MACHINES-1

NOTES

(Modified)

M/C'S – II

TUE.
29/07/08.

REF'S:

Electromagnetics – kraus & karver

for Theory:

Electrical Machines – Nagrath & kothari

Electrical Machinary – P.S. Bhimbra

Performance & Design of A.C. M/c's – M.G. Say (C.B.S.)

for Problems:

Problems in Electrical Machinary – Parker smith

Electrical Technology vol-II – B.L. Theraja

Electrical M/c's – Gupta. J.B.

TRANSFORMERS

features:

1. Constant frequency device.
2. Constant power device.
3. Electromagnetic energy conversion device (Internal conversion only)
4. Not an energy conversion device (If we consider overall T/f).
5. T/f is basically a coupled device. (Electrically isolated but Magnetically coupled).
6. T/f is a phase shifting device (offers 180° phase shift from i/p to o/p quantity).
7. Singly excited device
8. Negative feedback circuit (or) control circuit.
9. T/f is a 4 terminal, 2 port n/w (ABCD parameters are used to relate i/p & o/p quantities)

Working principle:-

faraday's law of Electro magnetic induction.

Basic requirements

(1). Magnetic field

(2). set of conductors

(3). Relative space variation (or) Relative time variation.

* Relative space variation: → dynamically induced emf (or) Motionally " "

Magnetic field → Time invarient

set of conductors → being moved

↓ Eg: DC Generator

* Relative time variation: → statically induced emf

Magnetic field → Time varient

set of conductors → stationary

↓ Eg: T/f

DI: emf :

This is the emf induced in set of conductors which are being moved inside a steady or time invarient magnetic field.

The nature of emf induced in DC Generator is DI. emf.

SI. emf :

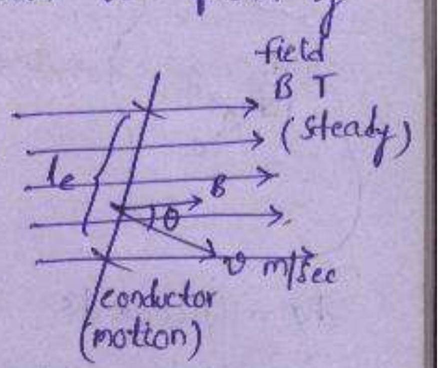
This is the emf induced in set of stationary conductors which are placed in time varying magnetic field

The nature of emf induced in T/f → SI. emf.

* The magnitude of DI emf can be found by flux cutting rule.

$E_d = B l_e v \sin\theta \rightarrow E_d = (\bar{v}\times\bar{B})\, l_e$

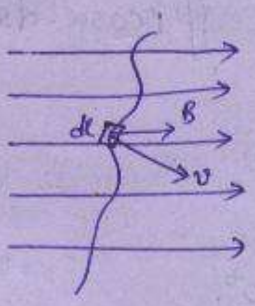
$\theta \rightarrow \angle$ b/w B & v



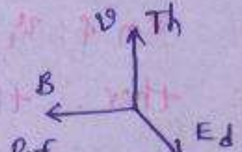
$dE_d = Bv\sin\theta\, dl$

$\rightarrow E_d = \int_{line} Bv\sin\theta \cdot dl$

$$\boxed{E_d = \int_{line} (\bar{v}\times\bar{B})\, dl}$$



The direction of DI emf can be found by applying fleming's Right Hand Rule.

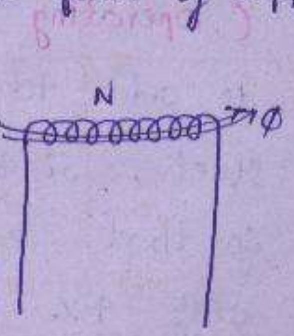


Acc. to F.R.H.R the dire. of DI emf is always ⊥er to the plane containing velocity & flux density vectors.

* The magnitude of SI emf can be found by applying faraday's 2nd law.

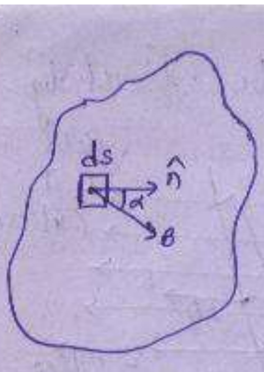
$N\phi$ = flux linkages.

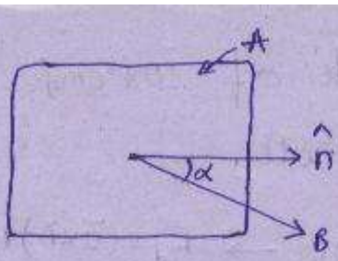
E_s = Rate of change of flux linkages.



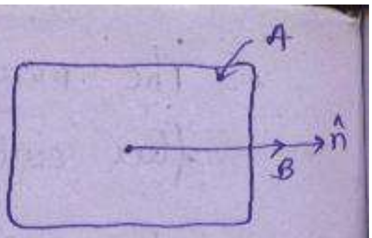
$$E_s = \frac{d}{dt}(N\phi)$$

$$= \underset{\substack{\downarrow \\ \text{due to} \\ \text{Lentz's law}}}{(-)}\left(N\cdot\frac{d\phi}{dt}\right) \rightarrow \text{due to faraday's 2nd law.}$$





$\phi = B\cos\alpha\, A$



$\phi = B.A$

$d\phi = B\cos\alpha\, ds$ $\qquad \vec{ds} = ds.\hat{n}$

$$\Rightarrow \phi = \iint B\cos\alpha.ds \quad , \quad E_s = -N.\frac{d}{dt}\left(\iint B\cos\alpha.ds\right)$$

$$= -N.\iint \frac{\partial B}{\partial t}\cos\alpha.ds$$

$$\boxed{E_s = -N.\iint \frac{\partial \vec{B}}{\partial t}.\vec{ds}}$$

WED. 30/07/08.

* Mutual induced emf also opposes the changes in applied volt. to satisfy lenz's law, so that emf & v_1 are also displaced by 180 from one another. that means in coupled ckts, self & mutual induced emf's are displaced by 0 apart and are in phase with one another.

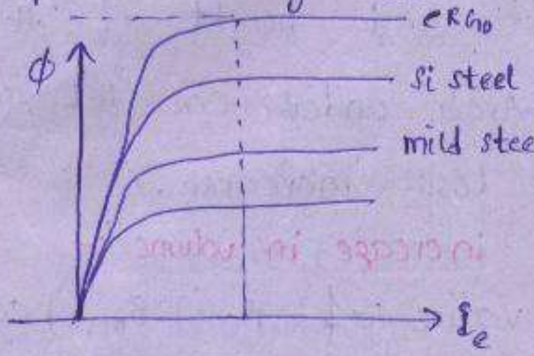
* T/f operated on mutual induct~~ance~~ion principle. (operating principle).

* In order to reducing the conductivity of the steel, Si content is added to the steel core. so that eddy currents are reduced. only 4% silica content is added to the steel, above this limit (4%), the brittleness of core increases then the mechanical strength of the core reduced.

Laminations of core also reduces conductivity of the core so that eddy currents are reduced.

* Si- steel has Crystaline structure.

* Magnetic leakage flux is the part of the load comp. of flux, its nomally completes path through air.



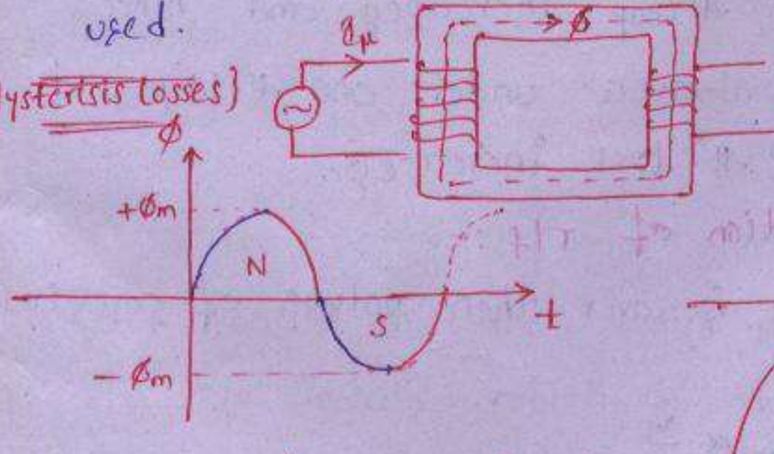
$B_{(Si\ steel)} = 1$ to $1.2\,T$

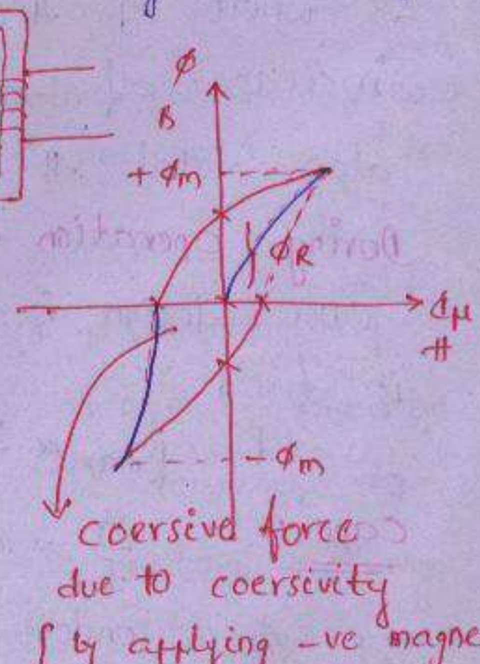
$B_{(CRGo)} = 1.2$ to $1.6\,T$

To maintain const. flux with superior 'B', the area of cs should be reduced $\phi = BA$

Rotating m/c is discontinuous (flux) magnetic ckt (air gap is present) so only Si steel is used.

[Hysteresis losses]





Residual flux (ϕ_R) is due to Retentivity property.

Coersive force due to coersivity [by applying -ve magnetising force to bring the (+ve residual flux) back to zero].

Area under one Hysterisis loop = $\eta B_{max}^{x} \cdot v$

no. of H. Loops = f.

$\Rightarrow \omega_h = \eta \cdot B_{max}^{x} f v$.

Effect of dimensions of Loop :-

→ If B_{max} is increase and v is const :

[By keeping volume of the core const, the peak value of B is increased then width of H.L. remains const. and height of H.L increases therefore Area under one H.L and hence total Hysterisis loss increases.

→ If B_{max} is const. and increase in volume :-

By keeping peak value of B [B_{max}) const. If the volume of core is increased during design the coersive force required increases ∴ width of H. Loop increases and hence increase of area under one H. Loop and also total H. loss increases.

During Operation of T/f :-

Once design is over then volume of core (v) is fixed.

and $B_{max} \propto \frac{V_1}{f}$.

Case(1) :- $\frac{V_1}{f}$ = const, B_{max} = const.

$\Rightarrow$ ∴ Area under one H. loop = const.

$\Rightarrow \omega_h \propto f$

Case(2) :- $\frac{V_1}{f} \neq$ const, $B_{max} \neq$ const. loop

Area under one H. Loop ≠ const. [vertically changes]

$$\Rightarrow \omega_h \propto \left(\frac{V_1}{f}\right)^x \cdot f$$

$$\propto V_1^x \cdot f^{1-x}$$

$$\Rightarrow \omega_h \propto v_1^{1.6} f^{-0.6} \quad ; \text{ if } x = 1.6$$

$$\Rightarrow \omega_h \propto \frac{v_1^{1.6}}{f^{0.6}}.$$

Eddy current losses :-

The main reason behind the production of eddy current losses is due to production of induced emf in the T/f core because of its finite conductivity.

→ Eddy current losses are reduced by the following techniques :-

(1). By adding si content to T/f core.
(2). By Laminating the T/f core.

Rating of T/f :-

Apparent power → VI
KVA

Active power → VI cosϕ
(True power) ↓ kW.

The rating of any electrical m/c is fixed based on the temp. dissipation capability of the m/c means which is designed based on temp. rise of the m/c. The temp. rise in any m/c due to losses. So rating of any electrical m/c is indirectly determine by the losses in that m/c.

In case of T/f, iron loss depends on volt. rating, cu loss depends on current rating and so total losses depends on product of V & I rating and ind. of load pf.

∴ T/f's are always specified with apparent power rather than active power.

At manufacturing stage of T/f, the manufacturer does't know the pf of the load at which T/f is going to be operated. So he'll fix only V & I ratings and he won't take account of load pf b'coz it is fluctuating one. So rating fixed by manufacturer is only in apparent powers.

can supply
when load pf is unity → 100 kVA
0.8 pf → 100 × 0.8

eg: 100 kVA T/f
↑
It is load side rating but not source side.

The kVA rating mentioned on name plate indicates load side kVA, if NL current of T/f is considered.

If NL current of T/f is neglected then source side kVA = load side kVA.

Efficiency :-

$$\eta = \frac{\text{o/p power}}{\text{o/p power} + \text{losses in T/f}}$$

$$\eta_{fl} = \frac{\text{o/p power}}{\text{o/p power} + \text{fl cu loss} + \text{iron loss}}$$

↑ s/c test ↑ o/c test

$$\eta_{fl} = \frac{(E_2 I_2)\cos\phi_2}{(E_2 I_2)\cos\phi_2 + I_2^2 R_{02} + W_i}$$

$$\eta_{x \text{ of } fl} = \frac{x(\overset{\xrightarrow{\text{from Name Plate details}}}{E_2 I_2}) \cdot \cos\phi_2}{x(E_2 I_2)\cos\phi_2 + x^2(I_2^2 R_{02}) + W_i}$$

(predetermination process.)

Conditions for Maximum Efficiency :-

(i). $\left.\frac{d\eta}{d\,xI_2}\right|_{\phi_2 = \text{const}} = 0$ (pf const) (for a given load pf)

(ii). $\left.\frac{d\eta}{d\phi_2}\right|_{xI_2 = \text{const}} = 0$.

$\Rightarrow x^2(I_2^2 R_{02}) = W_i$

$\rightarrow$ cu loss$_{x \text{ of } fl}$ = iron loss

Eg: fl cu loss = 400W

iron loss = 500W.

Then total losses corr. to $\eta_{max} = 500 + 500$

$= 1000\ W.$

$= \underline{2W_i}$

Fraction 'x' of fl corr. to

$\eta_{max} = \sqrt{\frac{\text{Iron loss}}{\text{fl cu loss}}}$ $\quad (\because x^2(\text{fl cu loss}) = \text{iron loss}$

By suitably adjusting ratio b/w iron loss & fl cu loss during design the max η can be achieved at any desired fraction of x of fl.

for getting η_{max} at fl ⇒ Iron loss = fl cu loss

" at ½ fl →

" at ¼ fl →

" at 70 to 75% of fl →

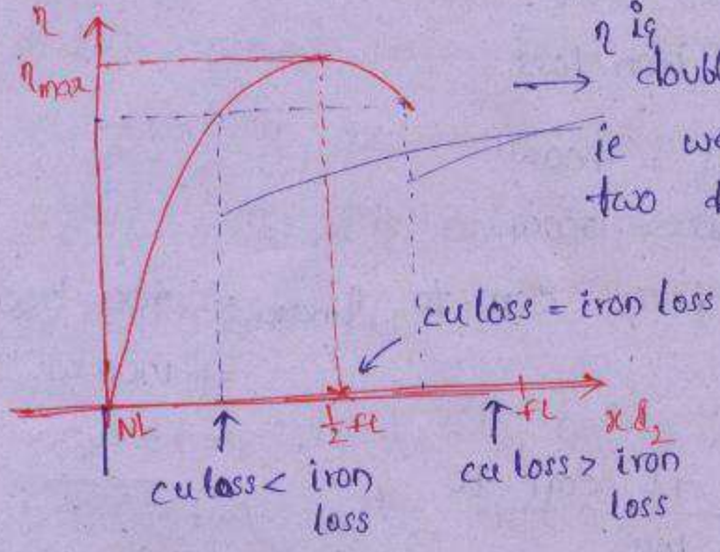
$x I_2 = I_{2m}$ $\qquad x^2 (I_2^2 R_{02}) = W_i$.

$\Rightarrow I_{2m}^2 R_{02} = W_i$

$\Rightarrow I_{2m} = \sqrt{\frac{W_i}{R_{02}}}$ → load current corr. to η_{max}.

$$\left(\frac{E_2}{1000} \cdot I_{2m} \right) = \frac{E_2 I_2}{1000} \cdot \sqrt{\frac{W_i}{I_2^2 R_{02}}}$$

$\Rightarrow$ KVA corr. to η_{max} = fl KVA × $\sqrt{\frac{\text{Iron losses}}{\text{fl cu losses}}}$



→ η is doubled valued fun. ie we get same η for two diff. load currents.

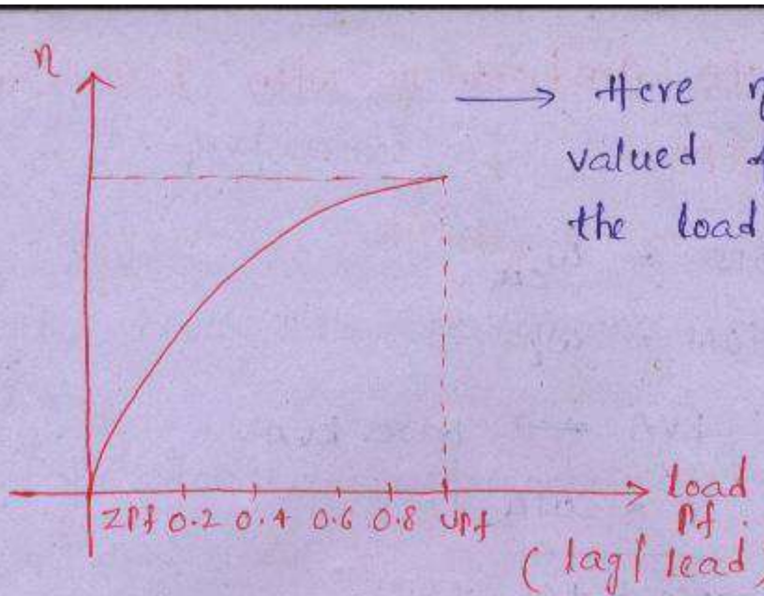
(ii). $\left. \frac{d\eta}{d\phi_2} \right|_{xI_2 = \text{const}} = 0$

$\Rightarrow \phi_2 = 0$

$\Rightarrow \cos\phi_2 = 1.$

for a given load const, if the load pf is varying then η is max exactly at unity pf.

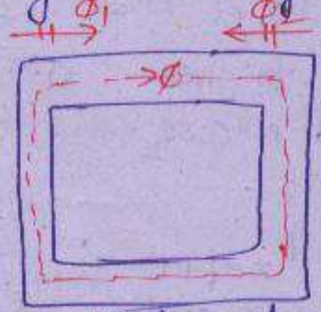
As theoretically η is ind. of type of load pf (ie leading or lagging) but depends on the magnitude of the load pf. (ie 0.8 or 0.6 ..)



$(x S_2 = \text{const.})$

→ Here η is a single valued fun. w.r.t mag. of the load pf.

η of T/f increases with increasing load pf and it becomes max exactly at unity pf.



* Theoritically η at $\overset{'x'}{0.8}$ lead is equal to the η at $\overset{'x'}{0.8}$ lag load pf.

* But practically η at lagging pf is not equal to the leading pf's of the load.

⟹ At lagging pf of loads the resultant flux in the T/f core slightly less than NL flux and at leading pf of loads the resultant flux in the T/f core slightly more than NL flux. That's why the iron loss in the T/f core are slightly less with lagging when compared to leading pf's. Because of this the η of the T/f at lagging pf is slightly more than the η of T/f at leading pf's..

⇒ procedure to find out η when losses are given in pu :-

pu fl cu loss = ω_{cu}

pu Iron loss = ω_i

choose fl KVA ⟹ base KVA.

$$\eta_{fl} = \frac{1 \times \cos\phi_2}{1\times\cos\phi_2 + \omega_{cu} + \omega_i}$$

corr. to $\cos\phi_2$

$$\eta_{1/2\,fl} = \frac{0.5 \times \cos\phi_2}{0.5\times\cos\phi_2 + \frac{1}{4}\cdot\omega_{cu} + \omega_i}$$

corr. to given load pf $\cos\phi_2$

$$\eta_{x\,of\,fl} = \frac{x \times \cos\phi_2}{x\cos\phi_2 + x^2\omega_{cu} + \omega_i}$$

for given $\cos\phi_2$

Eg: % R = 2%, % X = 6% & % Iron loss = 1%.

(i). η_{fl} upf = ? (ii). $\eta_{1/2\,fl}$ upf = ?

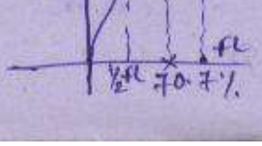
% R = % fl cu loss

fl KVA ⟹ Base KVA.

$$\eta_{fl\,upf} = \frac{1\times1}{1\times1 + 0.02 + 0.01} = \frac{1}{1.03}\times100$$

$$= 97.08\,\%$$

$$\eta_{1/2\,fl\,upf} = \frac{0.5\times1}{0.5\times1 + \frac{1}{4}\times0.02 + 0.01} = 97.08\,\%$$



power η or commercial η → To know the performance of power T/f.

Energy η or All day η or operational η to know the performance of Distribution T/f.

⇒ Operational differences b/w power & distr. T/f's :

Power T/f	Distr. T/f
→ used in transmission n/w	→ used in distr. n/w.
→ large HV T/f. > 33 kV	→ Below 33 kV, small LV T/f.
→ > 1 MVA	→ ≤ 1 MVA
→ Not directly connected to consumers.	→ directly connected to consumers.
→ load fluctuations are min.	→ load fluctuations are very high.
→ wdgs are loaded fully through out 24 hr's	→ wdgs are loaded based on load cycle of consumer.
→ Iron losses takes place fully through out 24 hr's	→ Iron losses → fully through out 24 hr's [∵ primaries are always excited].
→ cu losses → fully through out 24 hrs	→ cu loss → based on load cycle [based on loads on secondaries].
→ Design criteria: cu loss should be kept min.	→ we have to design these T/f's such that iron losses should be kept min. [for improved performance].

→ Designed to operate with high B_m (1.6 to 1.8 T).	→ In order to reduce iron loss, $W_i \propto B_m^2$, B_m should be kept small [1 to 1.2 T] → To get required emf eg 11kv/440v ↓ iron losses $\propto B_{max}^2$ ↓ $\underset{const}{E_1} \propto \underset{const}{\phi_m} \propto \downarrow B_m A \uparrow$

$$\text{Specific weight} = \frac{\overrightarrow{\text{weight}} \text{ of T/f}}{\text{kVA rating}}$$

→ specific weight is less.	→ specific weight is more.
→ size / kVA is less	→ size / kVA is more
→ $\frac{\text{Iron weight}}{\text{cu weight}}$ is less	→ $\frac{\text{Iron weight}}{\text{cu weight}}$ is more
→ Avg. load → FL or nearer to FL.	→ Avg. load → 70% to 75% of FL.
→ Designed to give η_{max} at Avg. load, ie η_{max} → FL (or) nearer to FL. ⇒ FL cu loss ≃ iron losses	→ Designed to give η_{max}, at avg. load ie η_{max} → 70 to 75% of FL. ⇒ FL cu loss ≃ 2× iron losses
→ operation of T/F ind. of time so performance basis is power basis → power η.	→ Operation of T/F also depends on time & power basis. ⇒ energy basis → energy η (or) all day η (or) operational η

$$\text{All day } \eta = \left.\frac{\text{o/p energy in kWH}}{\text{i/p energy in kWH}}\right|_{24\text{ hrs}}$$

$$= \left.\frac{\text{o/p in kWH}}{\text{o/p in kWH} + \text{losses in kWH}}\right|_{\text{during } 24\text{ hrs}}$$

Load cycle of consumer is :

500 kVA, $Cu\,loss_{fl} = 400$
Iron loss = 200 ω

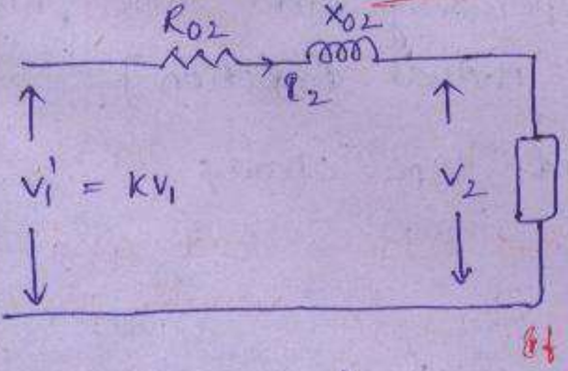
				Cu loss	Iron loss
upf	6 AM – 6 PM	½ fl	250 kVA	100 ω	200 ω
upf	6 PM – 11 PM	fl	500 kVA	400 ω	200 ω
upf	11 PM – 6 AM	¼ fl	125 kVA	25 ω	200 ω

$$\eta_{all\,day} = \frac{(250\times1\times12 + 500\times1\times5 + 125\times1\times7)}{(\quad\downarrow\quad) + \frac{100\times12 + 400\times5 + 25\times7}{1000} + \frac{200\times24}{1000}}$$

$\eta_{all\,day}$ of distr. T/f depends on load cycle of consumer and the load cycle of the consumer is not const. through out year, it may change from season to season. so all day η of distr. T/f is not const.

$$\eta_{all\,day} < \eta_{fl\,power}$$

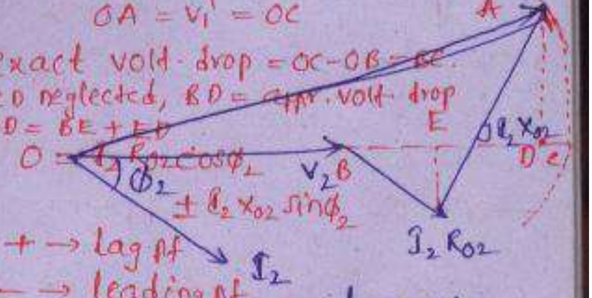
Approximate voltage drop in the T/f :-



→ Eq. ckt w.r.t secondary

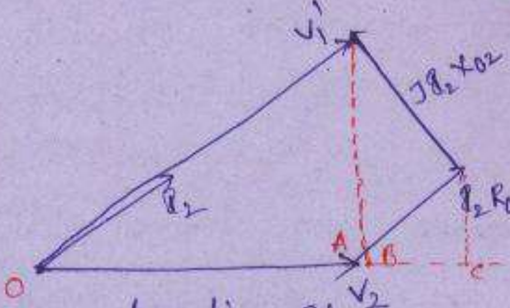
$$\bar{V}_1' = \bar{V}_2 + \bar{I}_2 R_{02} + j\bar{I}_2 X_{02}$$

$OB = V_2$
$OA = V_1' = OC$
exact volt. drop = OC − OB = BC
If CD neglected, BD = appr. volt. drop
BD = BE + ED

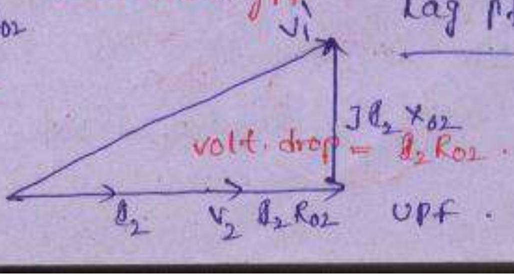


+ → lag pf
− → leading pf

Lag pf



leading pf



UPf.

THU.
06/11/08

3-ϕ Induction Motors

→ I. M/c is similar to T/f but with s/c'ed rotating secondary wdg.

→ In T/f, there is no change in freq. from primary to secondary, but in I. M/c stator is operating at supply freq and rotor will operate at low freq [ie 1 to 4 Hz].

→ T/f has continuous magnetic circuit but I.M has discontinuous magnetic circuit.

→ I.M/c required 25 to 35% of FL current as exciting current, but T/f requires 4 to 6%.

→ T/f is a singly excited device and I.M also a singly excited M/c.

→ I.M/c is a phase shifting m/c just like as T/f.

→ T/f & I.M are operating under same principle of operation [Mutual Induction].

→ I/M has DC shunt type chara.s

$P = \frac{2\pi N}{60} \cdot T$ → shunt motor → const. speed variable power m/c

(N is const. but T is var.)

→ $\theta_e = \frac{P}{2} \cdot \theta_m$

Eg: 4 poles, 90°(mech)

Then
$\theta_e = 120°$ (ele).

→ I.M.s can be designed for any no. of phases. But most popular is 3-Φ IM b'coz universal available supply system is 3-Φ.

⇒ In Syn. m/c's :-

→ Syn. reactance X_s is less in case of open slots. So voltage drop is less so volt. reg. is good.

$$\downarrow X_s = X_{ar}\downarrow + X_l\downarrow$$

$X_d >> X_q$; AR depends on airgap length.

less air gap → lesser I_μ required.

In open type slots → air gap is more

so, AR is less → $X_{ar}\downarrow \Rightarrow X_s\downarrow$

$$SS \text{ stability} \propto \frac{1}{X_s}$$

$$SCR \propto \frac{1}{X_s}.$$

$$\text{Rigidity factor} \propto \frac{1}{X_s}.$$

(Stiffness of coe.)

Open types are prefered in DC m/c's b'coz to improve commutation. [More openings reduces sparks due to delayed commutation].

But in Induction m/c's semi open slots are preferred.

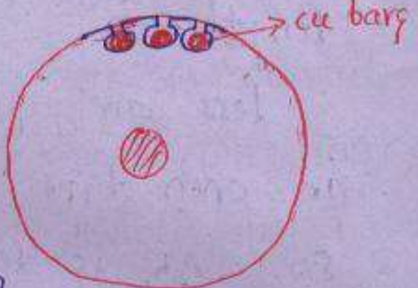
* The no. of poles present in the m/c = no. of poles available on each phase.

* Just like in syn m/c, the wdgs in I.M/C also distributed as well as short pitched.

As freq. of stator is high so eddy current losses are more so thickness of laminations is less.

As freq. of rotor is less [1 to 4 Hz] so eddy current losses are less so thick laminations are used.

Squirrel cage :- (Rotor)



End rings → with high conductivity, forged cu.
↓
[hardness of material is more]
↓
To provide Mech. strength (support) to cu bars from centrifugal forces.

In rotors cu bars are inserted into the semi open slots.

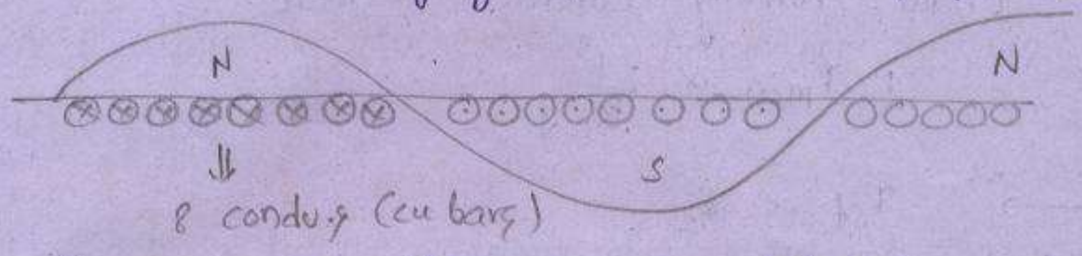
→ 2 end rings are required [front side & back side].

Features of squirrel cage rotor :-

→ This rotor doesn't has any definite no. of poles but same no. of stator poles will be induced in the rotor automatically by means of induction.

→ As rotor poles are induced poles from stator this type of rotor can respond automatically to the changes in stator no. of poles.

So pole changing speed control is possible.



In sq. rotor there are no definite no. of phases but one can treat sq. rotor with no. of ph.s = no. of cu bars under one pole. [Even though stator & rotor have unequal no. of ph.s, the operation of I.M/c is always possible.].

with unequal no. of poles operation of I.M/c is not possible.

As no wdgs & wdg overhangs are present in this rotor, it has smooth surface so than thin air gap length is enough b/w stator & rotor thereby requires less excitation current and operates at more NL & FL pf's.

FL pf of sq. cage I.M > FL pf of wound rotor I.M.

↑

More airgap length (due to more wdgs & wdg over hangs).

→ low leakage reactance due to less air gap.

As wdgs & wdg overhangs are absent, the rotor leakage reactance is less, so max T under running condi-s is more.

$$\uparrow T_{max} \propto \frac{1}{X_2 \downarrow}$$

→ $T_{st} \propto R_2$

R_2 - Rotor resistance

Drawbacks :-

→ As this type of rotor has low rotor resistance, its T_{st} is poor.

→ As sq. rotor has low rotor impedence [$R_2 \downarrow$, $X_2 \downarrow$] so stator draws very high currents at the time of starting which will damage the wdg so external starting methods are required to reduced starting current.

→ high starting starting current & poor T_{st}.

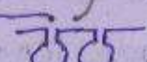
Conclusion :-

Sq. IM has good running performance but poor starting performance.

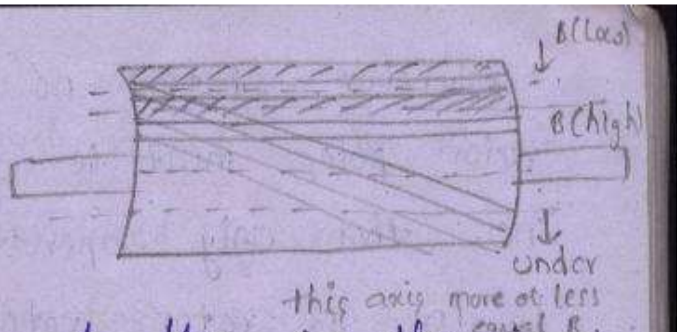
Skewing :-

un slotted area → more flux density

[in slotted area → less flux density

due to opening slots 

purpose of using skewed rotor slots in sq. rotor is to get uniform distr. of flux in the air gap there by to reduce harmonic torques in IM.



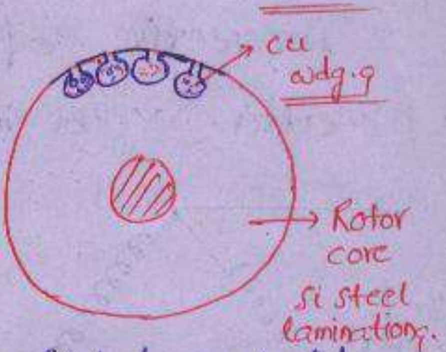
Functions of skewing :-

(1). It reduces cogging phenomenon at the time of starting

(2). It reduces crawling phenomenon under running condi.

(3). It helps to get smooth & silent operation of IM by reducing vibrations & noise.

wound Rotor :-



condi.s to be satisfied while placing rotor wdg:-

(1). Rotor wdgs must be distributed as well as short pitched just like stator wdgs.

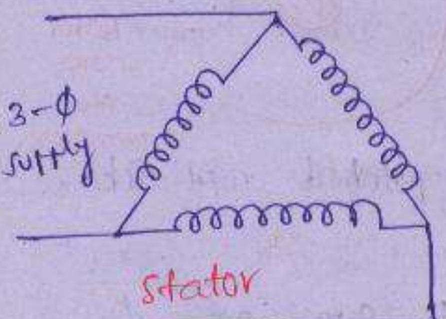
(2). Rotor must be provided with same no. of poles as that of stator [with unequal no. of stator & rotor poles operation of IM is not possible].

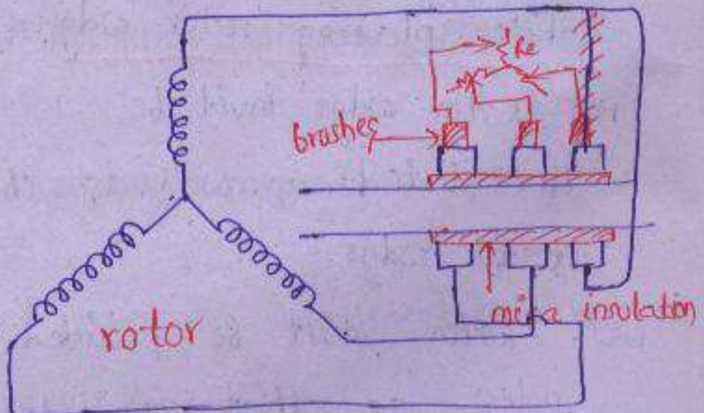
(3). This rotor can't respond automatically to the changes in stator no. of poles.

whenever stator no. of poles changed, then rotor poles must be changed to the same no. then only operation of IM possible. [In sq. rotor rotor poles are induced from the stator poles automatically. but this not possible in wound rotor.].

(4). Even though stator is provided with 3-ϕ, rotor need not be wound with 3-ϕ, but it can wound with any no. of ph.s except 1-ϕ. [In actual practice rotor is also provided with 3 ph.s to get symmetry in placement of wdgs there by to get good mech. balance of the rotor.]

(5). 3-ϕ rotor wdgs must be connected in Y, irrespective of stator wdgs are connected either Y or in Δ.





slip rings → made with phosphor bronze

In order to get external resistances in series with the (rotor) ph. wdgs, rotor must be connected in Y

$T_{st} \propto (R_2 + R_e)$.

Functions of external resistance in slip ring :-

(1). Increases T_{st} produced by IM.

(2). It limits the starting current drawn by IM, that's why no external starting methods are required to start slip ring IM.

(3). R_e increases starting rotor pf.

(4). If R_e is inserted under running condi.s the speed of IM can be controlled.

fl pf of wound rotor IM → 0.8 lag
fl pf of sq. cage IM → 0.85 lag.

Due to presence of R_e, this type of m/c has good starting performance such as high T_{st}, low starting current, more rotor pf. But inferior performance under running condi.s such as more I_μ, less $\overset{NL\&}{fl}$ pf & less max torque under running condi.

Over loading capacity of sq. cage is more when compared to wound rotor. B'coz the use of heavy cu bars the heat dissipation is more due to additional losses produced by over loading.

over loaded the sq. $\overset{\rightarrow 110\%}{\text{cage}}$ upto 10% but wound rotor over loaded upto 5%.

→ freq. of rotor current depends on the relative speed b/w stator & rotor poles.

So under stand still condi, relative speed $= N_s$

$\Rightarrow f_2 = f$.

under running condi. relative speed $= N_s - N$

$\Rightarrow f_r = sf$.

* Speed of rotor rotating magnetic field (ϕ_2) w.r.t. stator $= N_s$.

whenever rotor 3-ϕ currents are induced, the rotor rotating mag. field is produced acc. to rotating mag. field theory. The stator & rotor rotating MF's present in air gap rotate at syn. speeds and are stationary w.r.t. one another in the air gap, ∴ relative speed b/w stator & rotor mag. f's is always zero.

As relative speed b/w stator & rotor rotating M.f's is zero, the two rotating M.f's combined in the air gap and gives single M.f called resultant rotating M.f of air gap flux which also rotate at syn. speed in the air gap.

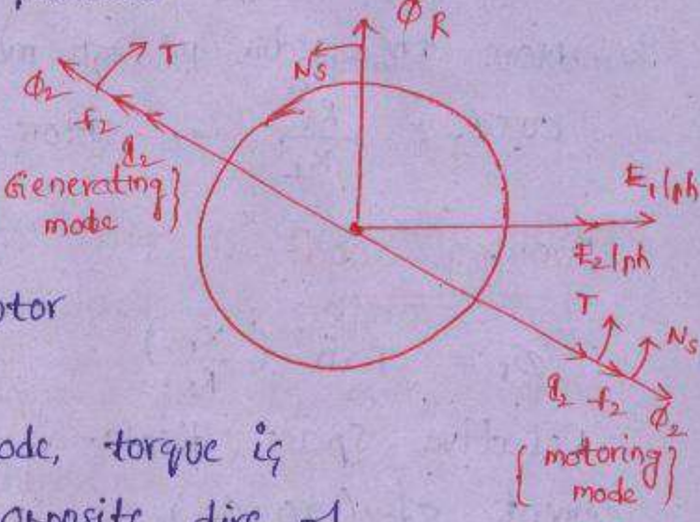
⟹ In the air gap there are 3 rotating M.f's are present. They are ϕ_1, ϕ_2, ϕ_r.

All are rotating with same speed ie N_s.

but with some space delay [time delay]. If space delay = 0 then no rotating torque will produce. ∴ So they are not rotating simultaneously.

→ Even though resultant & rotor rotating MF's rotating at N_s and relative speed b/w them is zero but there is a space displacement of $(90+\phi_2)$ b/w them.

→ ϕ_2 is always trying to allign with ϕ_R due to space displacement $(90+\phi_2)$, so the torque will be produced.



→ In motoring mode, torque is produced in the same dire. of rotor rotation.

In Generating mode, torque is produced in the opposite dire of rotation of rotor.

Torque is produced by I.M/c to allign rotor rotating MF with resultant rotating MF in the air gap. The dire. of torque is always from rotor $\overset{\text{rotating}}{\wedge}$ MF to resultant rotating MF.

In motoring mode of operation, the rotor flux is lagging behind in space from resultant rotating MF. ∴ dire. of torque is same as that of its rotating MF.

In generating mode of operation, rotor flux is advance in space from resultant rotating MF. so that the dire. of torque produced by m/c acts in the dire. opposite to its rotating MF.

$T \propto \phi_R \cdot \phi_2 \cdot \sin(90 + \phi_2)$

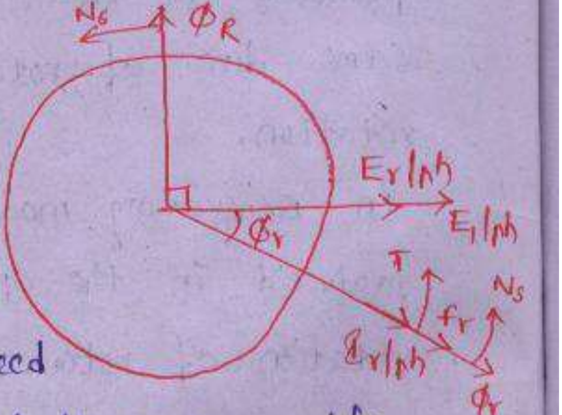
$\Rightarrow T \propto \phi_R \phi_2 \cos(\phi_2)$

$\Rightarrow T \propto \cos\phi_2$
(rotor pf)

More the rotor pf $\Rightarrow$ more the torque produced.

$\cos\phi_2 = \frac{R_2}{X_2}$ → More R_2 $\Rightarrow$ more rotor pf
→ more torque.

Running condi:-



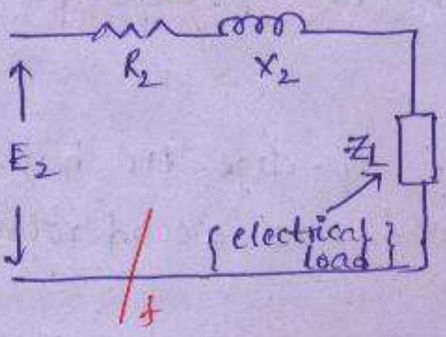
$\phi_r = \tan^{-1}\left(\frac{X_r}{R_2}\right)$

Relative space displacement of $(90 + \phi_2)$.

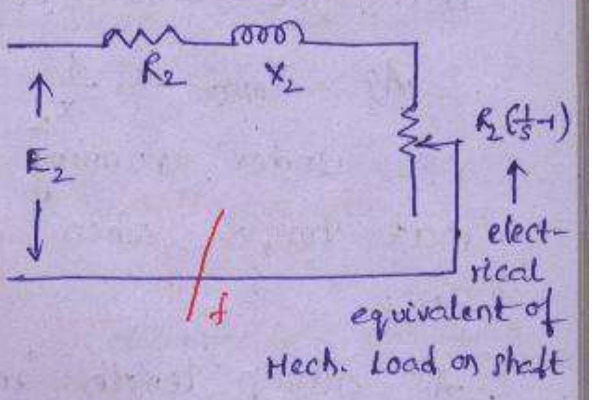
→ To get relative speed b/w ϕ_R & ϕ_2 is equal to zero, the rotor and stator must be wound for same no. of poles.

→ As the load on the IM increases, relative speed increases then slip also increases.

In T/F secondary



In IM rotor



As mech. load ⇑ $\Rightarrow s \Uparrow \Rightarrow R_2(\frac{1}{s}-1) \Downarrow \Rightarrow$
$I_2 \Uparrow \Rightarrow P_2 \Uparrow$.

So Mech. power developed by the motor increases to meet the increased mech. load. until $P_S = P_D$. [power supplied = power demanded by the load].

Under NL condi, slip is nearer to zero, so it can be considered as olpen circuit b'coz $R_2(\frac{1}{s}-1) \simeq \infty$. so $I_2 = 0$ ∴ NO mech. power developed.

Max. Torque :-

Max. torque is the heighest torque that can be produced by the m/c on the wedge of instability.

In Syn. m/c pull out torque is defined as the torque which pulls the rotor from the stator poles.

pull torque is the torque produced by IM, which pulls the rotor from stable operating region to unstable operating region.

As wound rotor IM has more leakage reactance when compared to sq. cage IM.

As $T_{max} \propto \frac{1}{X_2}$

$\therefore$ under running condi. sq. cage IM has more max torque when compared to wound rotor IM.

As airgap length increases in the IM, common flux reduces and leakage flux increases, so T_{max} is decreased.

If AG length b/w stator & rotor increases, the leakage reactance increases, which inturn decreases T_{st} produced by IM.

for given increase in AG length, reduction in T_{st} is more when compared to T_{max}.

$R_2 = 0.2\,\Omega/ph$.

stalline speed = 950 rpm

$N_s = 1000$ rpm

$R_e = ?$ to get 60% of T_{max} at starting.

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2} = 0.6$$

$$S_m = \frac{1000-950}{1000} = 0.05\text{ pu}$$

$$S_m = \frac{R_2}{X_2}$$

$$\Rightarrow a = 0.33, \cancel{X}$$

$$\Rightarrow 0.05 = \frac{0.2}{X_2}$$

$$a = \frac{R_2 + R_e}{X_2}$$

$$\Rightarrow X_2 = 4\,\Omega$$

$$\Rightarrow 0.33 = \frac{0.2 + R_e}{4}$$

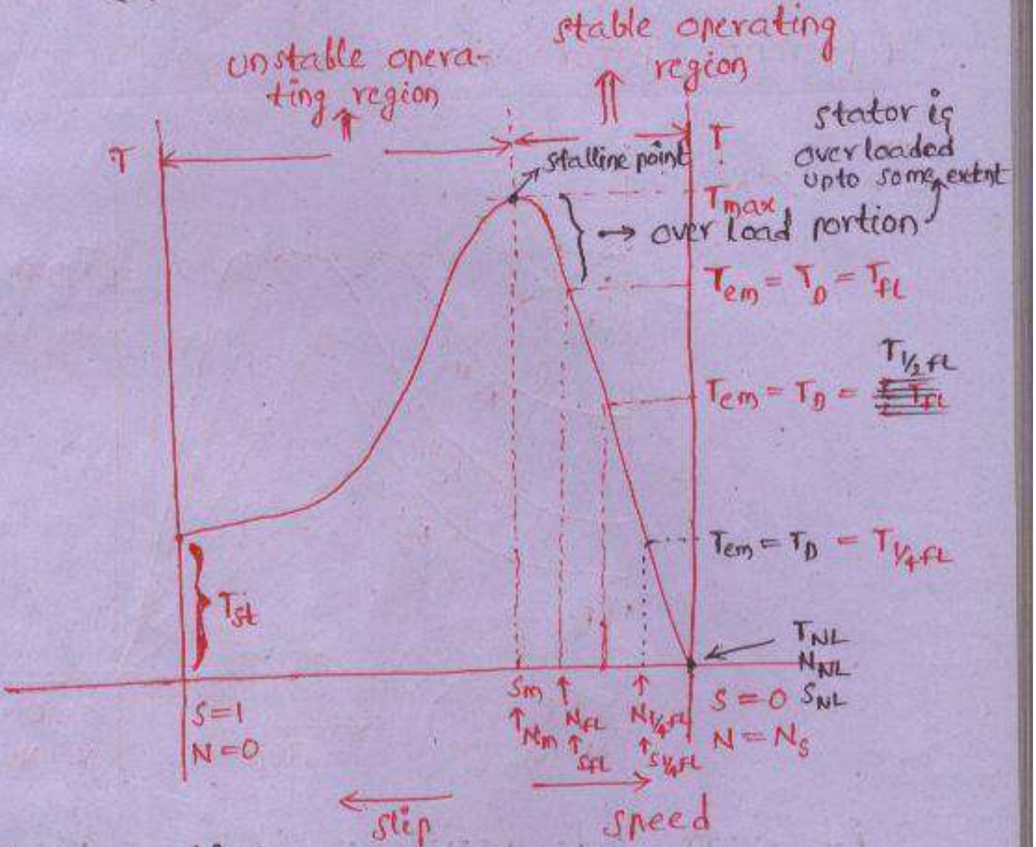
$$\Rightarrow R_e = 1.13\,\Omega/ph.$$

Torque – Slip char.s :
~~– speed char.s~~ :

Motoring mode: If 's' is low ⇒ $T \propto S$

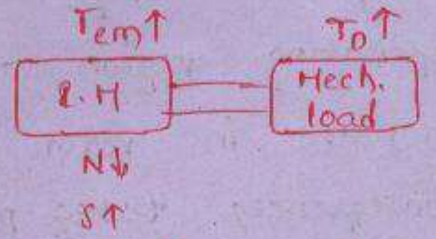
$0 \le N < N_s$ If 's' is high → $T \propto \frac{1}{S}$

⇒ $0 < S \le 1$



Stable operation:

$0 < S \le S_m$

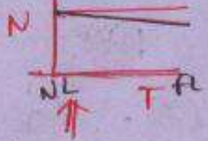


Unstable operation:

$S_m < S \le 1$

[loading can be expressed in terms of current drawn from the supply by the stator.]

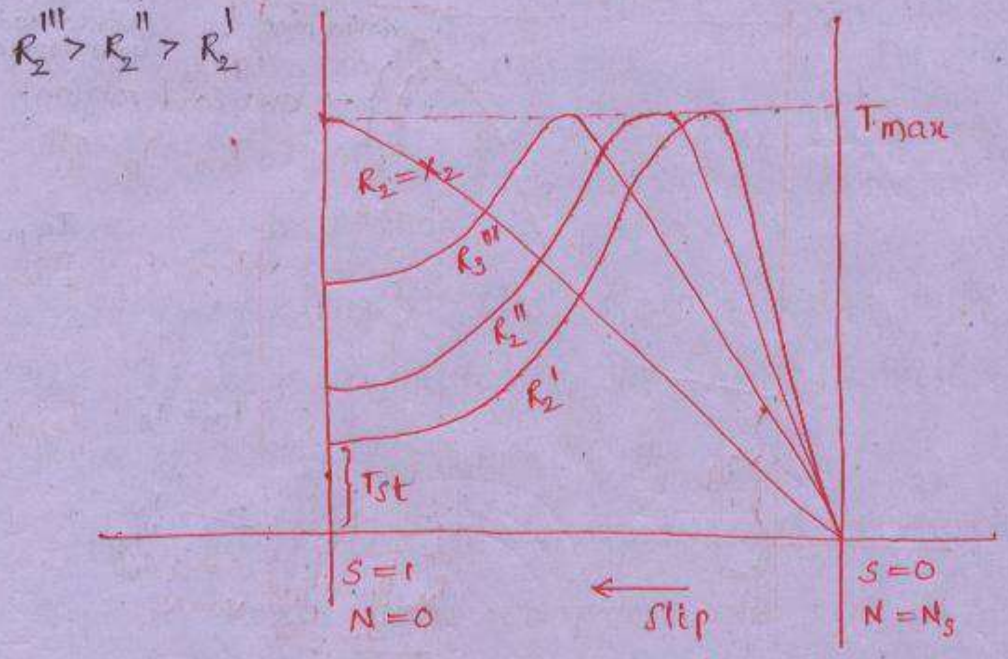
fl condi → given on Name plate
[current].



As change in speed from NL to FL in IM is very less. The IM can be treated as almost const. speed motor just like dc shunt motor. so IM is said to be having shunt type char.s.

Sq.(10%) IM has more overloading capacity than slip ring IM. (5%)

Variation of Torque - slip char.s with different rotor resistances:



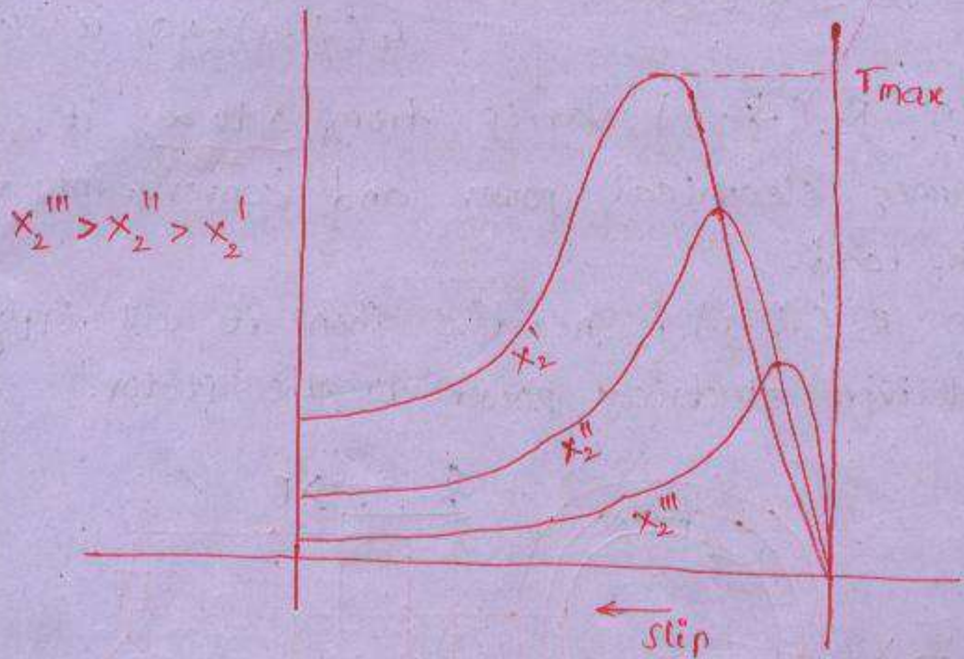
If rotor wdg resistance is more the stable operating region of IM increases but due to increase in rotor resistance following undesirable consequences takes place.

(1). rotor is with more resistance, rotor cu loss are very high and η of IM becomes poor.

(2). If rotor resistance increase the stable operating region becomes wider and the operation of m/c is away from N_s ∴ rotor cu loss are excessively high and results in poor η.

So IM are designed with low rotor resistance to get narrow stable operating region.

Variation of Torque - slip char.s with diff rotor leakage reactances:



As : $X_2'' > X_2'$;

$T_{max} \propto \frac{1}{X_2}$; $S_m = \frac{R_2}{X_2}$; $T_{st} \propto \frac{1}{X_2^2}$

Variation of Torque - slip char.s with diff. applied voltages by keeping freq. const.:

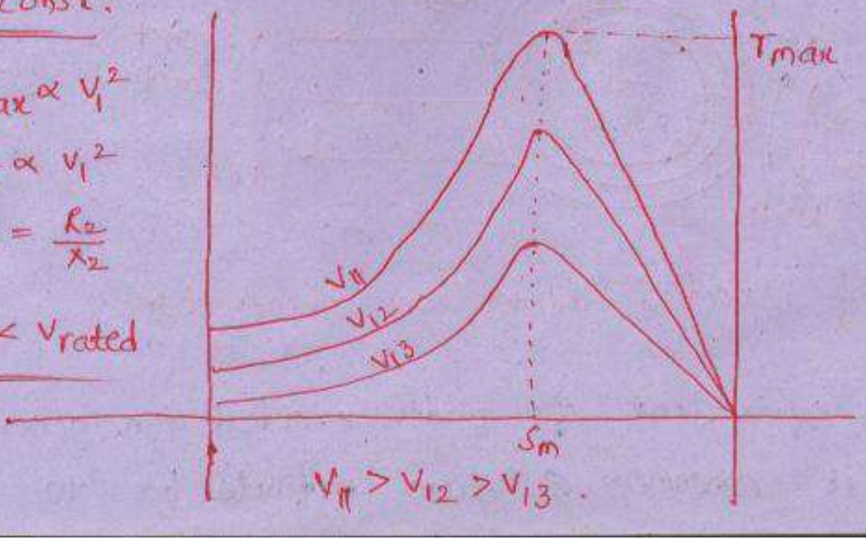
$f = const.$

$T_{max} \propto V_1^2$

$T_{st} \propto V_1^2$

$S_m = \frac{R_2}{X_2}$

$V\downarrow < V_{rated}$



$V_{11} > V_{12} > V_{13}$.

Generating Mode :-

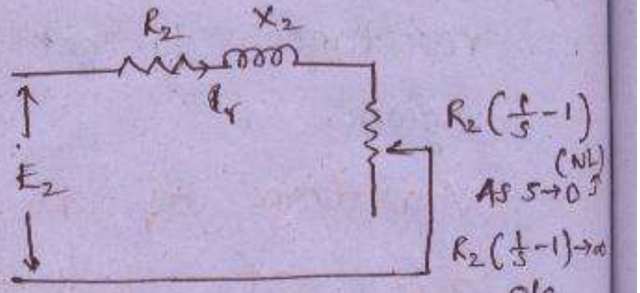
$N > N_s$

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

$= -Ve$

ie $s < 0$

$-\infty < s < 0$

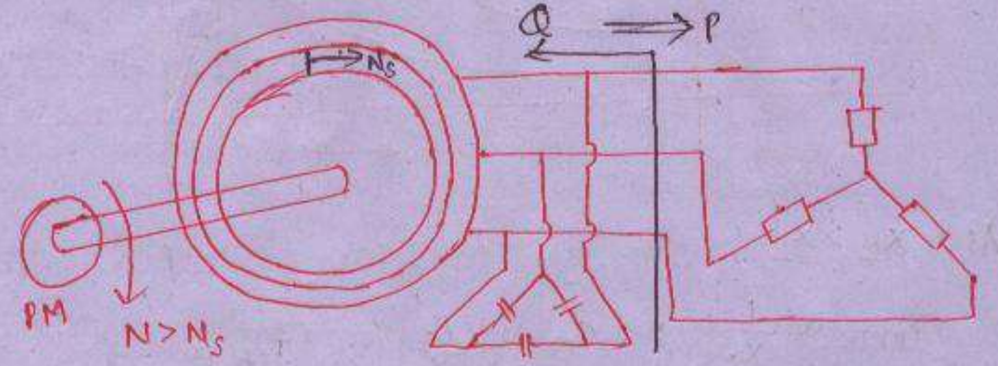


As $s \to 0$ (NL)
$R_2(\frac{1}{s}-1) \to \infty$
o/c

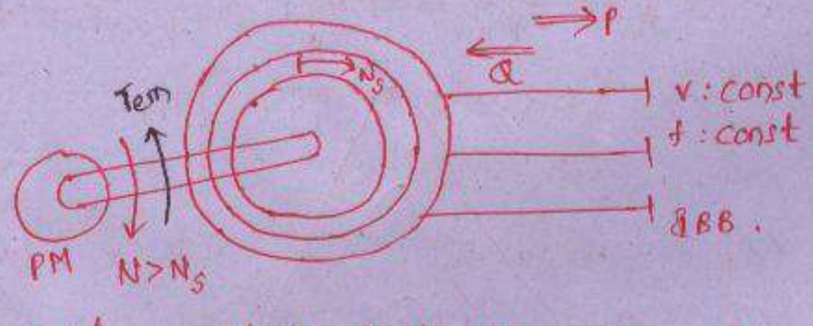
As $s \to 1$ (blocked rotor)
$R_2(\frac{1}{s}-1) \to 0$ ie s/c.

when $R_2(\frac{1}{s}-1)$ varies from $\underbrace{0 \text{ to } \infty}_{+ve}$; it consumes electrical power and converts into meet mech. load.

when $R_2(\frac{1}{s}-1)$ is negative then it will supply or deliver electrical power to the stator.



Seperately excited Induction Generator.



self excited Induction Generators.

I.G is equivalent to under excited Syn. generator b'coz it consumes Q from infinite bus to

Syn. Generator : over excited : P delivered, Q delivered.
under excited : P delivered, Q absorbed.
normal excited: P delivered, Q neither delivered nor consumed.

create rotating magnetic field in the air gap and in-turn delivers active power to infinite bus.

⟹ I.G. are used to generate electric power in conjuction with variable or fluctuating speed PM's such as wind mills, tidal and low head hydro power stations.

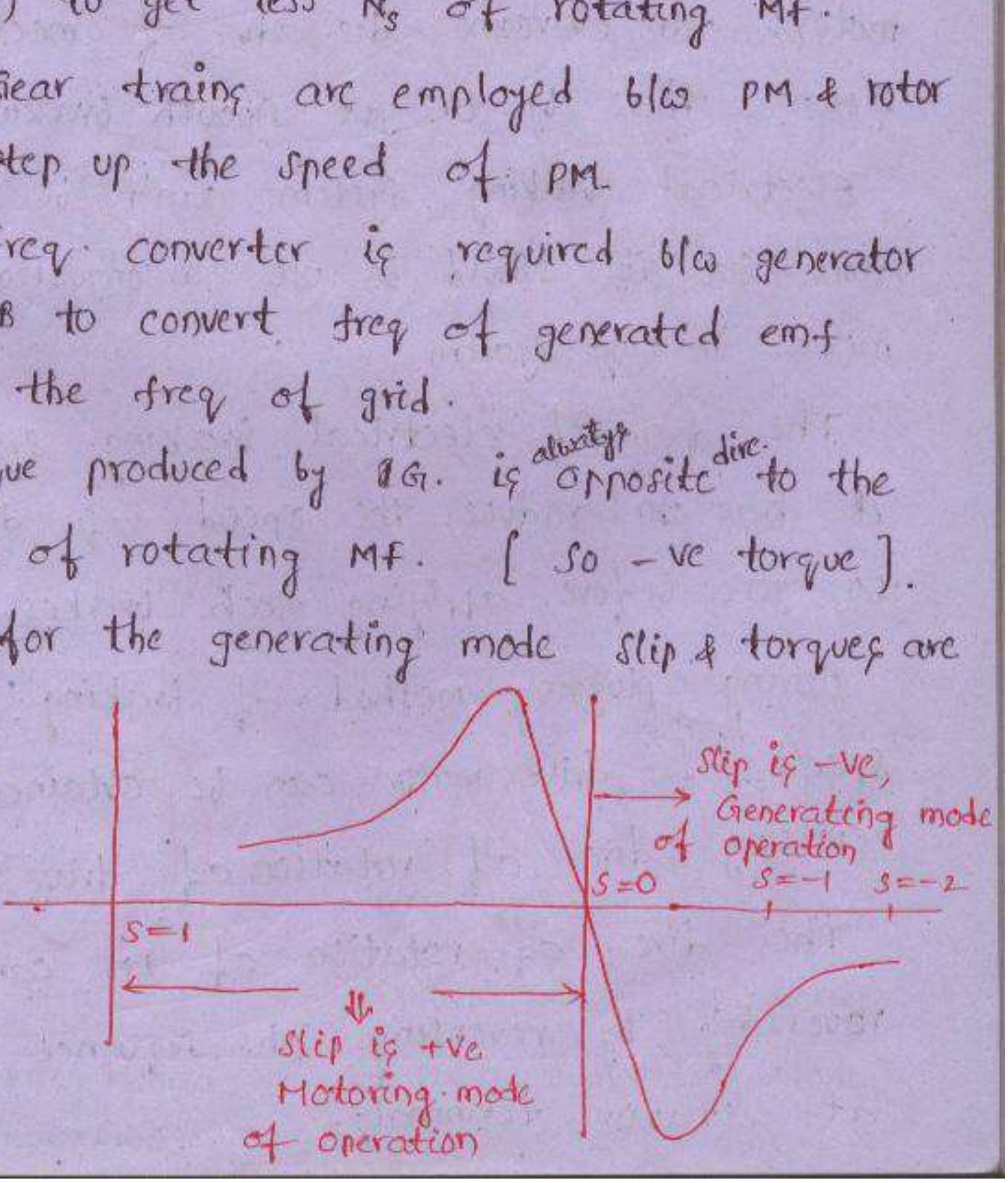
⟹ In order to get more speed of the rotor the following arrangements are required:

(1). I.G.s are ~~generated~~ designed with more no. of poles (>8) to get less N_s of rotating MF.

(2). Gear trains are employed b/w PM & rotor to step up the speed of PM.

(3). freq. converter is required b/w generator & IBB to convert freq of generated emf into the freq of grid.

* Torque produced by IG. is always opposite dire. to the dire. of rotating MF. [So –ve torque]. So for the generating mode slip & torques are –ve.



Braking Mode :-

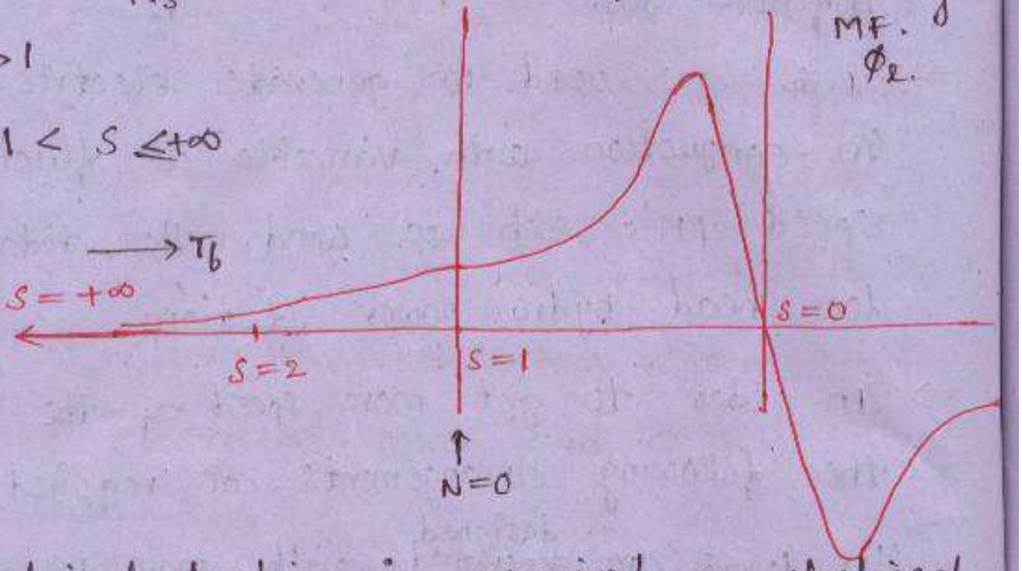
speed is -ve.
[braking torque and slip are +ve].

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

→ $S > 1$

→ $1 < S \leq +\infty$

Reference : Rotating MF. ϕ_2.



electrical braking is required on electrical motors to overcome dis. adv. of mech. braking system, there by to get smooth braking.

Electrical braking system can't be employed alone but it should be use inconjuction with mech. braking system.

The fun. of electrical braking system is it has to reduce the speed of drive motor to zero before applying mech. brakes.

During plugging method of braking, zero speed of drive motor can be obtained by reversing dirc. of rotation of drive motors.

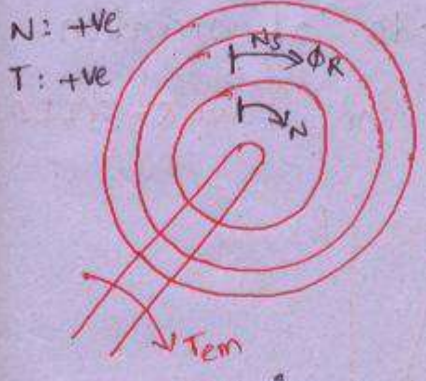
The dirc. of rotation of IM can be revers~~ing~~ed by reversing ph. sequence adopted at stator terminals.

If the ph. sequence adopted at stator terminals is reversed then the dirc. of rotating MF will be getting reverse and the rotor will also reverse its dirc. to satisfy lenz's law.

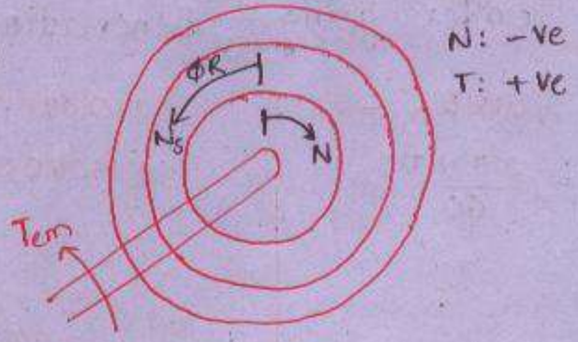
A 3-ϕ IM said to be under going braking $s = -\infty$ mode of operation, if the rotating MF of the rotor rotating in opposite dirc.s so that relative speed b/w them is $> N_s$ and the slip is > 1.

* TUE. 18/11/08 *

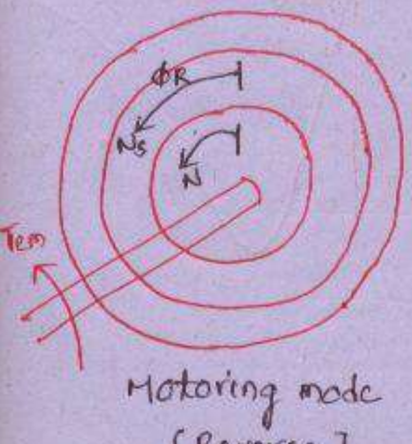
Shaft condi.s of 3-ϕ IM in all modes:



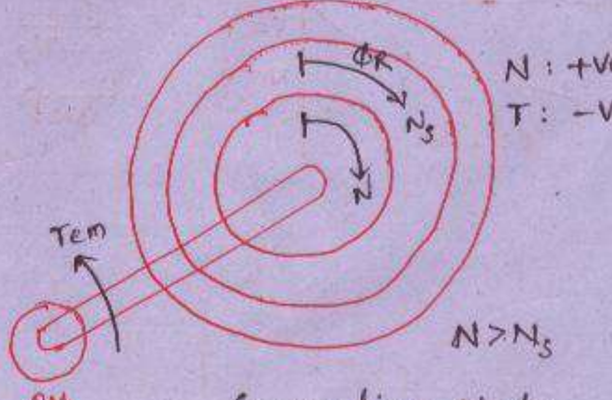
Motoring Mode
[forward]



Braking Mode



Motoring mode
[Reverse]

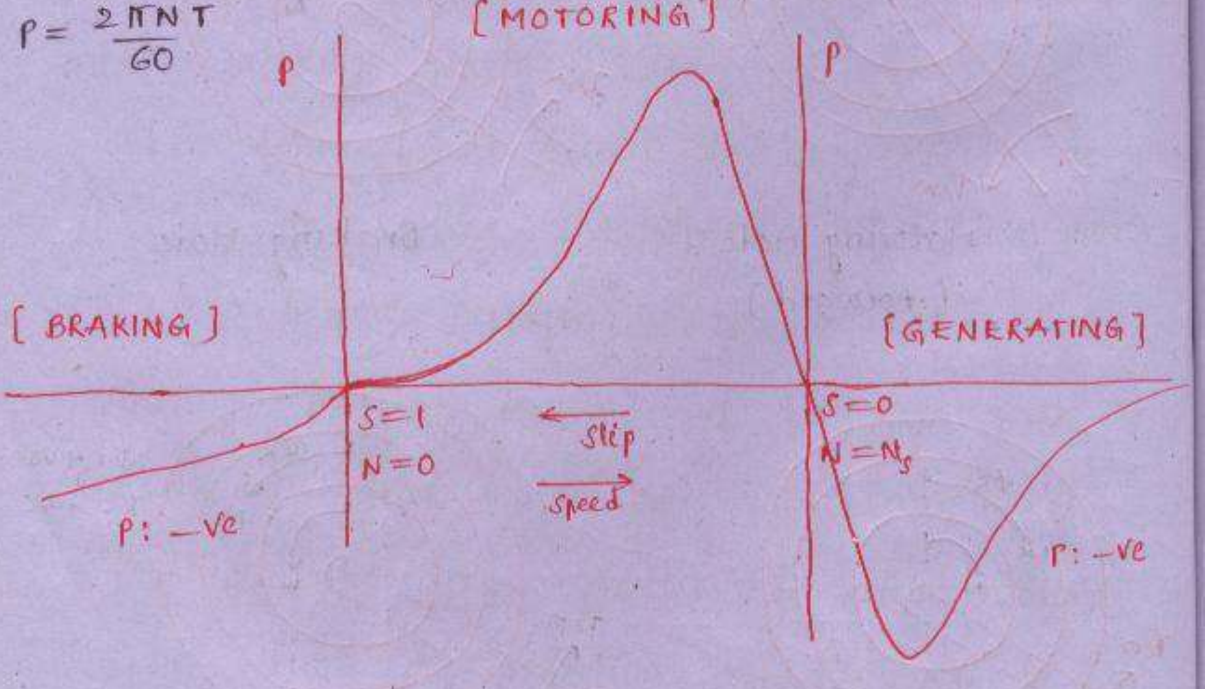


Generating Mode

* If the torque produced by m/c acts in the dire. same as that of its rotating MF and rotation of ~~rotat~~ rotor, Then m/c is said to be under going motoring mode.
* If the torque produced by m/c is in the same dire. of rotating MF and opposite to rotation of rotor then m/c said to be under going braking mode of operation.
* If the torque produced by m/c acts in the dire. opposite to rotating MF & rotation of rotor then the m/c is said to be under going Generating mode of operation.

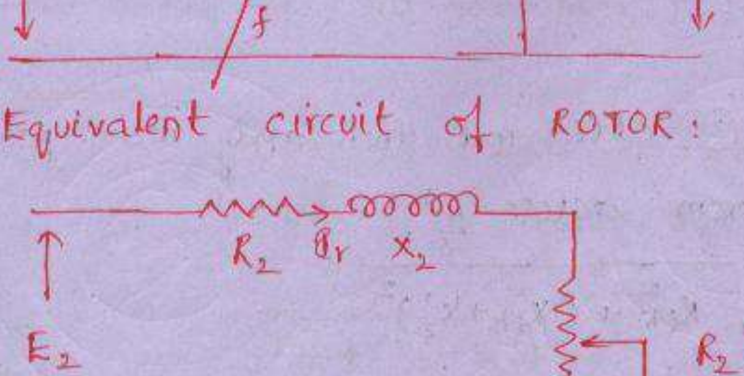
POWER - SLIP, characteristics (or) POWER - SPEED:

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

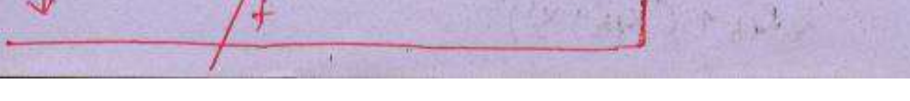


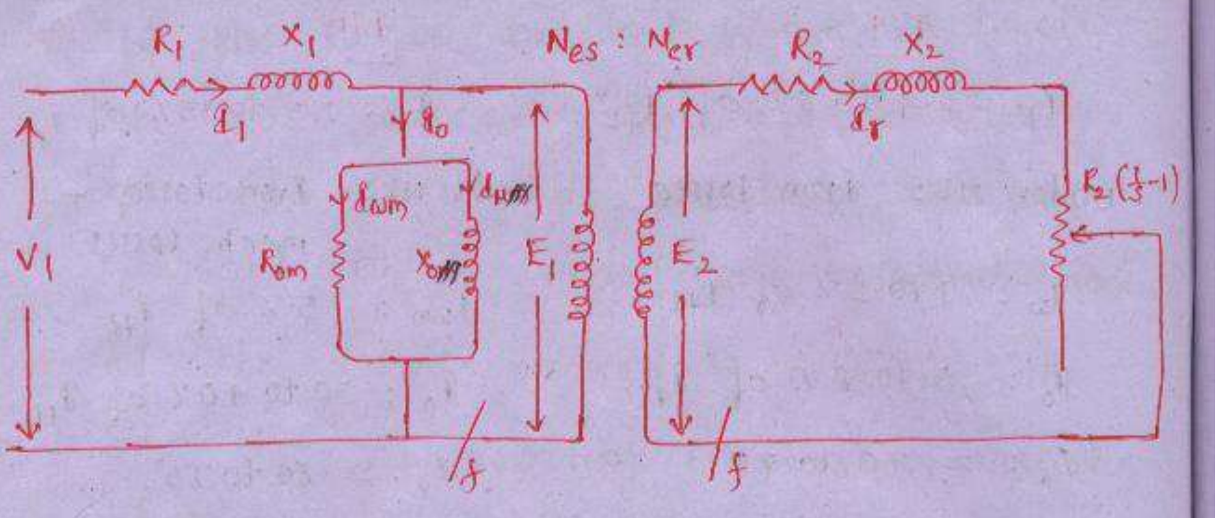
T/F	I/M
I_μ : 4 to 6% of I_{fL}	I_μ : 25 to 35% of I_{fl}
under NL: Iron losses	under NL: Iron losses + mech. losses.
I_w : 1 to 2% of I_{fl}	I_{wm} : 5% of I_{fl}
I_0 : 5 to 8% of I_{fl}	I_0 : 30 to 40% of I_{fl}
$\phi_0 : \simeq 70$ to $75°$	$\phi_0 : \simeq 80$ to $85°$
$\cos\phi_0 : \simeq 0.2$ lag	$\cos\phi_0 : \simeq 0.1$ lag
K : $\frac{E_2\|ph}{E_1\|ph} = \frac{N_2\|ph}{N_1\|ph}$ (Transformation ratio)	K of slip ring I.M. $E_1\|ph = 4.44\, N_{phs} \cdot \phi_R \cdot f \cdot k_{ws}$ $E_2\|ph = 4.44\, N_{phr} \cdot \phi_R \cdot f \cdot k_{wr}$ $k = \frac{E_2\|ph}{E_1\|ph} = \frac{N_{phr} \cdot k_{wr}}{N_{phs} \cdot k_{ws}}$ $= \frac{N_{er}}{N_{es}}$. $N_e \rightarrow$ effective no. of turns $= N_{ph} \cdot k_w$

Equivalent circuit of STATOR:



Equivalent circuit of ROTOR:





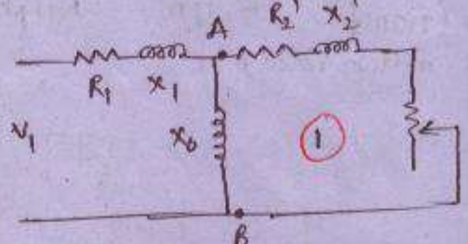
To findout T_{fl} :

DATA : N_1, f, P

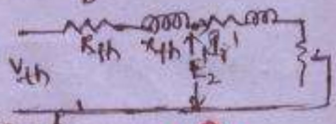
R_1, X_1, X_0, R_2', X_2'

S_{fl} or FL speed

$\Longrightarrow T_{fl} = ?$



step1 : findout I_r' at S_{fl} = —— $\Rightarrow$



②

step 2 : Rotor i/p at S_{fl} = —— $3 I_r'^2 \cdot \frac{R_2}{S_{fl}}$.

step 3 : $T_{fl} = \frac{60}{2\pi N_s} \times$ Rotor i/p at S_{fl}

To findout T_{max} :

DATA : V_1, f, P

R_1, X_1, X_0, R_2', X_2'

$\Longrightarrow T_{max} = ?$

STEPS :

(1). Draw ①, ② ckts and then apply max. power transfer theorem across $\frac{R_2'}{S}$.

$$\frac{R_2'}{S} = \sqrt{R_{th}^2 + (X_{th}+X_2')^2}$$

(2). $$S_m = \frac{R_2'}{\sqrt{R_{th}^2 + (X_{th}+X_2')^2}}$$

(3). I_r' at S_m

(4). Rotor i/p at $S_m = 3 I_r'^2 \cdot \frac{R_2'}{S_m}$

(5). $T_{max} = \frac{60}{2\pi N_s} \times$ Rotor i/p at S_m.

To find out T_{st} :

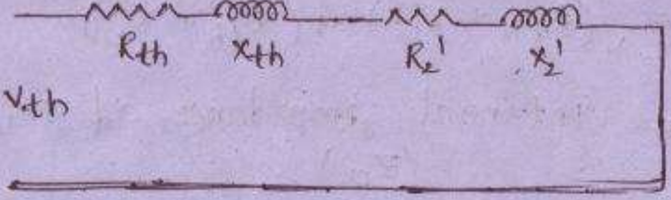
DATA : V_1, f, P

$R_1, X_1, X_0, R_2', X_2'$

$\Rightarrow T_{st} = ?$

STEPS :

$S = 1$, $N = 0$ & $R_2'\left(\frac{1}{S} - 1\right) = 0$



(1). I_r' at $S = 1$,

(2). Rotor i/p at $S = 1$; $= 3 I_r'^2 \cdot R_2'$

(3). $T_{st} = \frac{60}{2\pi N_s} \times$ Rotor i/p at $S = 1$.

Exact condition for max. starting torque :

DATA : V_1, f, P, k

R_1, X_1, X_0, R_2, X_2

$R_e = ?$, to get max T at starting.

STEPS :

(1). Draw ①, ② equi. ckts and apply max. power transfer th. across $\frac{R_2'}{S}$.

$$S_m = \frac{R_2'}{\sqrt{R_{th}^2 + (X_2' + X_{th})^2}}$$

But At starting $S_m = 1 \Rightarrow R'_{2\,(total)} = \sqrt{R_{th}^2 + (X_{th} + X_2')^2}$

$$\Rightarrow \quad R_2' + R_e' = \sqrt{R_{th}^2 + (X_{th} + X_2')^2} \quad (S.R.I.M)$$

$$\Rightarrow \quad R_e' = \underline{\quad\quad} . \qquad R_e = K^2 \cdot R_e'$$

$$(T_{st})_{max} = T_{max} .$$

Exact condition for max. mech. power o/p :-

$$\underset{(max)}{\text{Gross mech. o/p}} = 3 I_r'^2 \cdot R_2' \cdot \underset{\uparrow max.}{\left(\frac{1}{s} - 1\right)}$$

Acc. to max. power transfer th. across $R_2' \left(\frac{1}{s} - 1\right)$

$$R_2' \left(\frac{1}{s} - 1\right) = \sqrt{(R_{th} + R_2')^2 + (X_{th} + X_2')^2}$$

$$= \text{Internal impedance of IM} \; (Z_{01}) .$$

DATA :

V, f, P

$R_1, X_1, X_0, X_2', R_2'$

(1). $s = ?$, at max. mech. o/p.

(2). $N = ?$, " "

(3). $T = ?$, " "

LOSSES IN IM :-

pu cu losses are not defined for I.M , why b'coz rating on the Name plate refers the mech. load.

FL cu losses $= 3 I_1^2 R_{01}$.

As freq. of rotor under running condi. is very small (sf), the rotor core losses under running condi. are negligible

So core losses in the sense only stator core Losses .

In T/F

$B_m \propto \frac{V_1}{f}$

Case ①: $\frac{V_1}{f}$ = const, B_m = const.

$\Rightarrow \omega_h \propto f$ & $\omega_e \propto f^2$

Case ②: $\frac{V_1}{f} \neq$ const, $B_m \neq$ const.

$\Rightarrow \omega_h \propto V_1^{1.6} \cdot f^{-0.6}$ & $\omega_e \propto V_1^2$

In IM

case① During operation of IM,

$\frac{V_1}{f}$ = const, ϕ_R = const. $\phi_R \propto \frac{V_1}{f}$

$\omega_h \propto f$ & $\omega_e \propto f^2$.

case②:

$\frac{V_1}{f} \neq$ const, $\phi_R \neq$ const.

$\omega_h \propto \frac{V_1^{1.6}}{f^{0.6}}$ & $\omega_e \propto V_1^2$.

If V_1 = const & $f\downarrow$

$\Rightarrow \frac{V_1}{f} \neq$ const

$\Rightarrow \uparrow \omega_h \propto \frac{V_1^{1.6}}{f^{0.6}\downarrow}$ & $\omega_e \propto V_1^2$ ie remain constant.

If f = const & $V_1\downarrow$

$\Rightarrow \frac{V_1}{f} \neq$ const

$\therefore \downarrow \omega_h \propto \frac{V_1^{1.6}\downarrow}{f^{0.6}}$ & $\downarrow \omega_e \propto V_1^2 \downarrow$

for const freq. operation & V↓ ⇒ ω_i are appr. taken as $\omega_i \propto V_1^2$.

Iron losses are not dependent on the load variation.

Mechanical Losses:-

(1). friction losses < Bearing friction Losses (Both IM's)
Brush friction losses (S.R.I.M).

(2). windage losses

Bearing friction loss is the mech. power loss to overcome friction in bearings on both sides of the m/c

polishing nature
& with high thermal
↑ withstand
capacity

Bearing friction loss $\propto N$.

Brush friction losses are reduced by using carbon brushes.

Brush friction losses $\propto N^2$.

windage loss is the mech. power wasted in rotating m/c towards overcoming opposition offered by wind in the air gap.

windage losses depends on airgap length.

more AG length ⇒ more windage losses.

In Sq. IM AG length is min. as compared to slip ring so Sq. IM have less windage losses.

overall mech. losses are more in slip ring IM than Sq. IM.

↓
AG is more,
Brush friction loss

windage losses $\propto N^3$.

If speed increased by 10% Then

Bearing friction loss = 10% ↑

Brush friction losses $\propto N^2$

$$\propto (1.1N)^2$$

$$\propto 1.21N^2$$

$$= 21\% \uparrow$$

windage losses $\propto N^3$

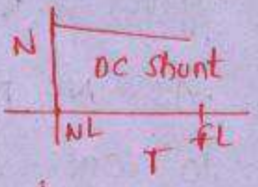
$$\propto (1.1N)^3$$

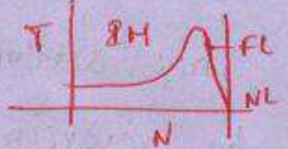
$$\propto 1.333\,N^3$$

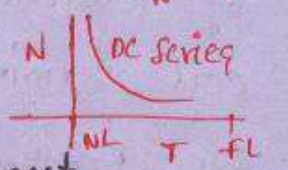
$$= 33.3\% \uparrow .$$

windage losses are more sensitive than frictional losses.

In DC shunt m/c mech. losses are treated as const. losses b'coz DC shunt m/c is a const. speed. m/c IM also a const. speed m/c. so the mech. losses are treated as const. losses.







Mech. losses are variable losses in case of DC series motor.

As IM & DC shunt motor are almost const. speed motor from NL to FL ∴ mech. losses which depends on speed are also almost const. from NL to FL. ∴ mech. losses in IM & DC shunt motor can be treated as const. losses.

TEST'S ON INDUCTION MOTOR'S :

(1). NO LOAD TEST :

A 3-ϕ IM under NL condi = A T/f with open circuted secondary. So NL test on IM is equivalent to open circuit test on T/f.

V_1	I_0	$W = W_1 + W_2$
Line to line	Avg. of 3 Ammeters (line)	(3-ϕ ph.)

In two wattmeter method:

If Load pf is < 0.5 then one wattmeter shows -ve reading.

when load pf = 0.5 then one wattmeter shows zero reading

If load pf > 0.5 both the wattmeters gives forward (+ve) reading.

As NL pf of IM is 0.1 which is < 0.5 so one wattmeter shows −ve reading.

This wattmeter reading can be taken as by reversing either current coil & pressure coil terminals.

$$\left.\begin{aligned} W_1 &= 800\,W \\ W_2 &= -200\,W \end{aligned}\right\} \begin{aligned} W &= W_1 + W_2 \\ &= \underline{600\,W} \end{aligned}$$

TO findout R_0 & X_0:

Δ- CONNECTED STATOR:

$$R_{om}|_{ph} = \frac{V_1|_{ph}}{I_{wm}|_{ph}} \quad ; \quad X_0|_{ph} = \frac{V_1|_{ph}}{I_\mu|_{ph}}$$

$$V_1|_{ph} = V_1$$

$$I_{wm}|_{ph} = I_0|_{ph} \cdot \cos\phi_0 \qquad I_\mu|_{ph} = I_0|_{ph} \cdot \sin\phi_0$$

$$= \frac{I_0}{\sqrt{3}} \cdot \cos\phi_0 \qquad = \frac{I_0}{\sqrt{3}} \cdot \sin\phi_0$$

W_0 = 3-φ power

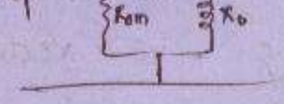
$$= \sqrt{3} \cdot V_1 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_0}{\sqrt{3} \cdot V_1 I_0}$$

$$\sin\phi_0 = \sqrt{1 - \cos^2\phi_0}$$

$$R_{om}|_{ph} = \frac{\sqrt{3}\,V_1}{I_0 \cos\phi_0}$$

$$X_0|_{ph} = \frac{\sqrt{3}\,V_1}{I_0 \sin\phi_0}$$



Y- CONNECTED STATOR:

$R_{om}|_{ph} = \frac{V_1|_{ph}}{I_{\omega m}|_{ph}}$ $X_o|_{ph} = \frac{V_1|_{ph}}{I_\mu|_{ph}}$

$V_1|_{ph} = \frac{V_1}{\sqrt{3}}$

$I_{\omega m}|_{ph} = I_o|_{ph} \cdot \cos\phi_o$ $I_\mu|_{ph} = I_o|_{ph} \cdot \sin\phi_o$

$= I_o \cdot \cos\phi_o$ $= I_o \sin\phi_o$

ω_o = 3-ϕ power $R_{om}|_{ph} = \frac{V_1}{\sqrt{3} I_o \cos\phi_o}$

$= \sqrt{3} \cdot V_1 I_0 \cos\phi_o$

$\Rightarrow \cos\phi_o = \frac{\omega_o}{\sqrt{3} V_1 I_o}$ $X_o|_{ph} = \frac{V_1}{\sqrt{3} \cdot I_o \sin\phi_o}$

$\sin\phi_o = \sqrt{1 - \cos^2\phi_o}$

To findout const. losses:

ω_o = Losses in IM under NL condition

= Iron losses (stator core losses) + Mech. loss + NL stator cu loss ($3 I_o^2 R_1$).

constant losses = $\omega_o - 3 I_o^2 R_1$

↳ NL current is 30 to 45% of full load current

stator & rotor wdg resistances are measured by using kelvin's double bridge.

SEPARATION OF CONST. LOSSES INTO IRON & MECH. LOSSES:

f_{rated} = const.   (1). ↓ Iron losses $\propto V_1^2$ ↓

V is variable,   (2). Mech. loss = const.

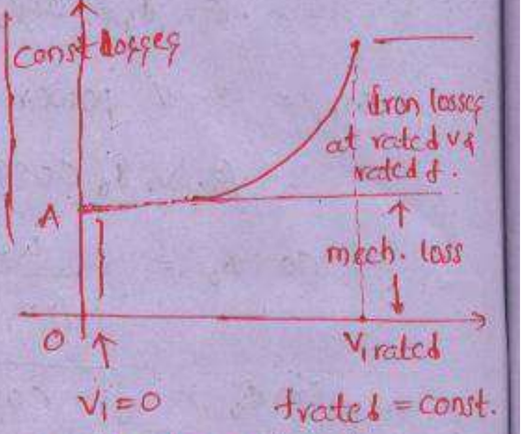
under NL condi., slip 's' is low,

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

$$T \propto \frac{s V_1^2}{R_2}$$

* By keeping applied 'V' const, freq of of IM is reduced, the speed of IM decrease irrespective of whether the m/c is loaded or not. ∴ mech. losses in IM will reduce. (mech. losses depends on speed.)

If the NL test is conducted at rated freq, but less than the rated voltage:



So Iron loss $\propto V_1^2 = 0$.

$f = f_{rated}$

$V_1 < V_{rated}$.

(1). $\downarrow \phi_R = \frac{V_1 \downarrow}{f - \text{const}}$.

Then m/c comes out of saturation. then I_μ required is reduced

(2). $I_\mu \downarrow$

(3). $\downarrow$ Iron loss $\propto V_1^2 \downarrow$

(4). mech. loss = const

(5). $I_{wm} \downarrow$

(6). $I_0 \downarrow$

(7). $\downarrow$ NL stator cu loss = $3 \downarrow I_0^2 R_1$

(8). $W_0 \downarrow$

(9). $\cos\phi_0 \uparrow$

(10). $\downarrow T_{st} \propto V_1^2 \downarrow$

(11). $\downarrow T_{max} \propto V_1^2 \downarrow$

when I_μ & I_{wm} are equally reduced then ϕ_0 = const. ⟹ pf = const.

But reduction in I_μ is more when compare to the reduction in I_{wm} ∴ so $\cos\phi_0 \uparrow$; $\phi_0 \downarrow$

If the NL test is conducted at rated voltage and reduced freq. :

$V_1 = V_{rated}$.

$f_1 < f_{rated}$

(1). $\uparrow \phi_R = \frac{V_1}{f \downarrow} = const$

(2). $I_\mu \uparrow$

(3). $\uparrow$ Iron loss $\Rightarrow$ $\uparrow W_h \propto \frac{V_1^{1.6}}{f^{0.6} \downarrow}$

$W_e \propto V_1^2$

(4). Mech. losses $\downarrow$

(5). I_{wm} = const.

(6). $I_0 \uparrow$

(7). $\uparrow$ NL stator cu loss $= 3 \uparrow I_0^2 R_1$

(8). $W_0 \uparrow$

(9). $\cos\phi_0 \downarrow$

(10). $\uparrow T_{st} \propto \frac{1}{f^3 \downarrow}$

(11). $\uparrow T_{max} \propto \frac{1}{f^2 \downarrow}$

BLOCKED ROTOR TEST :

Reduced applied voltage

short circuit current :- $\{I_{sc} = 5 \text{ to } 8 \text{ times } I_{fl}\}$ rated.

This is amount of current that would flow through stator wdg under BR condi corr. to rated applied v.

Blocked rotor current :-

BR current is the fl stator current that will through wdgs under BR condi corr. to reduced applied volt.

As s/c condis are prevailing in IM under blocked rotor condi. about 8 to 12 % of rated voltage is enough to produce rated stator current under blocked rotor condition.

% Z → T/f → 5 to 8 %.

% Z → IM → 8 to 12 % ← due to air gap.

V_{BR}
(line to line)
[8 to 12 % of rated V]

$I_{BR} = I_{fl}$
(line current)

$W_{BR} = W_1 + W_2$
(3-ϕ)

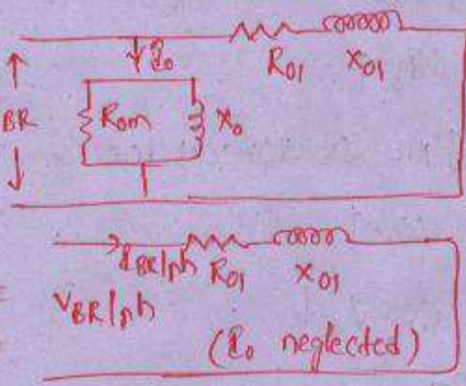
W_{BR} = losses in IM under BR condi.

= fl cu loss + iron loss (due to 8 to 12 % of V_1)

Small amount of Iron losses corr. to BR volt. neglected ∴ wattmeter reading during BR test can be directly taken as fl cu losses.

$$W_{BR} = 3\, I_{BR}^2|_{ph} \cdot R_{01}|_{ph}$$

$$R_{01}|_{ph} = \frac{W_{BR}}{3\, I_{BR}^2|_{ph}}$$



N = 0
S = 1
$R_2(\frac{1}{s}-1) = 0$

I corr. to V_1 is 30 to 45 % of I_{fl} but I corr. to BR volt is very small, so I_0 can be neglected.

$$V_{BR}|_{ph} = I_{BR}|_{ph}\,(R_{01} + jX_{01})$$

$$= I_{BR}|_{ph} \cdot Z_{01}|_{ph}$$

$$Z_{01}|_{ph} = \frac{V_{BR}|_{ph}}{I_{BR}|_{ph}}$$

$$X_{01}|_{ph} = \sqrt{Z_{01}^2|_{ph} - R_{01}^2|_{ph}}$$

NAME PLATE DETAILS:

3-ϕ, Δ, 440V, 50Hz, 100A, 5HP.

IM : ↑ Stator | wdg   rated freq   rated stator current (FL).   Net mech. power o/p at FL.

rated volt.

FL kVA of T/F is 100 kVA then ½ FL kVA is 50 kVA; ↓ electrical power rating.

DC m/c 10 kw → electrical power rating

But in IM At FL (100 A) → 5 HP

Then ½ FL (50 A) → 2.5 HP ← its not correct b'coz 5HP is not the electrical power rating.

$$\eta_{\substack{motor\\fl}} = \frac{\text{Net mech. power o/p at FL}}{(\downarrow) + \underset{\substack{\uparrow\\ \text{BR Test}}}{\text{fl cu loss}} + \underset{\substack{\uparrow\\ \text{NL Test}}}{\text{Const. losses}}}$$

To findout net mech. power o/p at any fraction of FL can be findout by constructing o'le diagram.

(or) $\eta_{x fl}$

3-ϕ, Δ, 440V, 50Hz, 100A, 5HP

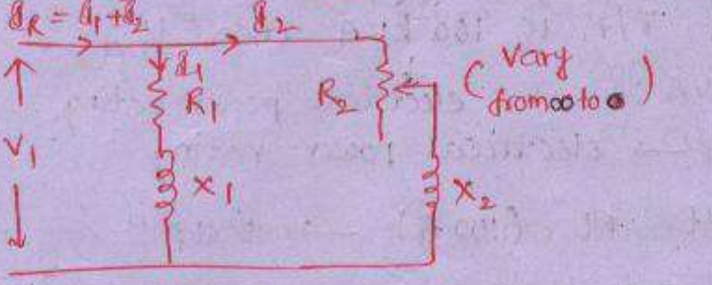
IG : ↑ FL stator terminal voltage   ↑ Rated freq. of generated emf.   ↑ FL stator current delivered to load   ↑ mech. power i/p at FL condi (PM)

In order to deliver (50A) ½ FL current the required mech power i/p is —? 2.5 HP this is not correct. It can be findout from o'le diagram.

$$\eta_{\underset{FL}{GEN}} = \frac{\text{Mech. power } \overset{\text{at FL}}{i/p} - \overset{\downarrow \text{BR Test}}{\text{FL cu loss}} - \overset{\downarrow \text{NL test}}{\text{Const. loss}}}{\text{Mech. power i/p at FL}}$$

↑ Name plate

CIRCLE DIAGRAM OF 3-ϕ IMIC :



CURRENT LOCUS DIAGRAM:

locus of current variation when variable element changes from ∞ to 0.

$$I_1 = \frac{V_1}{\sqrt{R_1^2 + X_1^2}} \angle -\tan^{-1}\left(\frac{X_1}{R_1}\right)$$

$R_2' < \infty$ (Reducing R_2 from ∞).

$$\Rightarrow I_2' = \frac{V_1}{\sqrt{R_2'^2 + X_2^2}} \angle -\tan^{-1}\left(\frac{X_2}{R_2'}\right)$$

further decrease in R_2' is $R_2'' < R_2'$

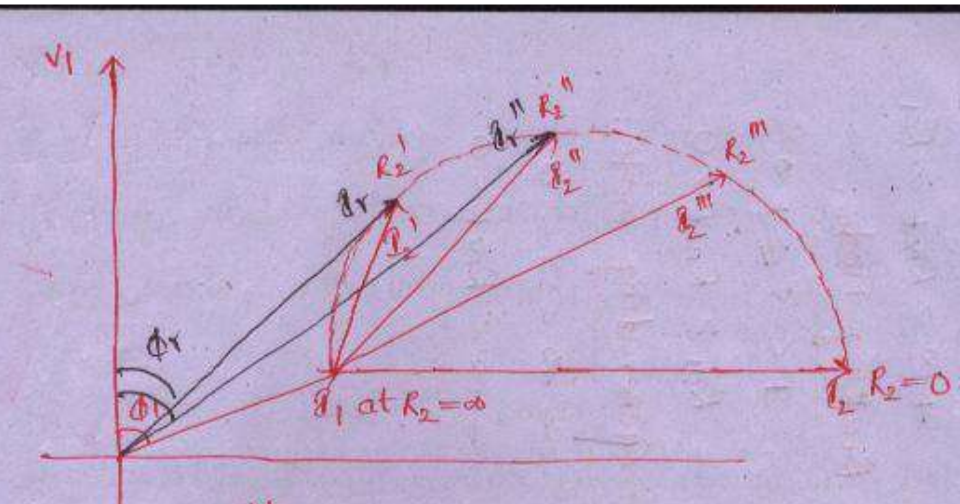
$$\Rightarrow I_2'' = \frac{V_1}{\sqrt{R_2''^2 + X_2^2}} \angle -\tan^{-1}\left(\frac{X_2}{R_2''}\right)$$

further decrease in R_2'' is $R_2''' < R_2''$

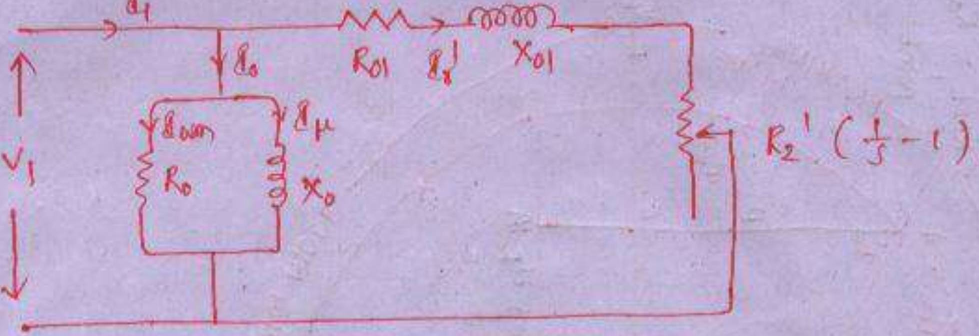
$$\Rightarrow I_2''' = \frac{V_1}{\sqrt{R_2'''^2 + X_2^2}} \angle -\tan^{-1}\left(\frac{X_2}{R_2'''}\right)$$

for $R_2 = 0$

$$\Rightarrow I_2 = \frac{V_1}{jX_2} \angle -90^\circ$$



Equivalent ckt of 3-φ IM:



O^{le} diagram of IM basically a current locus diagram which represents diff load condi.s on shaft of IM/c in all modes of operation

At NL,

$N \to N_s$ & $S \to 0$

$R_2'\left(\frac{1}{S}-1\right) \to \infty$

$R_{net} = R_{01} + R_2'\left(\frac{1}{S}-1\right)$

As load increases, N↓

$S\uparrow \to 0;\ R_2'\left(\frac{1}{S}-1\right)\downarrow \to \infty$

$\uparrow \phi = \tan^{-1}\left(\frac{X_{01}}{R_{net}\downarrow}\right)$

$I_r' \uparrow$

As load becomes heavy, N=0

$S = 1$ (BR condi)

$R_2'\left(\frac{1}{S}-1\right) = 0.$

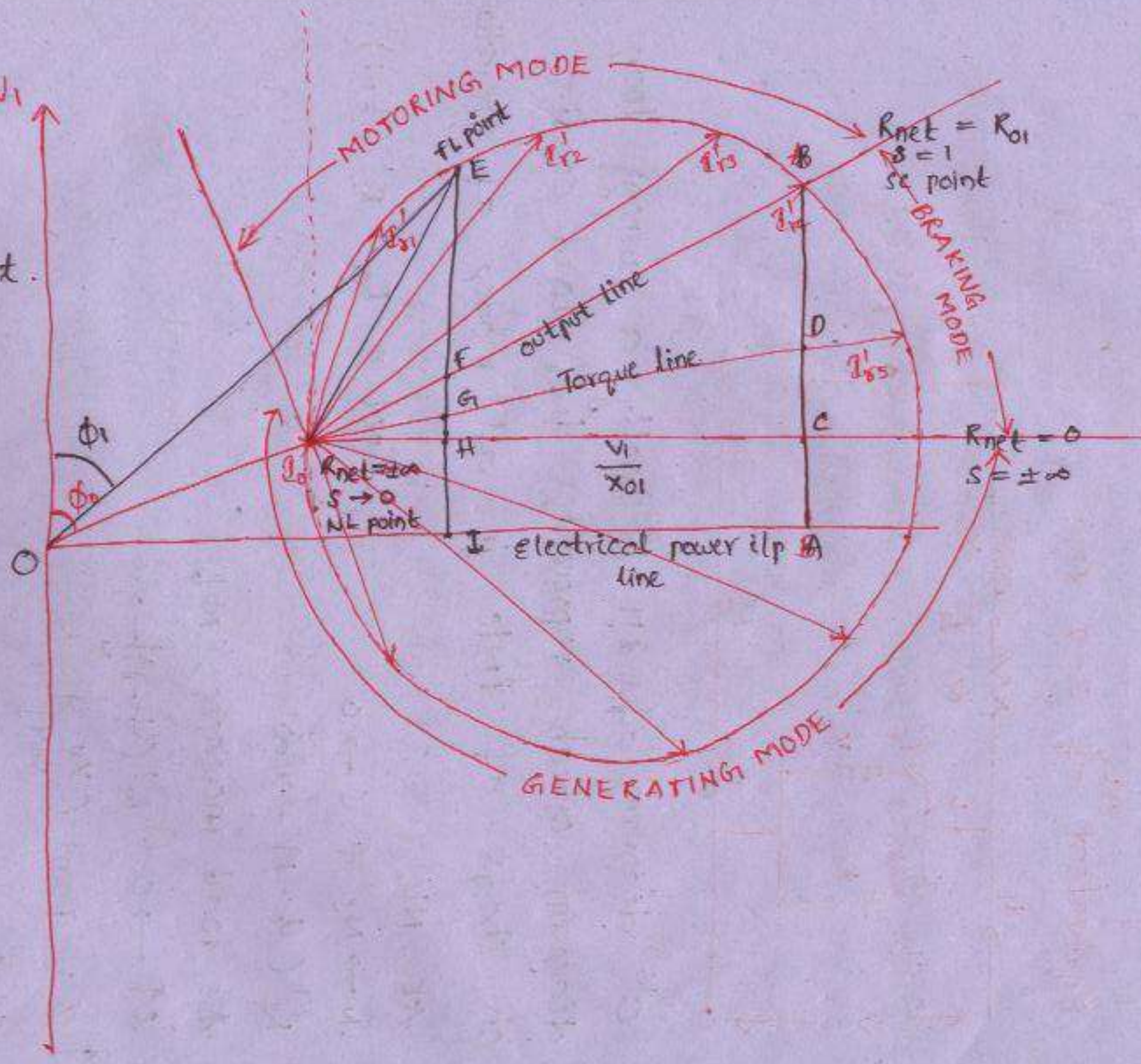
$\phi \uparrow$ & $I_r \uparrow\uparrow$

(s/c current under BR with rated volt.)

$\cos\phi_1 = fL$

pf of IM.

OE : fL
stator current.



Motoring Mode:

$0 < S \leq 1$

$+\infty > R_{net} \geq R_{01}$

Braking Mode:

$1 < S \leq +\infty$

$R_{01} > R_{net} > 0$

Generating mode:

$-\infty < S < 0$

$-\infty < R_{net} < 0$

when slip is >1,

$R_2'(\frac{1}{s}-1) \rightarrow -ve$ ie it consumes kinetic energy and deliver electric power ↓ This power is wasted in cu losses in R_{01}.

This mode : Braking mode.

so still it requires power from the stator, so still it is in motoring mode. [sink of active power].

b'coz generating power < power supplied

$R_2'(\frac{1}{s}-1) < R_{01}$ ⟶ Braking mode.

-ve +ve

$R_2'(\frac{1}{s}-1) < R_{01}$

-ve +ve

0.5Ω 1Ω

50W 100W

when $R_2'(\frac{1}{s}-1) = R_{01}$

-ve +ve

1Ω 1Ω

100W 100W

Neither Active sink nor source of active power.

$s = \pm\infty \Rightarrow$ still m/c acts in braking mode.

Entire power is supplied for losses.

if $N > N_s$,

$s \rightarrow -ve$.

$R_2'(\frac{1}{s}-1) > R_{01}$

-ve +ve

1.5Ω 1Ω

150W 100W

Net resistance is -ve

Net electrical power o/p = 50W at stator terminals.

∴ Generating mode [source of active power].

(1). The diameter of o^le in the o^le diagram is $\frac{V_1}{X_{01}}$, X_{01} – total reactance of IM when refer to stator side.

$X_{01} = X_1 + X_2'$

$I_r' = \frac{V_1}{jX_{01}} \angle -90°$.

If Rnet → +ve consumes active power.

Rnet → –ve generates active power.

In o^le diagram vertical lines are proportional to active power and horizontal lines are " to reactive power for a given load condition.

O/p line is the line joints NL point to SC point. The power available above the O/p line is net mech. power o/p for different load conditions.

AB – short circuit power under rated voltage

AC – const. losses

CB – cu losses in stator & rotor corr. to S/C current.

Torque line – It is the line which divides total cu loss at S/C condi. into stator and rotor cu losses in a specified ratio.

The power available above Torque line → rotor i/p power at diff. load condi.s.

CD – stator cu loss corr. to I_{sc}

BD – rotor cu loss corr. to I_{sc}.

At fL:

Torque line is also called as Air gap line

HI : const. losses

GH : fL stator cu losses

fG : fL Rotor cu losses

fE : Net mech o/p.

GE : Rotor i/p at fL

S_{fL} : $\frac{\text{Rotor cu loss at fL}}{\text{Rotor i/p at fL}} = \frac{fG}{GE}$.

$N_{fL} = N_s(1 - S_{fL})$

$\eta_{fL} = \frac{\text{Net mech. o/p at fL}}{\text{Electrical i/p at fL}} = \frac{fE}{EI}$.

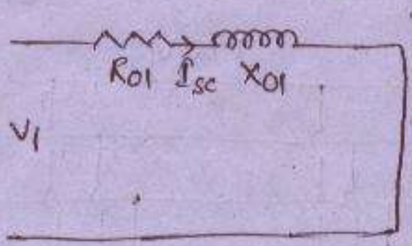
$T_{fL} = \frac{60}{2\pi N_s} \cdot \text{Rotor i/p at fL}$

$= \frac{60}{2\pi N_s} \cdot GE \times (\text{power scale})$

STARTING METHODS of 3-ϕ IM:

$N = 0;\ S = 1.$

$R_2'\left(\frac{1}{s} - 1\right) = 0.$



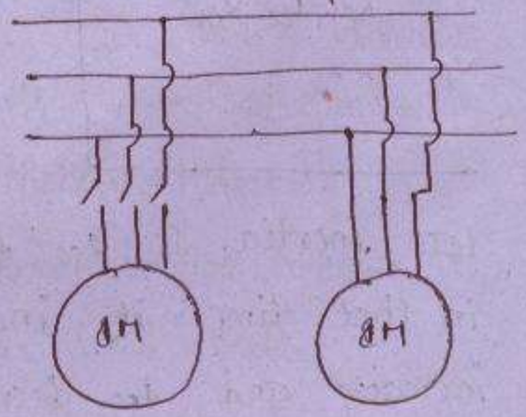
I_{sc} = 5 to 8 times I_{fL}.
whenever I_{sc} flows for a short duration then there is no damage.
Small IM < 5HP, having less inertia. So I_{sc} flows for a small duration in that time it increases speed and $R_2'\left(\frac{1}{s}-1\right)$ increases and I_{sc} decreases at a faster rate. So IM <5HP, no requirement of external starting methods.

* In case of small IM < 5HP, the inertia of rotor is less so that the rotor can pick up speed at a faster rate and reduces s/c current also at faster rate that means in small IM s/c current will flow through wdg over short duration of time and therefore no possibility of damage of wdg. Thats why small IM upto 5HP need not be started by using external starting methods.

* Large IM > 5HP, the above process takes place at a slower rate so that s/c current will flow through wdg over a long period of time which may damage wdg, so > 5HP motors must be started by using external starting methods.

$T \propto V_1^2$

* If IM are operated in conjuction with common bus bar if any one IM directly started, it draws very high current at the time of starting and produces large amount of volt. drop in the common bus bar. b'coz of this v. drop the operation of other IM's



connected to the bus will be effected.

* If the IM started directly T_{st} produced by IM high and the rotor may not respond to high T_{st} instantaneously because of its inertia. Then there is lot of mech. stress on shaft of IM which is known as shaft fatigue which may lead to damage of shaft.

$T_{st} \propto$ Rotor i/p at starting

$\propto I_{st}^2 \cdot R_2'$

$T_{fl} \propto$ Rotor i/p at fl.

$\propto I_{fl}^2 \cdot R_2'/s_{fl}$

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 \cdot s_{fl}$$

SERIES REACTOR / RESISTOR METHOD OF STARTING:

	I_{st}	T_{st}
DOL starting:	900 A	200 N-m
series reactor/ resistor method: ($x = 0.5$)	450 A	50 N-m

As starting torque reduction is more when compared to starting current reduction, so this is not sutable to start IM which handles high T_{st} demanded loads. Thats why this method of starting employed for start IM which handles fan and pump type loads.

AUTO T/F METHOD OF STARTING:

	I_{st}	T_{st}
DOL	900 A	200 Nm
Series reactor/ resistor	450 A	50 Nm
Auto T/F	225 A	50 Nm.

For same starting current rating, T_{st} reduction is less in Auto T/F

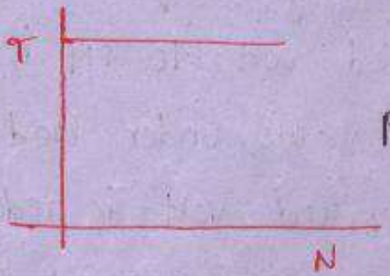
In Auto T/F method, the starting current drawn by IM is further reduce by x, when compared to series reactor/resistor method, for same reduction in T_{st}.

B'coz of less reduction in T_{st} for a given reduction in starting current, this method can be used for starting which demands high T_{st}.

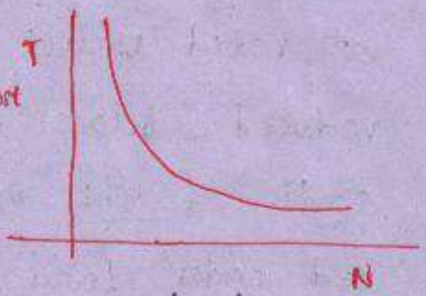
Auto T/F method is used for large motors >20 HP where starting current reduction is less than 1/3. [By the use of tappings]. But with Y-Δ method starting current reduction is fixed at 1/3. only. so it can be used for starting below 20 HP motors.

* FRI. 21/11/08 *

SPEED CONTROL TEQ.S OF IM'S:



$$P = \frac{2\pi N T_{const}}{60}$$



cont torque,
variable power.
drive.

Arm. control technique
on dc motor.

constant power
variable torque
drive

IN D/c m/c's.

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

$\downarrow T_a \propto \downarrow \phi I_a$

field weakening
method or flux
control technique
on dc motor.

Ideal requirement of any speed control technique is the torque produced by m/c is maintain const. irrespective of variable speed. ie const. torque, variable power drive.

① Slip control Techniques:

(i). voltage control

(ii). Rotor resistance

(iii). Rotor emf injection technique

②. Syn. speed control techniques:

(i). frequency control

(ii). pole changing

(iii). cascading of 2 IM's.

VOLTAGE CONTROL TECHNIQUE :

In this method, by keeping freq const. at rated value, the applied volt. to IM is reduced below its rated value under load condi. of the m/c. If applied volt. is reduced under load condi. slip is increased to maintain load torque, so speed of IM falls below its rated value.

Speeds below rated value can only be achieved.

$f = f_{rated}, \quad V_1 \downarrow < V_{1rated}$.

under load condi,

$$\underset{\text{const.}}{T} \propto \frac{\uparrow s V_1^2 \downarrow}{R_2 \rightarrow \text{const}}$$

During this speed control, IM ~~has~~ acts const. torque variable power drive.

$T = \text{const}$.

$s V_1^2 = \text{const}$

$\rightarrow s_1 V_{11}^2 = s_2 V_{12}^2$.

400V, 50 Hz

$\downarrow$

300V, $f = \text{const}$, $N_2 = ?$

$\Rightarrow 0.05\,(400)^2 = s_2\,(300)^2$

$\Rightarrow s_2 = \_\_\_$

$N_2 = N_s(1 - s_2) = \_\_\_$.

DRAWBACKS:

$\bar{I}_1 = \bar{I}_0 + \bar{I}_r$, if I_0 is neglected,

$$\bar{I}_1 \simeq \bar{I}_r = \frac{E_r'}{\sqrt{\left(\frac{R_2'}{S}\right)^2 + {X_2'}^2}}$$

If $\frac{R_2'}{S} >> X_2'$; $\bar{I}_r = \frac{SE_2'}{R_2'}$

$T \propto \frac{\overset{\times 2}{\uparrow S}\, V_1^2 \frac{1}{\sqrt{2}}\downarrow}{R_2}$ $\qquad I_1 \propto \frac{SV_1}{R_2'}$

$\qquad T \propto \frac{\overset{\times 3}{\uparrow S}\, V_1^2 \downarrow 1/\sqrt{3}}{R_2}$

$\underset{\sqrt{2} I.}{\overset{}{\uparrow}} I \propto \frac{\overset{\times 2}{\textcircled{S}}\, V_1 \downarrow \frac{1}{\sqrt{2}}}{R_2'}$ $\qquad \sqrt{3}I \uparrow I \propto \frac{\overset{\times 3}{S}\, V_1 \downarrow 1/\sqrt{3}}{R_2'} \rightarrow 1.732 \Rightarrow 73.2\%$ over loading.

$\longrightarrow$ 41.1% stator overloading.

(1). IM draws high currents at low voltages and it leads to over loading of stator wdgs. Due to over loading of stator wdgs, this tech. is not suitable for long duration speed control, but it can be implemented for short duration speed control.

In this method stator overloading increases with reduction in speed, thats y this method not suitable to get wide range of speed control. But it can be implemented for narrow range of speed control.

To findout % overloading;

$I_1 \propto SV_1$

$$\rightarrow \frac{I_1''}{I_1'} = \frac{S_2 V_{12}}{S_1 V_{11}} \qquad \begin{matrix} N_s = 1000 \downarrow \\ N_1 = 950 \end{matrix}$$

$$= \frac{0.08 \times 300}{0.05 \times 800} = 1.2 \Rightarrow 20\% \text{ over loading}$$

ROTOR RESISTANCE METHOD OF SPEED CONTROL:

↓ Slip ring IM.

$$\underset{\text{const}}{T} \propto \frac{\uparrow s V_1^2 = \text{const.}}{R_2+R_e} \Rightarrow \frac{s}{R} = \text{const.}$$

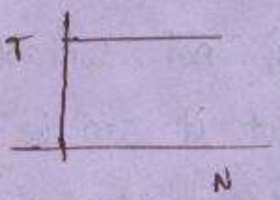
$$\downarrow N = N_s(1-s\uparrow)$$

In this method, some external resistance is to be inserted in series with rotor to control speed of IM.

If external resistance inserted under load condi. slip of IM increases to maintain load torque const. there by speed of IM falls below its rated value.

In this method, speeds below the rated value can only be achieved.

In this, IM acts as const Torque, variable power drive.



Torque ⟹ const.

$$\Rightarrow \frac{s_1}{R_2} = \frac{s_2}{R_2+R_e}$$

$R_2 = 0.2\Omega$ /ph

$N_s = 1000$ rpm.

$N_1 = 950$ rpm

$R_e = ?$ for reduce speed from 950 to 800 rpm.

$$\frac{s_1}{R_2} = \frac{s_2}{R_2+R_e} \Rightarrow \frac{0.05}{0.2} = \frac{0.2}{0.2+R_e}$$

$$\Rightarrow R_e = 0.6\,\Omega/\text{ph}.$$

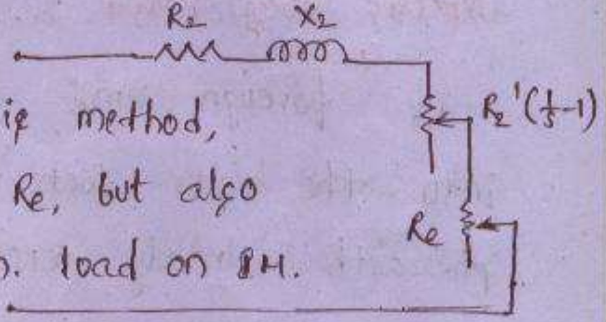
DRAWBACKS :

(1). Due to additional cu losses in R_e, η of IM reduces in this method.

(2). Due to excessive heat produced in R_e, this method is not suitable for long duration speed control, but it can be implemented for short duration speed control.

(3). In this method η of IM, decreases with reduction in speed (increase in R_e value), so this method is not economical for wide range of speed control. but it can be implemented for narrow range of speed control.

(4). speed of IM in this method, not only depends on R_e, but also on magnitude of mech. load on IM.



That's y this method of speed control has poor speed regulation.

ROTOR EMF INJECTION METHOD :

{ Suitable on slip ring IM }

In this method some external emf is to be injected at slip freq through slip rings of SRIM & under load condi.

Depending upon phase of injected emf w.r.t already existing emf in rotor, the speed of IM can be controlled.

In this method, speeds below as well as above rated value can be achieved.

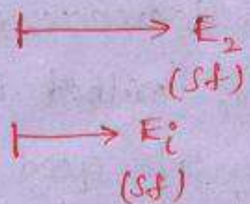
$\Rightarrow E_{2R} = E_2 - E_i$

(we can get speeds below its rated speed).

$T \propto \frac{SV_1^2}{R_2}$

$\Rightarrow \underset{\text{const}}{T} \propto \uparrow \frac{S E_{2R}^2 \downarrow}{R_2 = \text{const}}$

$\downarrow N = N_s(1 - S\uparrow)$



$\Rightarrow E_{2R} = E_2 + E_i$

$\underset{\text{(const)}}{T} \propto \downarrow S \; E_{2R}^2 \uparrow$

$R_2 = \text{const}$

(we can get speeds above rated speeds).

$\uparrow N = N_s(1 - S\downarrow)$

If foreign emf is injected at slip freq. into the rotor such that it is 180° out of ph. with already existing emf in the rotor then resultant emf across rotor decreases and slip increases to maintain load torque const. so speed of IM falls below its rated value.

If foreign emf is injected such that it is in ph. with already existing one then the resultant emf increases and slip falls to maintain load torque const. there by speed of IM rises above its rated value.

→ Const. torque, variable power drive.

→ All slip control techniques → having const. torque, variable power drive behaviour.

$T =$ const.

$\Rightarrow sE_{2R}^2 =$ const.

$\Rightarrow s_1 E_2^2 = s_2 (E_2 \pm E_i)^2$; $+ \rightarrow$ inphase injection
$- \rightarrow$ outofph. injection.

$E_2 = 200\,V \longrightarrow N_1 = 950$ rpm

$E_i = \overset{(\text{inph.})}{\underset{30V}{20V}} \longrightarrow N_2 = ?$ $\quad N_s = 1000$ rpm.

(180° out of ph.)

$\Rightarrow 0.05\,(200)^2 = s_2\,\overset{(220^2)}{(180)^2}$

$\Rightarrow s_2 = \overset{(0.04)}{\underset{0.07}{0.06}}$

$\therefore N_2 = N_s(1 - s_2)$

$= 1000(1 - 0.06) = \overset{930\text{ rpm}}{940}$ rpm. (960 rpm)

$\rightarrow$ Smooth & wide range speed control is possible.

FREQUENCY CONTROL TECHNIQUE:

By varying f, below & above rated values, the speed of IM can be varied both below & above rated values.

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

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

Below N_{rated},

$V_1 = V_{1rated}$, $f < f_{rated}$.

$\uparrow \phi_R \propto \frac{V_1 \text{ const}}{f \downarrow}$ $\qquad$ doesn't desirable

goes into deep saturation, I_μ increases $(\underset{\Uparrow}{} I_\mu \uparrow)$

$\cos\phi_0 \downarrow$ & $\cos\phi_{fl} \downarrow$.

pure freq. control is not desirable

By keeping applied volt. const, if the freq. of operation is reduced below its rated value, Then the following undesirable consequences takes place and makes the operation of IM poor.

(a). $\phi_R \uparrow$, $I_\mu \uparrow$, $\cos\phi_0 \downarrow$, $\cos\phi_{FL} \downarrow$.

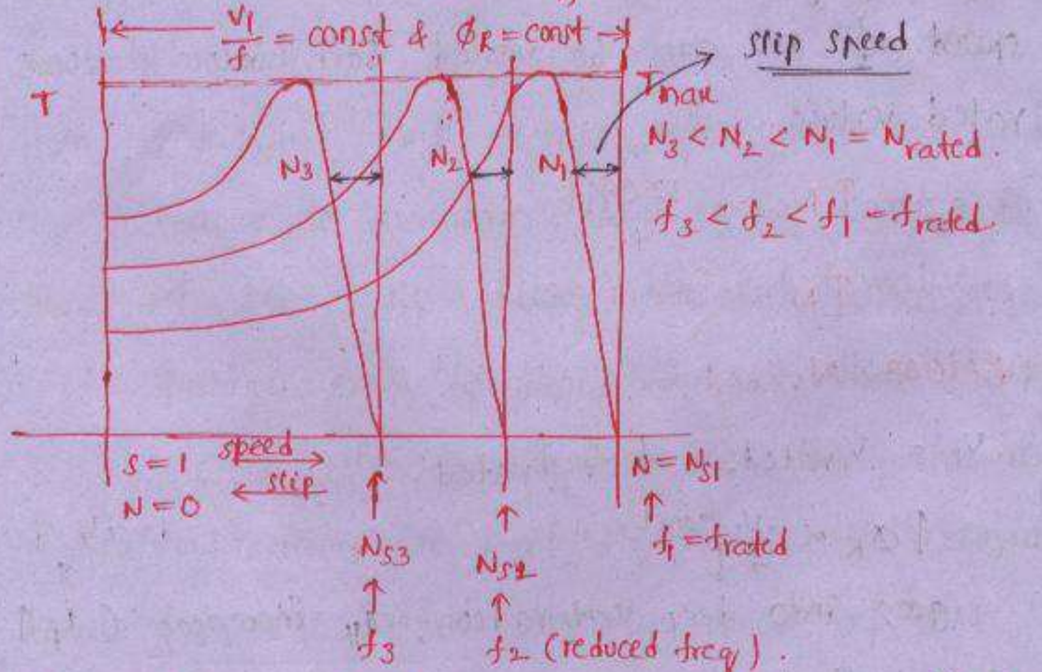
Due to above undesirable consequences pure freq. control tech. not employed to get speeds rated value instead of that $\frac{V_1}{f}$ control tech. is employed for satisfactory operation of IM during speed control.

$\frac{V_1}{f}$ control technique,

$\frac{V_1}{f} = \text{const.}$; $T_{max} = \text{const.}$

$T_{st} \propto \frac{1}{f}$

$S_m \propto \frac{1}{f}$



For getting constant torque - variable power drive,

$$T = \frac{180}{2\pi N_s} \cdot \frac{sV_1^2}{R_2}$$

$$= \frac{180}{2\pi N_s} \cdot \left(\frac{N_s - N}{N_s}\right) \cdot \frac{V_1^2}{R_2} = \text{const}$$

$\Rightarrow \quad T \propto \left(\frac{V_1}{f}\right)^2 (N_s - N)$

To maintain Torque constant,

(1). $\frac{V_1}{f}$ = const. (Air gap flux should be maintain const.)

(2). slip speed should be maintain const. ie

$(N_s - N) \qquad (N_{s1} - N_1) = (N_{s2} - N_2) = (N_{s3} - N_3) = \text{const.}$

During $\frac{V_1}{f}$ control technique, in order to get const torque behaviour, the above two condi.s should be satisfied.

If the above condi.s are satisfied, 3-φ IM acts as const torque - variable power drive in the range of below rated speeds.

400V, 50Hz, $N_1 = 950$ rpm ; $N_s = 1000$ rpm

300V, 37.5 Hz $N_2 = ?$

verify for const. T; → ①. $\frac{V_1}{f}$ = const. $\left\{ \frac{400}{50} = \frac{300}{37.5} = \text{cons} \right.$

②. $N_{s1} - N_1 = N_{s2} - N_2$

$N_{s2} = \frac{120 \times 37.5}{6} = 750$ rpm.

$1000 - 950 = 750 - N_2$

$\Rightarrow N_2 = 700$ rpm.

ABOVE RATED SPEED :

$V_1 = V_{rated}$. $\qquad \downarrow \phi_R \propto \frac{V_1 = \text{const}}{f \uparrow}$

$f > f_{rated}$.

$\Rightarrow I_\mu \downarrow, \ \cos\phi_0 \uparrow, \ \cos\phi_{NL} \uparrow$.

pure freq. control only is possible, $\frac{V_1}{f}$ control is not possible b'coz V_1 can't be increased above V_{rated}.

If so more stress on the insulation of wdgs and may get damage
($V > V_{rated}$).

V_1 = const ; f ↑ > f_{rated}.

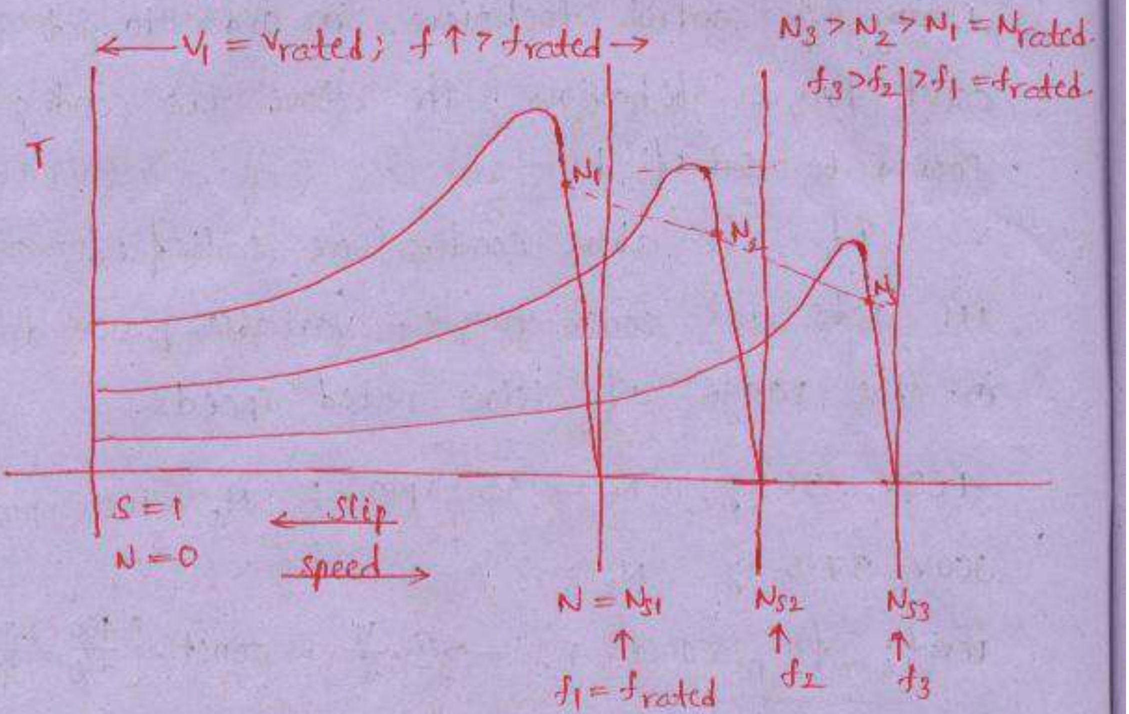
$T_{max} \propto \frac{1}{f^2}$

$T_{st} \propto \frac{1}{f^3}$

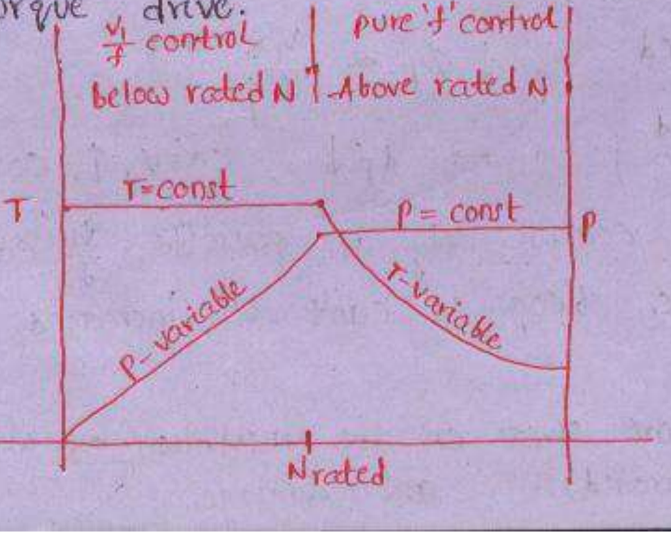
$S_m \propto \frac{1}{f}$

Maintaining const. torque is not possible.

$\therefore \frac{V_1}{f}$ is not const.



As $\frac{V_1}{f}$ ratio can't be maintain const, with pure freq. control technique, the torque produced by IM can't be maintain const. That's y above the rated speed IM acts as constant power - variable torque drive.



ward Leonard method of speed control in dc shunt motor is equivalent to freq. control technique in IM.

In ward leonard,

below N_{rated}	Above N_{rated}
Arm. controlled	flux controlled
const T; var. P	const P; var. T

Harmonic Torque in 3-Ø IM:

ph. spread angle ($m\beta$) = 120 & 60°.

3m, m = odd ⇒ 3, 9, 15, 21 . . . . are absent.

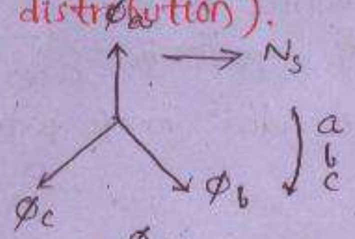
Then 5, 7, 11, 13, 17, 19 . . . are present in the resultant mmf wave. (space harmonics).

ie $6m \pm 1$, m - integer.

Resultant mmf wave is a trepezoidal wave form. (due to wdg distribution).

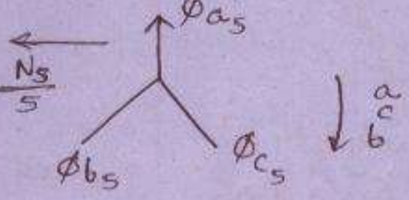
Fundamental flux:

(0, 120, 240)



5th harmonic flux:

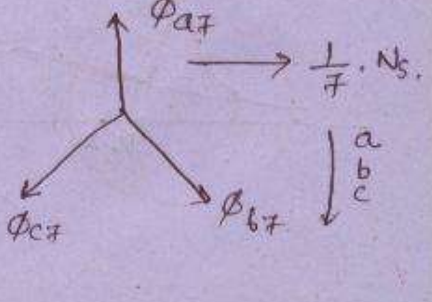
(0, 240, 120)



7th harmonic flux:

(0×7, 120×7, 240×7)

= (0, 120, 240)



Relative speed b/w $(6m \pm 1)$ with respect to fundamental : $\frac{6m}{6m \pm 1} N_s$.

$$\left.\begin{array}{l} \longmapsto N_s \\ \longmapsto \frac{1}{7} N_s \end{array}\right\} \frac{6N_s}{7} \qquad \left.\begin{array}{l} \longmapsto N_s \\ \longleftarrow\!\!\dashv \ \frac{1}{5} N_s \end{array}\right\} \frac{6N_s}{5}.$$

fundamental $\phi \longrightarrow$ funda. torque $T_f \longrightarrow$ Nearly N_s (Motoring)

5th harmonic $\phi_5 \longrightarrow T_5 \longrightarrow -\frac{1}{5} N_s$ (braking mode).

7th har. flux $\phi_7 \longrightarrow T_7 \longrightarrow \frac{1}{7} N_s$ (Motoring mode).

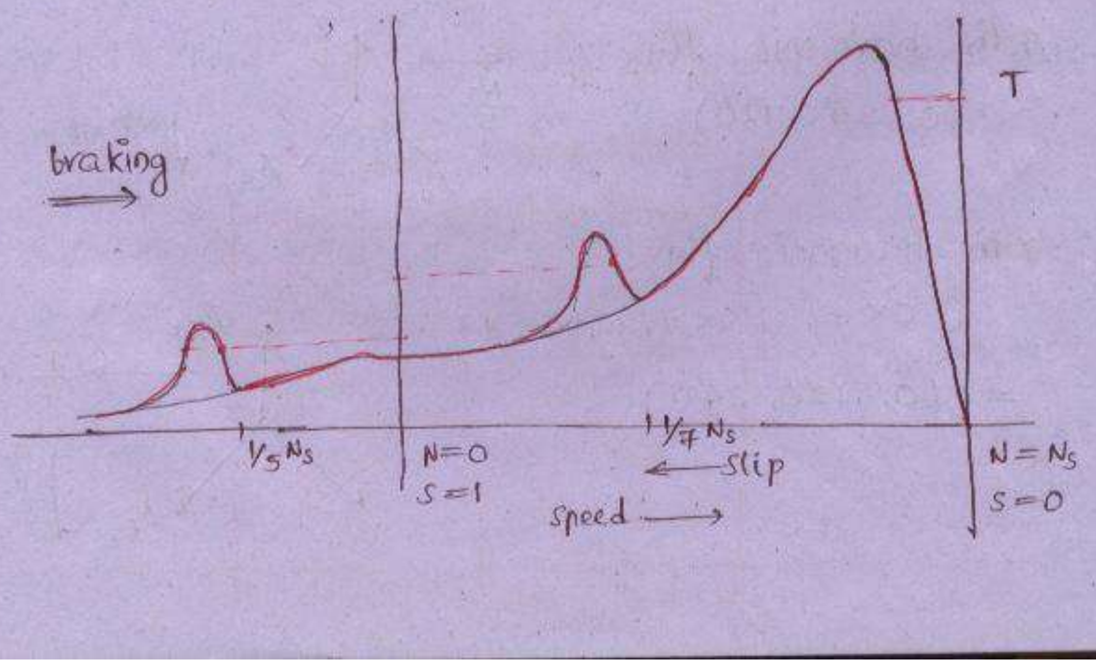
11 th har. flux $\phi_{11} \longrightarrow T_{11} \longrightarrow -\frac{1}{11} N_s$ (Braking mode).

: etc.

$(6m \pm 1)$ harmonics → space harmonics.

Harmonics are due to trapezoidal mmf wave.
⇓ (space har.s).

trapezoidal mmf wave due to wdg distribution.



chrawling :- Stable operation of 8IM. is at $\frac{1}{7} N_s$ instead of approaching linear portion of actual torque with fundamental. slip corr. to $\frac{1}{7} N_s$ is $\frac{6}{7}$.
ie out of 7 parts, 6 parts of power wasted in cu loss.

Even though getting stable operation but η is too poor. at $\frac{1}{N} N_s$, due to production of 7th harmonic torque. (motoring mode).

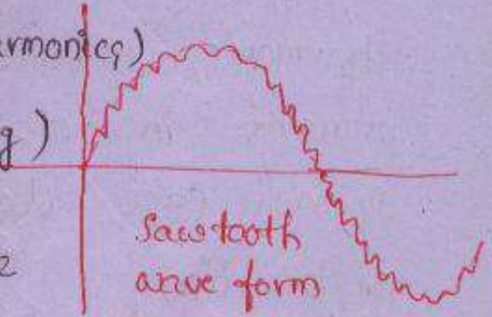
In braking mode, due to 5th harmonic torque, when the rotor speed falls to zero, there is a linear portion due to 5th harmonic torque, so the rotor settled in stable at $\frac{1}{5} N_s$ and will not reach to zero. This is the chrawling phenomina in braking mode.

Slot harmonics :-
(or) (Tooth harmonics)

$n = 6mg \pm 1$ (Stator slotting)

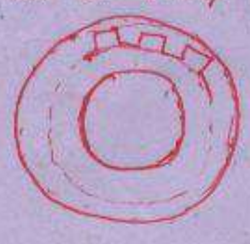
m - integer

g - no. of slots / pole / phase


Saw tooth wave form due to slots (stator)

Eg: 3-Ø, $P = 4$, $S = 24$.

$\therefore g = \frac{24}{3 \times 4} = 2$.



For, $m = 1$.

$-11, +13$.

$\xleftarrow{\quad} \quad \xrightarrow{\quad}$

$-\frac{1}{11} N_s, \; \frac{1}{13} N_s$

for $m=2$,

-23 & 25

$$-\frac{N_s}{23} \qquad \frac{N_s}{25}$$
$$\longleftarrow\!\mid \qquad \mid\!\longrightarrow$$

Eg : 3-Ø, 4-pole
36 slots.

$$g = \frac{36}{3 \times 4} = 3.$$

for $m = 1$;

-17 & 19

$$-\frac{1}{17} N_s , \quad \frac{1}{19} N_s$$
$$\longleftarrow\!\mid \qquad \mid\!\longrightarrow$$

Rotor slotting

→ saw tooth wave form.

order n: $2\left(\frac{S_2}{p}\right) \pm 1$.

S_2 → no. of rotor slots.

p → no. of poles.

Eg: $S_2 = 20$ slots.
$p = 4$.

$$n = 2\left(\frac{20}{4}\right) \pm 1$$
$$= \underline{-9}, \quad \underline{+11}$$
$$\frac{1}{9} N_s \qquad \frac{1}{11} N_s$$
$$\longleftarrow\!\mid \qquad \mid\!\longrightarrow$$

harmonics of order $3m$, m - odd are also present in rotor mmf only in case of squirrel cage b'coz in sq. cage no wdg distribution.

3-Ø, 4-pole IM: (stator only) $(6mg \pm 1)$ $\underline{(m=1)}$ $2\left(\frac{S_2}{p}\right) \pm 1$

S_1	S_2	g	Stator harmonics	Rotor harmonics
24	20	2	$-\textcircled{11}$, +13	−9, $+\textcircled{11}$
24	28	2	−11, $+\textcircled{13}$	$-\textcircled{13}$, +15
36	32	3	$-\textcircled{17}$, +19	−15, $+\textcircled{17}$

36 40 3 -17 $+19$ -19 $+21$

when harmonic poles are same then at a perticular speed locking of those harmonic poles. (ie relative speed b/w stator & rotor harmonic poles = zero). ⟶ synchrozing har. torque.

{ space harmonics ⟶ Asyn har. torque).

⟶ speed of 11 th harmonic stator pole w.r.t stator $= -\frac{1}{11} N_s$.

Speed of 11 th harmonic rotor pole w.r.t stator = speed of 11th harmonic rotor pole w.r.t rotor + speed of rotor w.r.t stator.

$$= \frac{N_s - N}{11} + N$$

$$\Rightarrow -\frac{1}{11} N_s = \frac{N_s - N}{11} + N$$

$$\Rightarrow N = -\frac{1}{5} N_s. \quad \longleftarrow \text{(cogging)}$$

IM. will get a tendency at $\frac{1}{5} N_s$, due to 5th space harmonic & and also with 11 th slot harmonic.

with 13 th slot harmonic,

$$\frac{1}{13} N_s = -\frac{N_s - N}{13} + N$$

$$\Rightarrow N = \frac{1}{7} N_s. \longrightarrow \text{(In motoring mode.)}$$

24 24 2 −11 +13 −11 +13.

Relative speed b/w 13thstator & rotor poles = 0, when,

$$\frac{1}{13} N_s = \frac{N_s - N}{13} + N$$

$\rightarrow N = 0. \longleftarrow$ cogging. { Chrawling at starting itself }

ie when $S_2 = S_1$, $S_2 = m.S_1$ } magnetic locking or cogging..

with $m = 2$.

24 48 2 −23 25 −23 25.

Space harmonic torque (Asynchronous harmonic torque) are avoided by the proper short pitching of wdg. $\rightarrow \{ \alpha = \frac{180}{n} \}$.

↑ pitch angle.

Slot harmonic torques (synchronizing har. torques) can be reduced by selecting $S_2 \neq S_1$

$S_2 \neq mS_1$

S_1 & $S_2 \neq 6px$; x – integer

p – no. of poles.

S_1 & $S_2 \neq$ ~~6px ± 4~~ $6p \pm 2x$.

Slot harmonic torques also can be reduced by skewing of rotor slots.

1). $\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2} = 0.6 \Rightarrow a = 0.33 ✓, 3 ✗$

$a = \frac{R_2 + R_e}{X_2}$

$\Rightarrow 0.33 = \frac{0.25 + R_e}{2}$

$\Rightarrow R_e = 0.41\ \Omega/ph.$

$N_m = 875$ rpm

$S_m = 0.125$

$S_m = \frac{R_2}{X_2}$

$\Rightarrow 0.125 = \frac{0.25}{X_2}$

$\Rightarrow X_2 = 2\Omega$

5). $f_r = sf.$

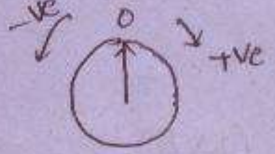
120 oscillations/min

$= \frac{120}{60}$ osc/sec

$f_r = 2$ Hz.

$\Rightarrow s = \frac{f_r}{f} = \frac{2}{50} = 0.04$ pu.

6). 30 osc/min



$= \frac{30}{60}$ osc/sec

$= 0.5$ osc/sec

$f_r = 0.5$ Hz

$S = \frac{0.5}{5} = 10\%.$

$N = N_s(1-S)$

$= 1000(1-0.1) = 990$ rpm.

23). Rotor cu loss in wdg $= 3I_{FL}^2 R_2$

Net mech. o/p = 25 Hp.

$= 25 \times 735.5$

$= 18.38$ kw

Gross mech power o/p $= 18.38 + 1 \leftarrow$ mech losses.

$= 19.38$ kW

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

$$= \frac{1000 - 960}{1000} = 0.04.$$

Rotor cu loss = Gross mech. o/p $\times \frac{S}{1-S}$

$$= 19.38 \times \frac{0.04}{0.96}$$

$= 807.5$ W.

cu loss in gear.

Rotor cu loss in wdg $= 807.5 - \overset{\downarrow}{250}$

$= 557.5$ W.

Rotor cu loss in wdg $= 3 I_{fl}^2 \cdot R_2$

$$557.5 = 3(35)^2 \cdot R_2$$

$$\longrightarrow \quad R_2 = 0.752 \ \Omega/\text{ph}.$$

24). $(KVA)_{Auto} = \sqrt{3} \cdot V_L \cdot I_L$

$V_L = V_1 = 440$

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

$I_{sc} = 6 \cdot I_{fl}$

$= 6 \times 65.61$

$= 393$ A.

$$I_{fl} = \frac{50 \times 10^3}{\sqrt{3} \times 440}$$

$= 65.61$ A

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

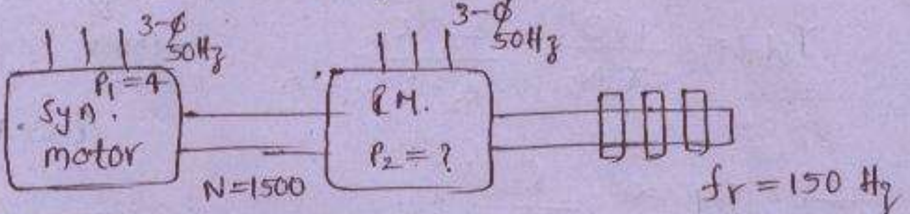
$= (0.5)^2 \cdot 393$

$= 98.25$ A.

$$(kVA)_{Auto} = \sqrt{3} \times 440 \times 98.25$$

$$= 75 \text{ kVA}.$$

25).



$N_s = 1500.$

$$S = \frac{f_r}{f} = \frac{150}{50} = 3. \longleftarrow \text{slip} > 1 \rightarrow \text{braking mode.}$$

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

$$\cancel{3} = \frac{\cancel{1500} - \cancel{N}}{\cancel{1500}} \Rightarrow N = 1500 \text{ rpm}.$$

$$\Rightarrow 3 = \frac{N_s - 1500}{N_s}$$

$$\Rightarrow N_s = -750 \text{ rpm}.$$

$$\therefore P_2 = 8.$$

26). $$N_{set} = \frac{120 f}{P_1 + P_2}$$

$$= \frac{120 \times 50}{8 + 6} = 428 \text{ rpm}.$$

$$N_{set} = \frac{120 f}{P_1 \sim P_2}$$

$$= \frac{120 \times 50}{2} = 300 \text{ rpm}.$$

If stator losses in main IM are neglected,

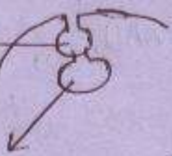
Rotor i/p of m.IM = 50 kW

Electrical power i/p to A.IM $= P_{gm} \cdot \frac{P_2}{P_1 + P_2}$

$$= 50 \times \frac{8}{14}$$

$$= 28.57 \text{ kW}.$$

27).



$$T_{st} = \frac{180}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

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

$$(T_{st})_{outer} \propto \frac{R_{2o}}{R_{2o}^2 + X_{2o}^2} = 1.376$$

$$(T_{st})_{inner} \propto \frac{R_{2i}}{R_{2i}^2 + X_{2i}^2} = 0.05$$

$$\Rightarrow \frac{(T_{st})_{outer}}{(T_{st})_{inner}} = \frac{1.376}{0.05} = 2.479.$$

30). $(I_{st})_Y = 120\ A$

$(I_{st})_\Delta = 120 \times 3 = 360\ A$ ← direct starting

$= I_{sc}.$

$I_{fl} = \frac{360}{6} = 60\ A.$

$(KVA)_{IM} = \sqrt{3} \cdot V_L \cdot I_L$

$= \sqrt{3} \times 440 \times 60$

$= 45.72$ KVA.

42). NL Loss (power) $= \omega_0$

Mech. loss $= \frac{1}{3}\omega_0$

$\Rightarrow$ Iron loss $= \omega_0 - \frac{1}{3}\omega_0$

$= \frac{2}{3}\omega_0.$

Stator cu loss $= \frac{2}{3}\omega_0$

Rotor cu loss $= \frac{2}{3}\omega_0$

#/ Electrical power i/p $= \dfrac{50 \times 735.5}{0.9}$

$= 40.86$ kω.

Total losses $= 40.86 - 36.7$

$= 4.11$ kω

$\Rightarrow \omega_0 + \frac{2}{3}\omega_0 + \frac{2}{3}\omega_0 = 4.11$

$\Rightarrow \omega_0 = .1765\ \omega$

Slip $= \dfrac{\text{Rotor cu loss}}{\text{Rotor i/p}}$

Rotor i/p = mech o/p + Mech. loss + Rotor cu loss

$= 36.7 \times 10^3 + 588 + 1176$

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