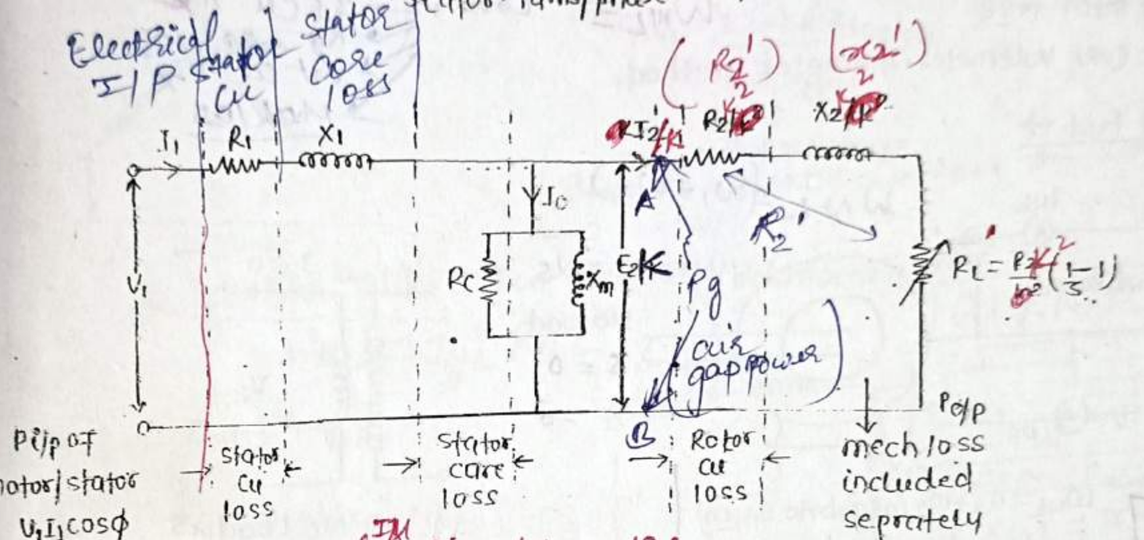
* $I_m \to$ Rated load

$S \to 1$

$R_L \to 0$ (SC)

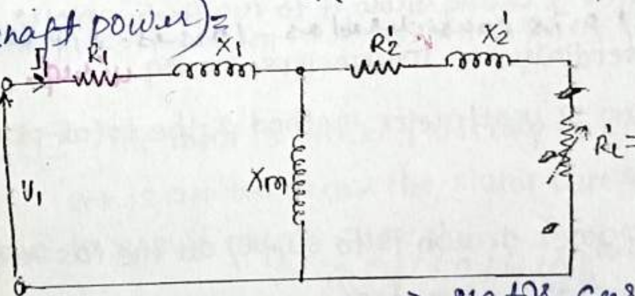


$$k = \frac{\text{Rotor turns/phase}}{\text{Stator turns/phase}} = \frac{E_2 \text{ @stand still}}{E_1}$$



Eq. ckt Rep of IM Refferred to stator

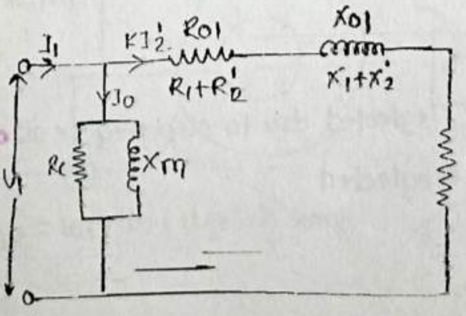
IEEE standard ckt representation → shunt branch resistance is eliminated in the std ckt but core losses & mech. losses should be included in net (shaft power) power caln. This will be accurate analysis.



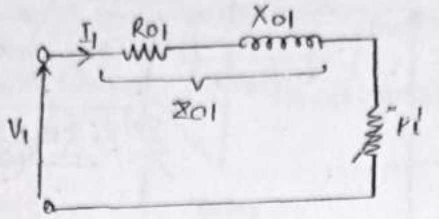
Rc (Stator core loss) are not considered ~~But~~

Shaft power ⇒ stator core + Mech = Rot loss should be included.

Approx Eq. ckt →



Neglecting shunt branch →



DATE-07/12/14

*** Determination of eq: ckt parameters →** It requires 3 tests to be performed:-

(1.) No Load

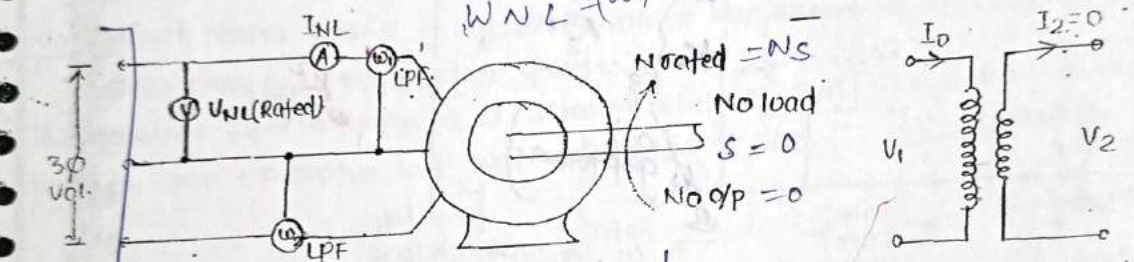
(2.) Blocked rotor test

(3.) DC test (OR) Voltmeter-Ammeter method.

$W_{NL} =$ Losses → St. core loss; → St Cu " ; → Rot core " ✗; → Rot Cu " ✗; → Mech loss

(1.) No Load test →

$W_{NL} = (W_1 + W_2)$



Auto Trf^r

$W_{NL} = W_1 + W_2$ (algebric sum)

↓

(P i/p drawn)

Can measured using dc test and No load stator Cu loss is eliminated.

In order to find Const loss, stator Resistance

I/p = O/p + Total Loss

* Apply rated vol. across the stator & along allow it to run freely on NL: given 2 W meter
as there is no O/P I/P is considered as losses. O/P

* Connect necessary meters & essentialy LPF wattmeters are required.

* The 3φ power is measured using 2 wattmeter method & the total power is algebric 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 = (1) Stator coreloss ✓

(2) Stator cu loss ✓

Rotor core loss → Neglected due to slip freq. less $\propto (S f)^2 = (0.15 f)^2 \ll$

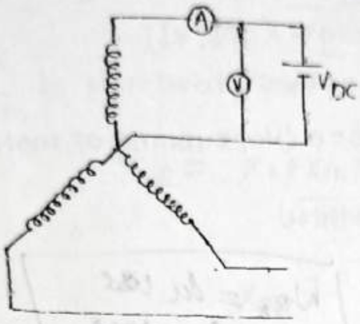
Rotor cu loss → Neglected

(3) 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.

DC test (OR) V-m, A-m method →



V/A Ratio R_{1DC}/phase

$R_{1AC}/ph = \underbrace{1.2-1.6}_{\text{skin effect \& Hot resistance}} R_{1DC}/ph$

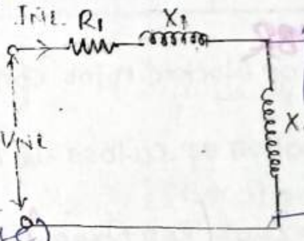
$\left(3I_{NL}^2 R_1 \rightarrow \text{stator Cu loss on } 3\phi\right)$

$W_{NL} - 3I_{NL}^2 R_1$ = constant Loss/ Rotational loss

$W_{NL} = 3I_{NL}^2 R_{NL}$

$\boxed{R_1 \neq R_{NL}}$

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



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

from ckt

$\boxed{X_{NL} = x_1 + X_m}$

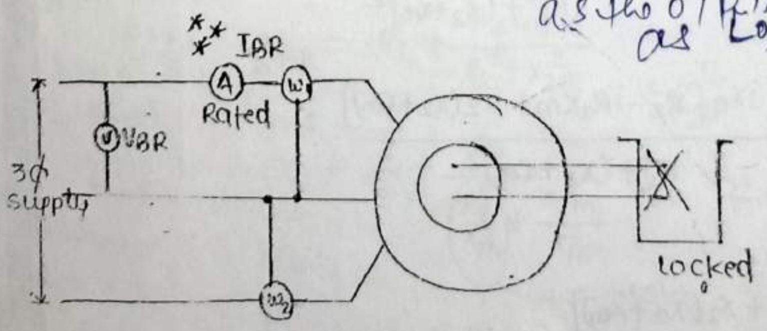
$Z_{NL} = R_1 + j(X_m + X_1)$

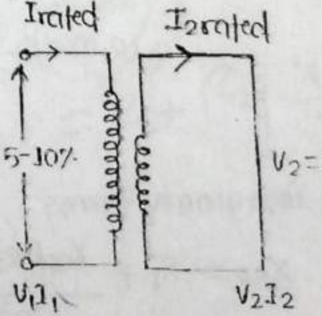
$Z_{NL} = V_{NL}/\sqrt{3} / I_{NL}$ (per phase)

From the meter reading Z_{NL} is calculated, From blocked rotor test X_1 is cal. & the magnetising reactance X_m is determined using the above eq^n.

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

as the O/P is zero I/P is considered as Loss





$W_{BR} = W_1 + W_2$ (algebric sum)

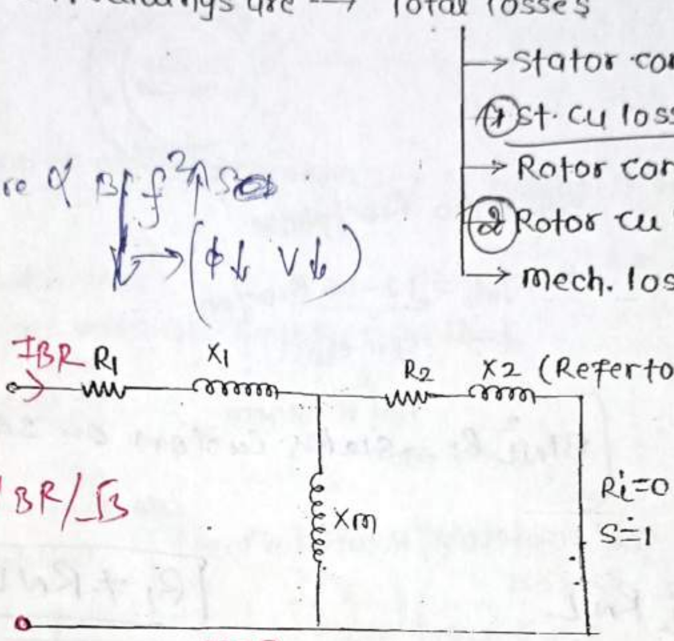
$$P = \frac{2\pi NT}{60} \quad (N=0)$$

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

So W-M readings are ⟶ Total losses
- → Stator core loss ✗ (vol. is low)
- (1) St. Cu loss ✓ (Rated current)
- → Rotor core loss ✗ ($\phi\downarrow, V\downarrow$)
- (2) Rotor Cu loss ✓
- → mech. loss = 0 (Not running of motor)

core $\propto B, f^2 \uparrow$ Sec

$\rightarrow (\phi\downarrow\ V\downarrow)$



W_{Br} = Cu loss (stator + Rotor)

Eq. ckt on blocked rotor condⁿ.

* This tests gives the information of cu loss at rated current condⁿ.

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

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

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

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

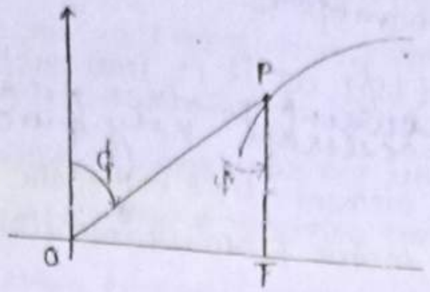
$$= (R_1 + jX_1) + \frac{jX_m [R_2^2 - jR_2X_m + X_2(X_2 + X_m)]}{R_2^2 + (X_2 + X_m)^2}$$

Equating imaginary terms

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

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

Power Factor →



From Δ OPT

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

DATE-08/12/14

IM self starting but draws huge current

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 Xmer 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.

$I_2 = E_2 \propto \phi \downarrow \propto V \downarrow$

$T_{st} \uparrow \propto E_2 I_2 \cos\phi_2 \downarrow$ if we insert the R in rotor

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

Reduced vol. starting

3φ I.M are self starting in nature. Starting methods are used to control starting current only. During starting (S=1) current in rotor is excessively high if Vrated apply across stator. This situation is quite similar to a Xmer apply rated voltage across primary when sec. is S.C. The high rotor currents make the stator to draw high current during starting (7–10) ms. This will produce unacceptable voltage dip in supply line where it is connected. ~~It may also damage~~

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

I.M are popular for construction. S.C. motors will be started with reduced voltage starting which affects starting torque.

Slip ring motors are started by adding rotor resistance which technically best method as it controls starting current while increasing starting torque.

supply.. → (Isc)

* starting current is very high but it is inrush type.
  If the motor starts quickly..
* It is only suitable to small rating motor
  most popular under 2kW segment (1ϕ) as it is low cost.
  due to small rating I_{st} current produce permissible dip.
* There are 2 protection:- they accelerate very quickly.
(1) ~~over load~~ Overload protection using thermal elements like bimetallic strip
(2) No volt Undervol protection to prevent the motor from unintentional start after a power failure.

(2) Stator resistance/Reactors starting →

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

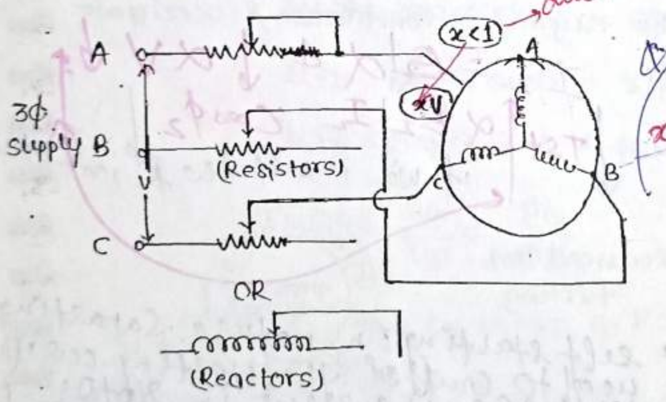
so;

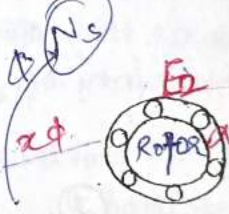
$$I_2 = \frac{E_2}{\underbrace{(R_2 + jX_2)}_{\text{Fixed}}}$$

$E_2 \downarrow$, $I_2 \downarrow$

so, $E_2 \downarrow \longrightarrow \phi \downarrow \longrightarrow V_1 \downarrow$

$x < 1$





E_2 I_2

$x E_2$ $x I_2$

so starting current is reduced by $x I_{st}$

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

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

I_2 (during start) → I_{st}

$T_{st} \propto \frac{I_{st}^2}{S_{st}}$ | $T_F \propto \frac{I_F^2}{S_F}$ → Full load $(S_{st} = 1)$

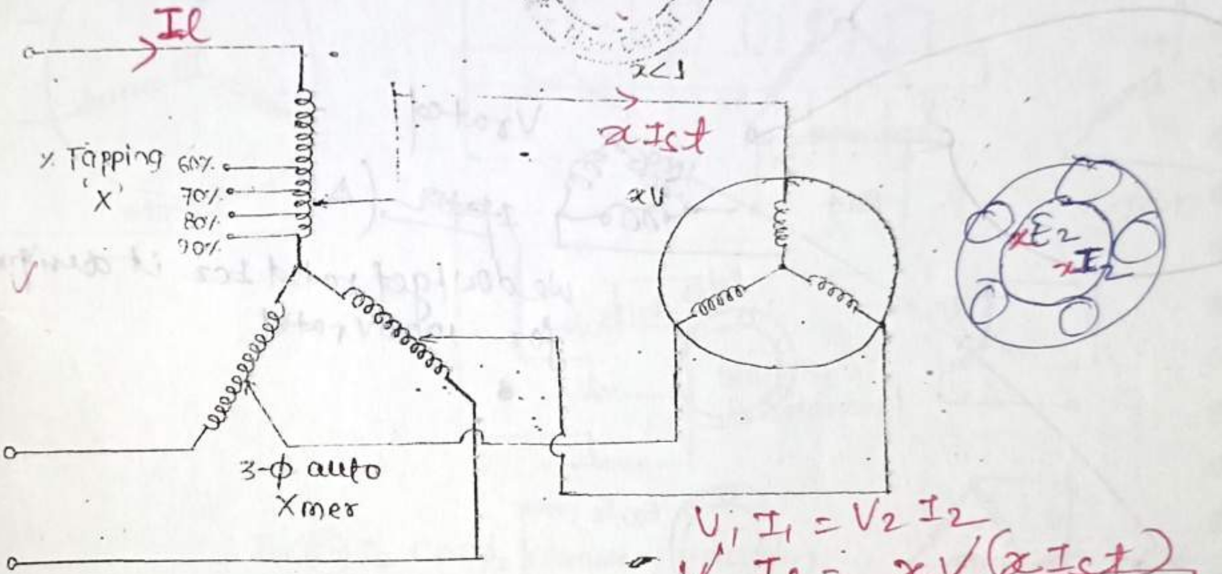
$S_{st} = 1$

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

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

* By adding some external resistance in series with each phase equally & into stator some vol. gets dropped & reduced vol. by xV will appear across stator which correspondingly control the (starting current ↓) by $x I_{st}$ This is generally used up to normal starting as it produce high loss and temp rise.
* Reactors also can used where η is not greatly effected but pf of the motor will be low lagging & starting torque also less. Reactors produce less loss but they affecting pf and Torque development.
* The effect of starting torque is expressed in above relation.

(2) Auto Xmer starting →



$V_1 I_1 = V_2 I_2$

$V I_l = xV(x I_{st})$

$\boxed{I_l = x^2 I_{st}}$

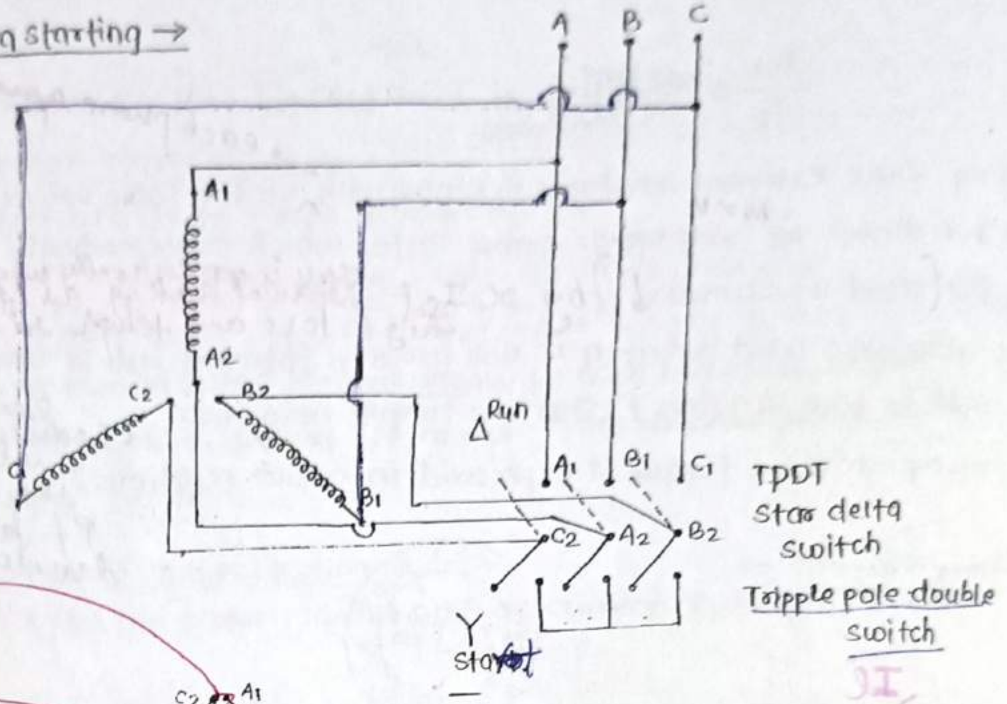
* This is generaly prefered for starting large rating IMs due to its flexibility & high η but expensive method.
* It requires a suitable rating 3φ auto Xmers which has addjustable tapping.
* Depending on % tapping (x<1) → only decreasing I_{st} ↓

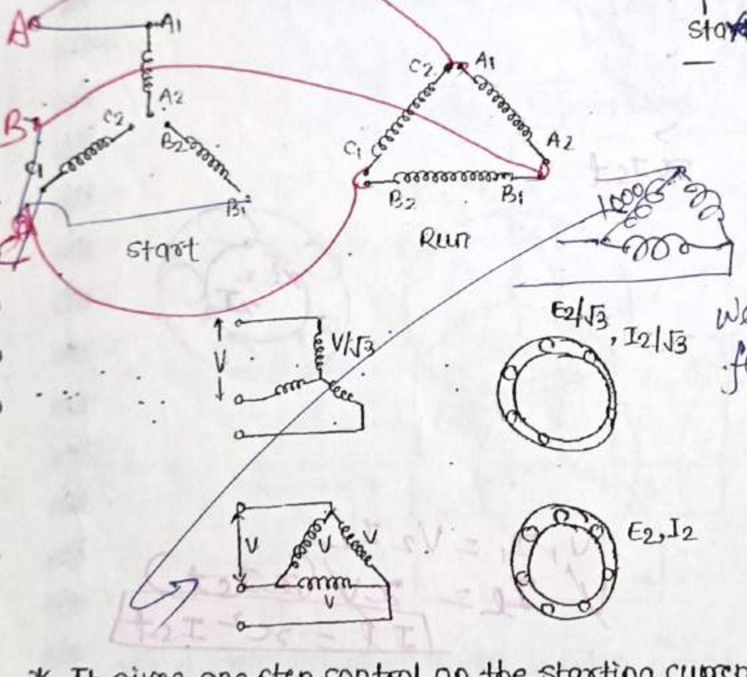
Depanding on tapping starting current control & effect of starting torque expressed

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

The effect of I_{st} is expressed in Tapping

(9.) Star-delta starting →





Vrated
stator (Δ)
we don't get rated bcz it designed for 1000V rated.

* It gives one step control on the starting current.

It is most simple & economic starter with a TPDT switch only. cost is low ∴ used in industrial appli.
But can not preferred motor voltage rating 3.3 KV bcz for such high voltage stator are rating are preferred to be in star.
The stator 3φ wdg is connected as shown.

* It is suitable for motors which are stator designed for Δ under running condⁿ.
It requires simple switch.
1st the stator is connected the λ which results in reduced vol. & current in rotor about 57.7% only ($V_{ph} = V_L/\sqrt{3}$).

Under running the switch should be thrown out to Δ atleast the motor reach 90% of rated speed for normal rated operating condⁿ ($V_L = V_{ph}$).

The motor is started by throughing the switch down (Y) ∴ I_{st} is reduced by ($\frac{I_{st}}{3}$). under running condition the switch is throught into delta then motor operate with full voltage.
It is only one step control. ∴ I_{st} is effective.

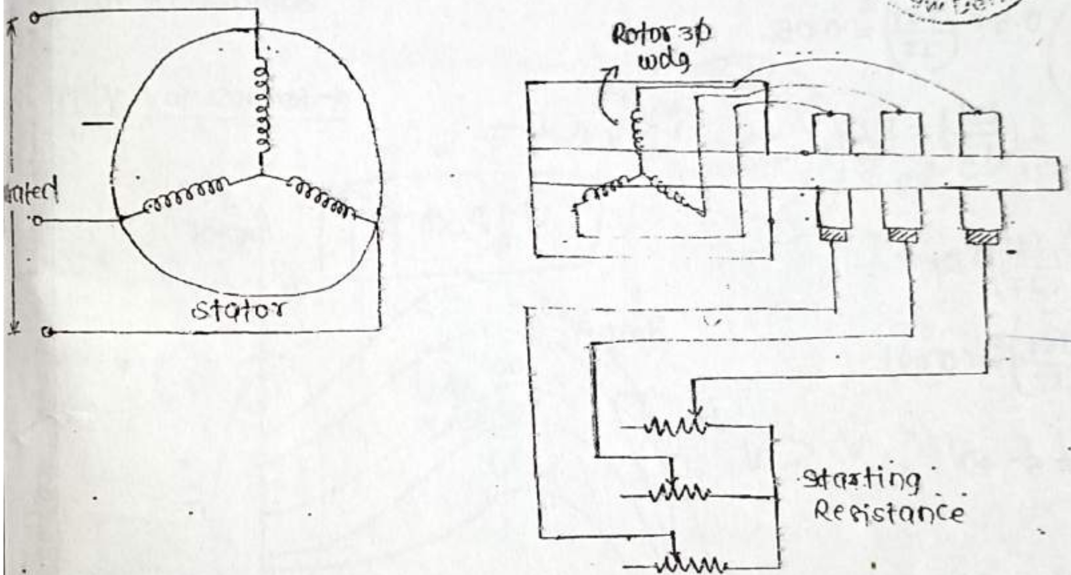
Not suitable for extra high vol. rating greater than 3.3kV because those motors stators are preferabley designed for λ.

$$T_{st} \propto \left(\cancel{\tfrac{1}{\sqrt{3}}} I_{st}\right)^2$$

$$\boxed{\frac{T_{st}}{T_f} = \frac{1}{3}\left(\frac{I_{st}}{I_f}\right)^2 \cdot s_f}$$

The ratio of starting to FL torque is expressed above.

Rotor resistance starting →



$$T \propto E_2 I_2 \cos\phi_2$$ ↑ very (Because of resistance)

E_2 ↓ Rated

This is technacaly best way to start IM. motor design is different from squirrelcage complex & expensive, high maintanance due to brushes and slip rings used only for high loads

It is fundamental method of starting slip ring motors by inserting some resistances into rotor of suitable value through slip rings & brushes. Eg: Tracti...

it increase T_{st} by

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 prefered for high starting torque appln like electric traction.

And also insert

$N = N_s(1-s)$

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

$\boxed{T \propto \frac{s}{R_2}}$

$\boxed{T \propto sV^2}$

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 prefered because of there effective speed control.

Speed control can be done from stator side & rotor side (slip ring)

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.

$T \propto \frac{sV^2}{R_2 f}$

supply vol. control →

$T \propto sE_2^2 \propto sV^2$

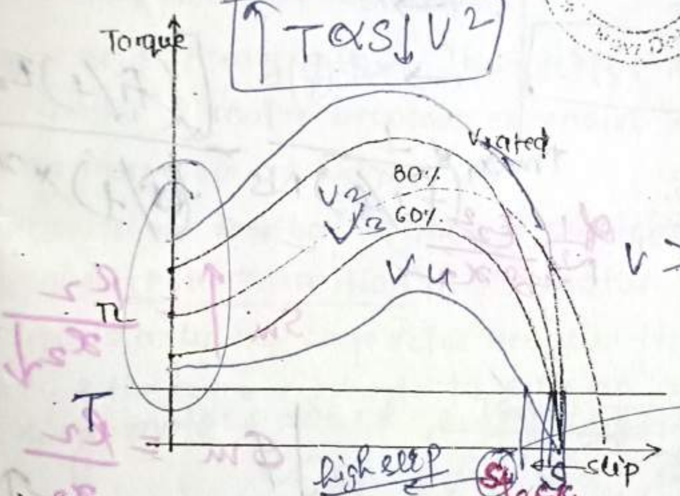
$\boxed{\uparrow T \propto s \downarrow V^2}$

$T_{st} \propto E_2^2$

$T_{max} \propto E_2^2$

$T_f \propto E_2^2$

$\propto V^2$



$V > V_2 > V_3 > V_4$

don't operate there bcz rotor loss depends on slips

It requires an auto Xmer of suitable ratings for getting variable vol. across stator.

If the motor run 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.

* If the voltage is reduced to maintain const Torque, S ↑ and thus speed decrease. However, it doesn't offer a wide range as it affects $\frac{\eta}{}$

The variable voltage and variable f control which makes this method expensive. If the voltage & freq. are varied while keeping flux density constant. In the control region Max. breakdown, pull out

(2) Freq. (V/f) control →

* freq. is varied by keeping V/f ratio constant in order to maintain flux density constant. Torque remains const. for a const. torque condition slip speed remains const.
* Otherwise the stator & rotor core gets deeply saturated & motor draws large magnetising current.
* It requires expensive power electronic converter ckt for variable vol. & freq.

$$\boxed{V_1 = E = 4.44 f N_1 B_m A}$$

$$\boxed{B_m \propto \frac{V}{f}}$$

But generally for T_{max} $E_2 \rightarrow$ const.

$$T_{max} \propto \frac{1}{N_S}\frac{E_2^2}{(2X_2)} = \frac{3\times 60}{2\pi N_S}\left(\frac{E_2^2}{2X_2}\right) \rightarrow \text{variable}$$

$f \rightarrow N_S$	$f \rightarrow E_2$	$f \rightarrow X_2$
$f_1 \rightarrow \boxed{N_{S_1} = \left(\frac{f_1}{f}\right) N_S}$	f_1 $\boxed{E_{2_1} = \left(\frac{f_1}{f}\right) E_2}$	$f_1 \rightarrow X_{2_1} = \left(\frac{f_1}{f}\right) E_2$

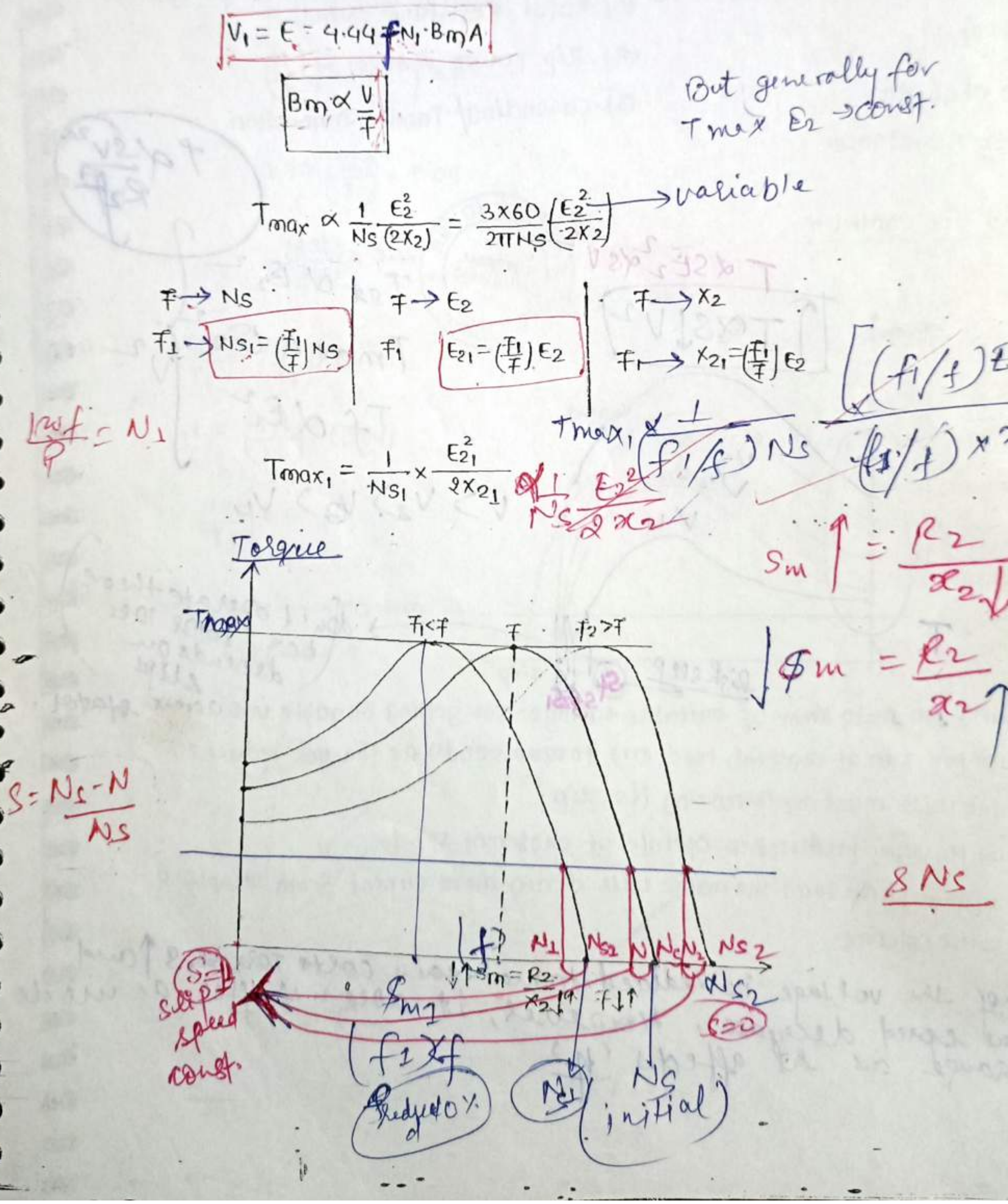
$\frac{120 f}{P} = N_1$

$$T_{max_1} \propto \frac{1}{(f_1/f) N_S} \cdot \frac{\left[(f_1/f) E_2\right]^2}{(f_1/f) \times x_2}$$

$$T_{max_1} = \frac{1}{N_{S_1}} \times \frac{E_{2_1}^2}{2X_{2_1}} \propto \frac{1}{N_S}\frac{E_2^2}{2x_2}$$

$S_m \uparrow = \frac{R_2}{x_2 \downarrow}$

$\downarrow S_m = \frac{R_2}{x_2 \uparrow}$

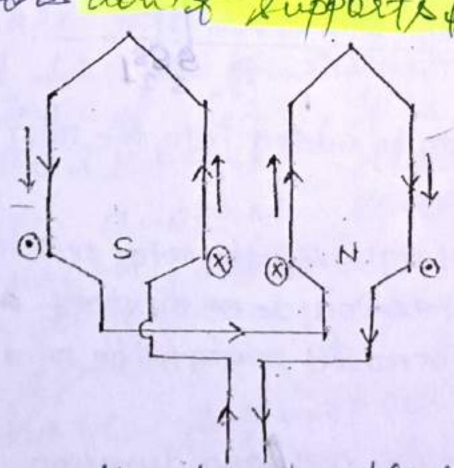


- within the control range the max^m & breakdown torque remain same.
- However it doesn't offer wide range as the voltages also correspondingly reduced.
- method is very expensive.

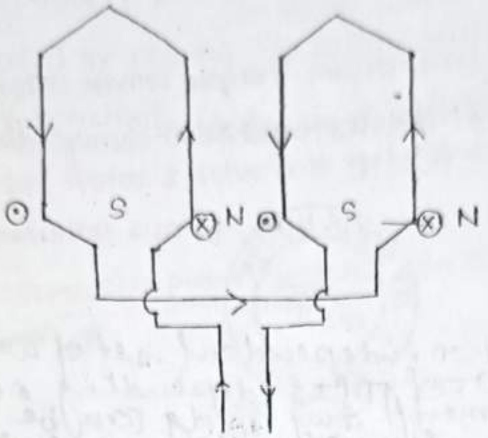
Pole exchanging →
- multiple wdgs
- Concequent pole changing.

(1) It requires two independent set of wdg designed for two different no. of poles depending on speed requirement, any wdg can be connected to supply leaving the other dis connected in star. This will demand large stator slot and size ↑ cost ↑

The stator slot contains 2 independant sets of wdg designed for different no. of pole.
eg:- 2,4 (OR) 4,8.
Depanding on the speed requirement either wdg can be connected to the supply & other one left disconnected.
The wdgs are prefearabely in ⅄. This will increase stator size & overall size of motor & motor becomes expensive & economically not advantages for more sets of wdgs.
Another alternate method is through switching the wdg externally for a concequent pole formation in the stator.
It supports only sq. cage rotor because the poles are formed automaticaly & the rotor responds to any no. of poles on stator. Slip ring motors don't supports this speed control bcz rotors are specifically designed for perticular no. of poles.



By externally changing the connection the poles are formed consequently, it doesn't offer any another step.



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

(4) Stator resistance →

* It is the same method used start the motor.
* It is advantagenous starting than speed control because it will greatly effect the η but prefered because of low cost for small rating.
* Principle is identical to vol. control.
* It requires only resistances to reduce vol. across stator.
  It is not suitable for large rating appl. $\eta \downarrow$ $I^2R \uparrow$

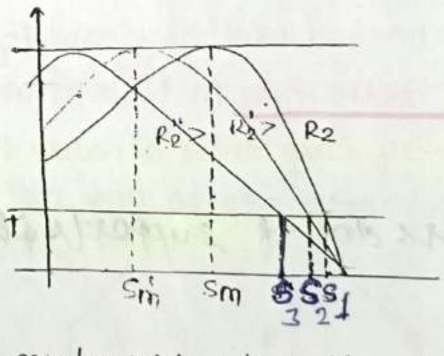
* Rotor side →

(1) Rotor resistance control →

$T \propto \frac{s\uparrow}{R_2\uparrow}$ constant

$R_3 > R_2 > R_1$

$S_3 > S_2 > S_1$



* In slip ring motors external resistance can be added into the rotor ckt under running condn
* If the motor runs at const. load (or) torque as the rotor resistance increases slip increase corrospondingly to maintain torque ~~on~~ constant. and reducing speed
* As the rotor resistance increased with increased current the rotor loss increases gets overheated practicaly.

Therefore it is not suitable for wide range (or) long duration.

* It doesn't offer a wide range and η is also affected.

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:-

1.) Injecting the vol. to add the exsisting rotor vol.

$$\boxed{T} \propto \downarrow S \, E_2^2 \uparrow$$

Constant

speed ↑

$$T \propto \uparrow S \, E_2^2 \downarrow$$

speed ↓

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.

Conceqently speed ↓

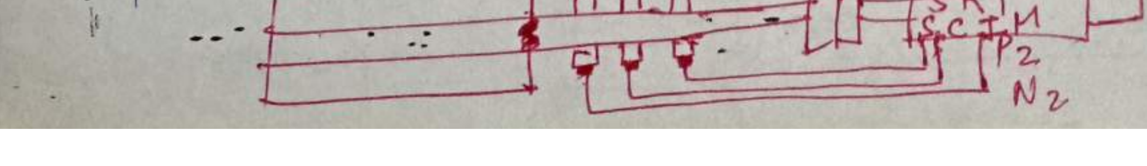
'subsynchronous'

DATE-09/12/14

Cascading/Tandem connection →

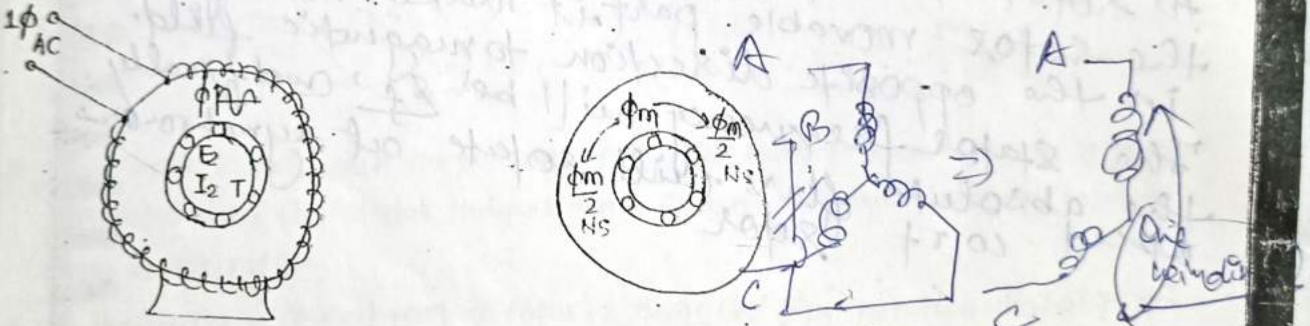
* It requires two I.M.s One essentially slipring type.
* Both are mechanically coupled and electrically connected the second motor is energised through slip ring of first. It is basically acting as a load or external resistance on the main motor to produce another speed depending on the cascading type with individual operation of individual are obtained. ∴ Total two different speed or four speed can be achieved from this method.

If the phase sequences are same in both motors then the connection is cummulatively cascaded. Other wise differentially cascaded. for differential cascading the no of poles in both motors should be different other wise the drive won't operate.



Single phase Ind^n motors

* If the Fuse blows off in 3ϕ motors when running at light weight cond^n it won't stop but continue to run as 1ϕ motor with reduced speed & increased current. Increased slip.
* 1ϕ motor are popular because of there small ratings 1w to 1kw & domastic supply is 1ϕ. 1ϕ I M are quit similar to 3ϕ but —
* There construction is as identical to 3ϕ motors.
* Stator contain 1ϕ wdg for 2, 4, 6 no. of poles generaly. designed for starting method the basic
* Depanding on the starting method adopted stator wdg differs. drawback of 1ϕ I.M. due to non-self starting in nature.
* Rotors are essentialy sq. cage type with ~~skeying~~. skewed slot
* The basic limitation of 1ϕ motors compare to 3ϕ 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 1ϕ supply is applied across stator containing one wdg then a pulsating (or) alternating magnetic field is produced. It induce voltage, current and develops torque.
It links with rotor & results in induced emf as the rotor is essentialy closed it develops current & torque but rotor doesn't start as the net torque in the rotor during starting is becoming zero. If an external force applied the rotor continues to rotate in the dir^n of force & reaches its rated speed. in any direction

This behaviour is analysed acc. to double field revolving theory.

Double Field Revolving Theory:

Acc. to this theory a pulsating magnetic field contains 2 magnetic fields running at synchronous speed (Ns) at equal magnetude ($\phi m/2$) & in opposite dir^n. the rotor reacts to both the fields the forward field produce forward torque and want to make the rotor rotate at (N) and the backward field produce backward torque and ~~want~~ to rotate the motor at ($-N_s$). During starting (s = 1) both the torque are equal and opposite and the net torque is zero. ∴ the motor doesn't start.

Forward:- ϕ_f $\quad \phi m/2 \quad N_s \quad T_f \quad N \quad S_f \Rightarrow S_f = \frac{N_s - N}{N_s} = S$

Backward:- ϕ_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/n 2 extreme boundary cond^n 0 & 2.

at start $S = 1$

$S_f = 1, \quad S_b = 1$

motoring region for 1ϕ IM

$S = (0 \quad 1, \quad 2)$

Running $S = 0$

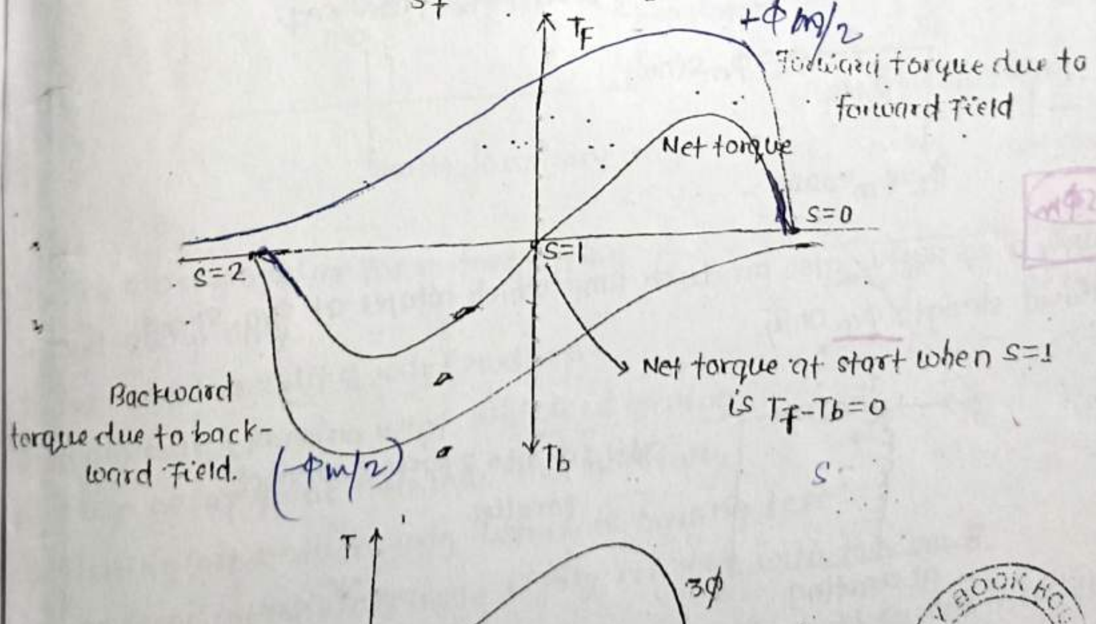
$S_f = 0, \quad S_b = 2$

During starting

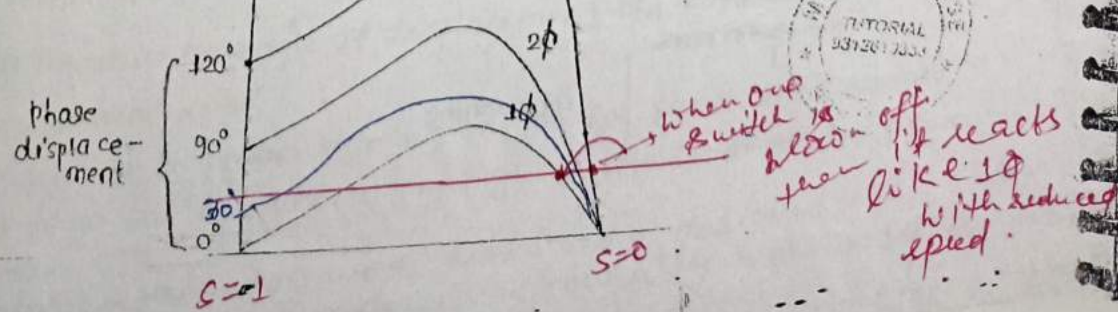
$\boxed{T_f = T_b}$

$$T_g = \frac{60}{2\pi N_s} \times \frac{RCL}{S}$$

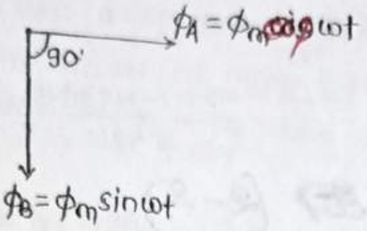
$$T_f \propto \frac{I^2 R_2}{S_f} \; ; \; T_b \propto \frac{I^2 R_2}{S_b}$$



S



* RMF with 2-ϕ supply →

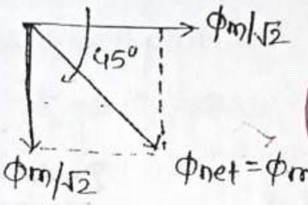


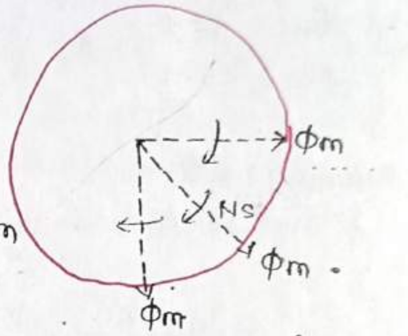
at $\omega t = 0$; $\phi_A = \phi_m$,

$\phi_B = 0$

at $\omega t = 45°$; $\phi_A = \phi_m/\sqrt{2}$

$\phi_B = \phi_m/\sqrt{2}$

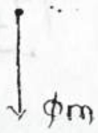




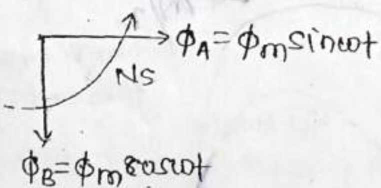
Rotate in cw dirn

at $\omega t = 90°$ → $\phi_A = 0$

$\phi_B = \phi_m$

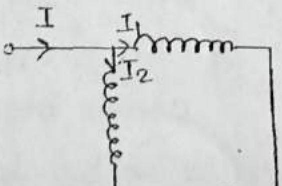


If we want to change the dirn of Field the reverse the phase seq.



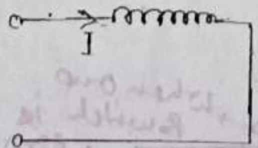
1.5ϕ_m

* Like a 3ϕ supply a 2ϕ supply also produce RMF which rotates at syn-speed but with reduced strength ϕ_m only.



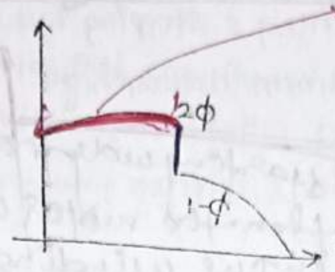
at starting

split 1ϕ into 2 parts & connect parallel.



at running

for Less time if we start the 1ϕ as 2ϕ and then we again convert it in 1ϕ



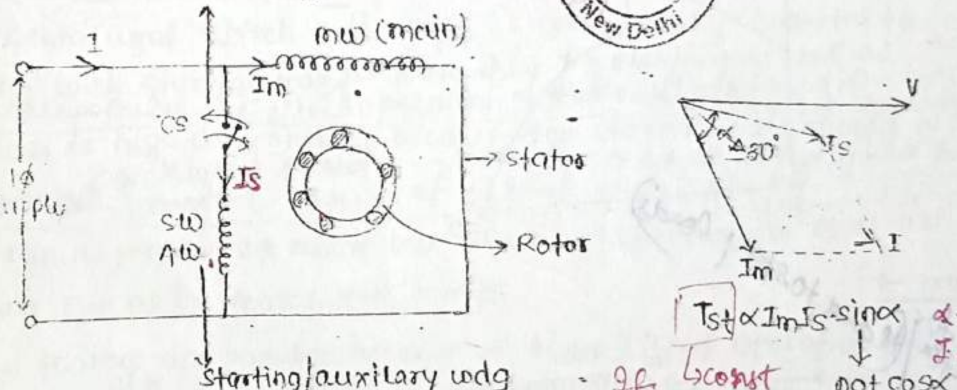
→ split phase

Depending on starting method adopted $1\text{-}\phi$ motors are classified into 2 types:-
These are basically classified -

(1.) Split-phase → Resistance split phase/split phase; → Capacitor start; → Capacitor start & capacitor run/capacitor run motor.

(2.) Split-pole → Shaded pole.

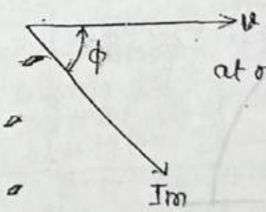
Resistance split-ϕ →



$\boxed{T_{st} \propto I_m I_s \sin\alpha}$ — If const, not $\cos\alpha$

$\alpha \to 0$, I_m, $I_s \uparrow$

$\alpha \to 90°$, $I_s \downarrow$



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) auxillary wdg which is having less no. of turns intentionally made highly resistive with thin cond^{r}.

This will introduce an angle of displacement b/n both current in wdgs Im & Is around $\alpha = 30°$.

It is sufficient to produce starting torque for small rating motors. It is not suitable for high inertia loads abouts 250W around 250W but not suitable for high inertia loads abouts 250W ratings.

(1) Stator contain two wdg main wdg designed for least possible Resistance - Naturally more no of turns - produce more reactance ($\propto N^2$) → Turns

(2) Starting winding intentionally designed for a high resistance with thin wire and less no. of turns with less reactance

Both the wdg are spaced 90° to each other. When 1ϕ supply given to motor starts with partially of motor. The displacement factor b/w current winding is around 90° which is sufficient to start normal load. These are not suitable for high inertia load which demand high starting torque. When the motor reaches 70 to 80% rated speed the centrifugal switch gets open

* This are not suitable for frequent starting & stopping but for continuous operation in its segments α is low current drawn high. (Because of temp. rise in the resistor)

And disconnect starting wdg from the supply. Then the motor continues to run winding only. The operating pf is low.

Appli^n →

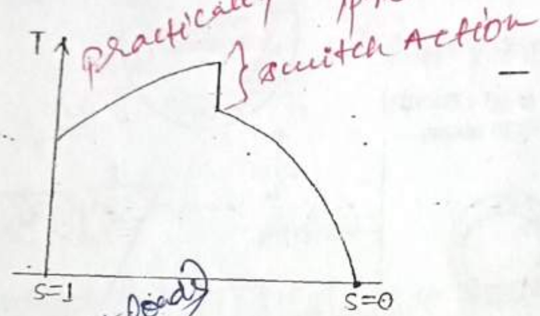
250W

Domestic/ sump motors

Centrifugal motors

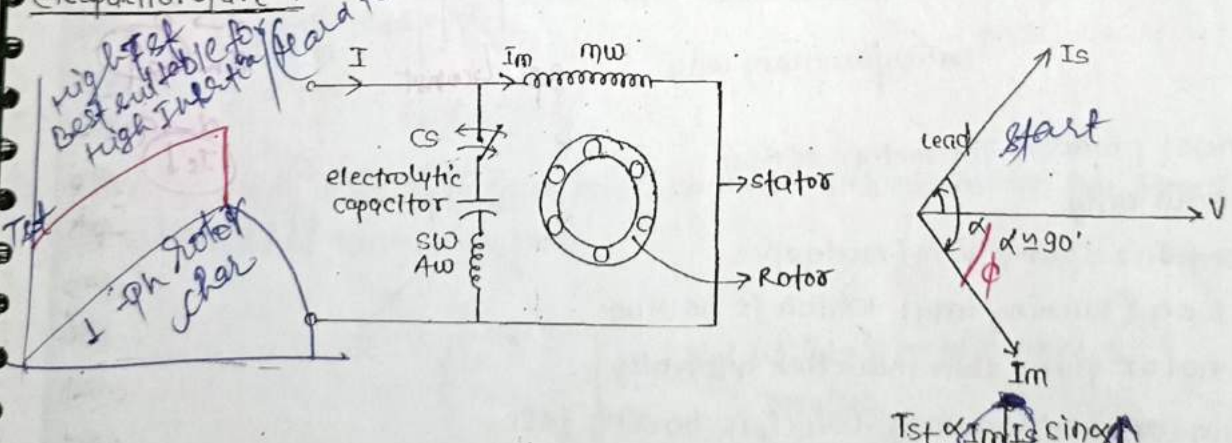
Fans/ blowers.

*Once the motor starts & reach 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 →

hard to start load
high Tst
Best suitable for high Inertia



$T_{st} \propto I_m I_s \sin\alpha$ ↑

* In order to create a Large ϕ diff b/n Im & Is (α≃90°) a capacitor is included in series with starting wdg through a switch.

* As α is high the starting current drawn is comparitively low.

* It has high starting torque & used for high inertia load (hard to start) of 245d-750W.

fans / Blower, Refrigerator some air conditioning.

* As the motor reaches near rated value of speed the centrifugal switch will gets

Office / dairy Machinery

This motor is quit similar to resistance split phase but the difference lies b/w which provides Tst ↑ best suit for high inertia load. And frequent start and stop. When the motor reaches 70-80% rated speed the

The starting current drawn as

opened & ~~this~~ disconnects both capacitor & starting wdg.

Under running condn it is quite similar resistance split phase starting.

This is prefered for frequent startings & stopping load specially.

plications →

250–750W

Fans/ blowers

sump pumps/ centrifugal pump

refrigerator units, AC, washing m/c, grinders etc.

$\boxed{\text{Electrolytic capacitor} \rightarrow \text{cost effective}}$

Capacitor start & capacitor Run →

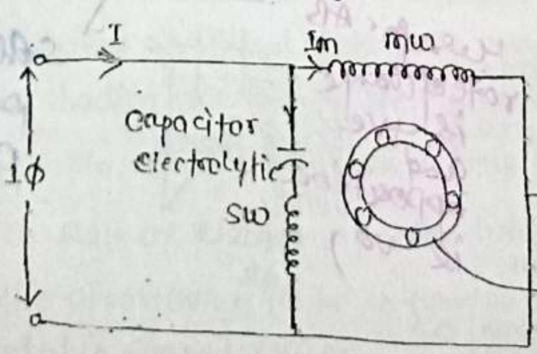
There is no centrifugal switch & the capa. is contineoully connected to supply along with starting wdg permanently i.e. starting as well as running.

These are popular for silent operation. Intentionally designed for balanced 2φ condition, i.e. there is no backward field by (high pf). NO present backward speed, which motor runs at silent.

The design cost is high comparitively because the starting wdg should efficient.

It starts & run as perfect 2φ motor but capacitor start motor start as 2φ motor but run as 1φ motor. with low PF.

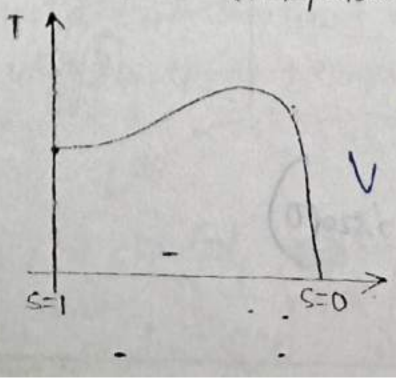
Capacitor run motors are popular because of there silent operation with smooth T-S c/s & good starting as well as running torques.

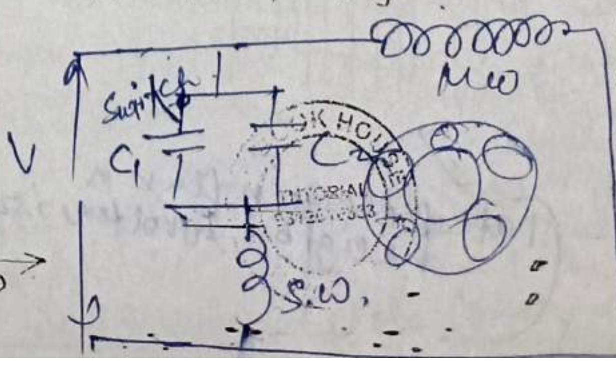


It is also called as permanent split phase motor as the capacitor is permanently. In order to achieve better optimal and running condition. True value of double valued Cap. start run motor.

Appli^n →

All ceiling fans, AC & motors in (fans/blowers/pumps) of ratings 750–1000W





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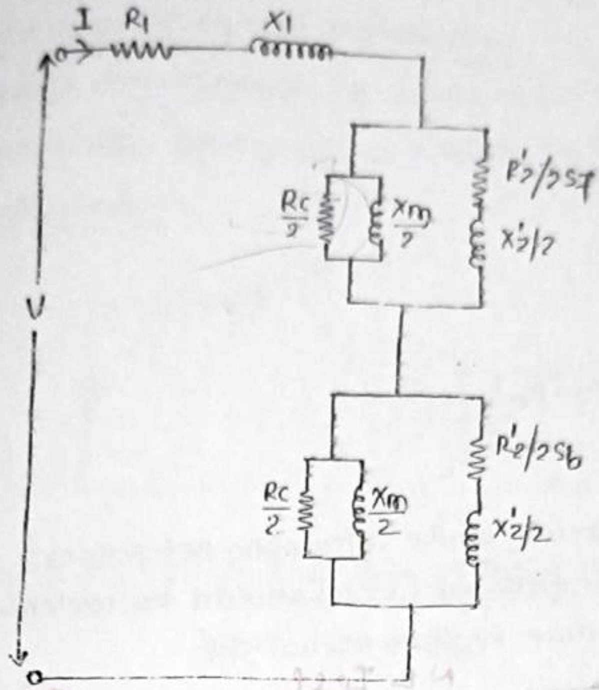
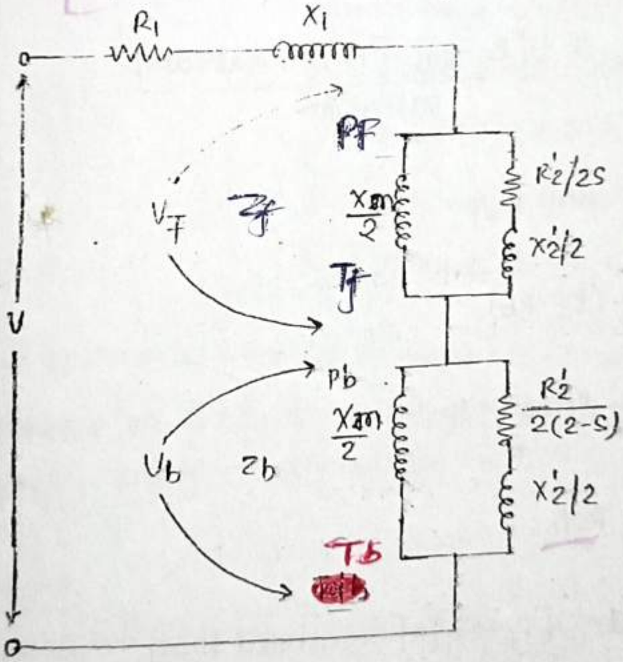
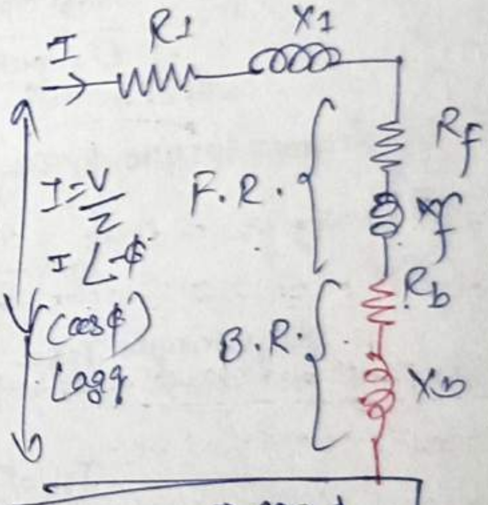




$\Rightarrow$



$$\boxed{P_{i/p} = VI\cos\phi}$$

* $Z_1 = R_1 + jX_1$
* $Z_f = j\frac{X_m}{2} \,||\, \frac{R_2'}{2S} + j\frac{X_2'}{2}$

$Z_f = R_f + jX_f$

* $Z_b = j\frac{X_m}{2} \,||\, \frac{R_2'}{2(2-S)} + j\frac{X_2'}{S}$

$Z_b = R_b + jX_b$

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$$Z_{eq} = Z_1 + Z_f + Z_b$$

$$I = \frac{V}{Z_{eq}}$$

$I\angle\phi \quad \therefore PF = \cos\phi$ (Lagg)

Power i/p to forward rotor $\rightarrow I^2R_f = P_f$

Power i/p to backward rotor $\rightarrow I^2R_b = P_b$

Net P i/p to rotor (OR) Air gap power $= P_f - P_b$

Power o/p of rotor $= (1-S)(P_f - P_b)$

* For accuracy in the analysis from eq. circuit while calculating net power cal^n iron, friction & windage (const. or rotational losses) should be included while eliminating shunt branch resistance R_c from actual ckt

NL Test

Net/shaft/motor o/p $= (1-S)\cdot[P_f - P_b] - [$Rotational loss / Constant loss$]$

$$\eta = \frac{\text{Shaft o/p}}{\text{E. Input}} = \frac{(1-S)[P_f - P_b] - [\text{Rotational loss}]}{VI\cdot\cos\phi}$$

$$\text{Gross torque } T_g = \frac{60}{2\pi N_S}\,\text{Rot. P i/p}$$

$$T_g = \frac{60}{2\pi N_S}(P_f - P_b)$$

$$\text{Shaft torque } T_{sh} = \frac{60}{2\pi N}\,\text{shaft o/p}$$

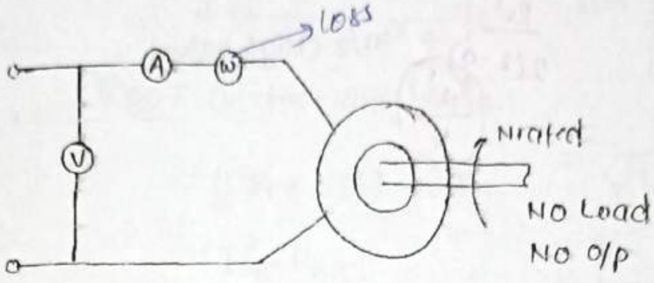
$$T_{sh} = \frac{60}{2\pi N} P_{sh}$$

$$\text{Shaft o/p} = P_{sh} = (1-S)[P_f - P_b] - [\text{Rotational loss}]$$

* 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. It requires NL, B.R. DC Test parameters.

(1) No Load test →



* Apply rated vol. across the given 1ϕ IM & allow it to run freely on NL. As the motor is on no load its I/P is considered as loss

$$I_p = \cancel{O/p} + loss(total)$$

$$I_p = loss$$

- → stator cu loss
- → stator core loss
- → Rotor cu loss × (current is low)
- → Rotor core loss × (sf is small) & f is ↓ due ru
- → 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.

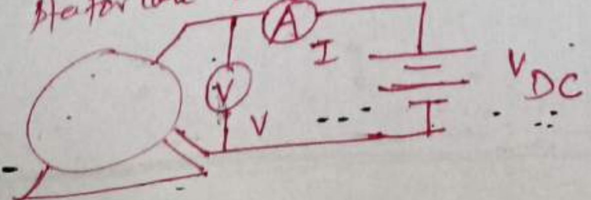
(2) DC test →

* 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. $\boxed{R_{1AC} = 1.5 R_{DC}}$

$$W_0 - I_0^2 R_1 = \text{Rotational loss (Iron, Friction \& windage)}$$

* From stator resistance value rotational loss is calculated.

stator core and mech



$$\frac{V_{NL}}{I_{NL}} = Z_{NL} \quad \therefore X_{NL} = \sqrt{Z_{NL}^2 - R_{NL}^2}$$

$$\boxed{I_{NL}^2 R_{NL} = W_{NL}} \quad \therefore \boxed{R_{NL} = \frac{W_{NL}}{I_{NL}^2}}$$

from ckt

$$\boxed{X_{NL} = X_1 + \frac{X_m}{2} + \frac{X_2'}{2}}$$

$$\boxed{V_{AB} = I_0 \times \left(\frac{X_m}{2}\right) \quad \therefore X_m = \frac{2V_{AB}}{I_0}}$$

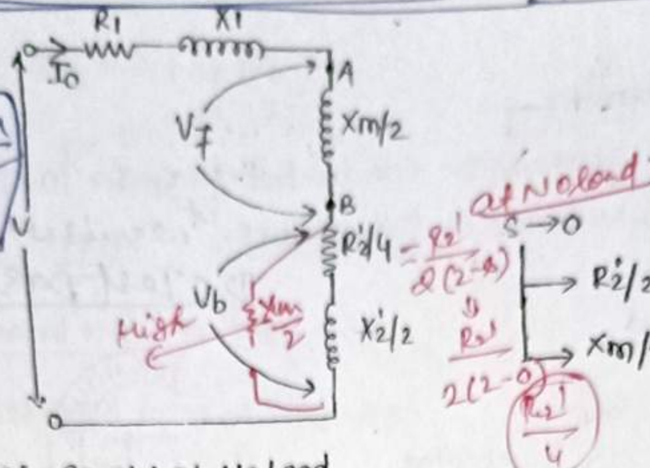
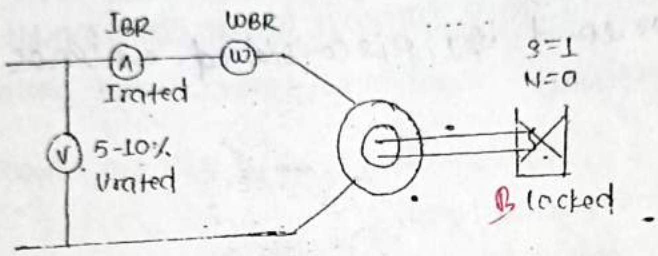


Fig:- Eq. ckt at No Load

(3) Blocked Rotor test →



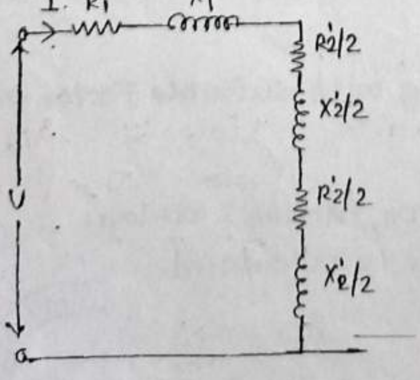
* Rotor is initialy blocked & small vol. is applied across stator through a suitable auto xmer while insuring rated current drawn by motor. as there is no O/P the I/P is considered as loss

small voltage applied across it

Total loss →
- → stator cu loss
- → stator core loss × (V is least)
- → Rotor cu loss
- → Rotor core loss × (V is least)
- → Mech. loss × (N=0)

wattmeter Reading → only cu loss

* In this test wattmeter reading represent both stator & rotor cu losses.



$X_m/2 \uparrow\uparrow$ than $R_2'/2$ $\therefore$ $X_m/2$ neg

S=1

Fig:- Eq. ckt on blocked rotor cond?