ElCoM
ELECTRICAL COMPUTER MECHATRONICS

تقدم لجنة ElCoM الاكاديمية

دفتر لمادة:

الات كهربائية (2)

جزيل الشكر للطالب:

عدنان حوراني

م٥ الات كهربائية 2 عدنان الجوراني

Three phase Transformers :-

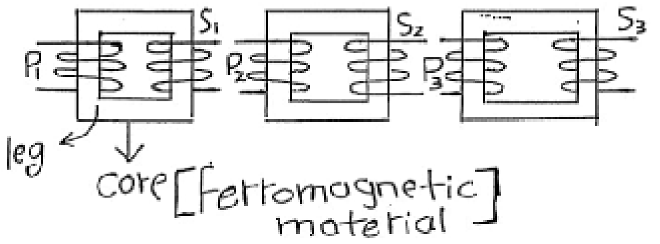
All major power systems in the world are Three phase .

Three phase Transformers

- Three Single phase Transformer.
- Single three phase Transformer.
  - *Smaller
  - *lighter
  - *Cheaper
  - *Slightly more efficient

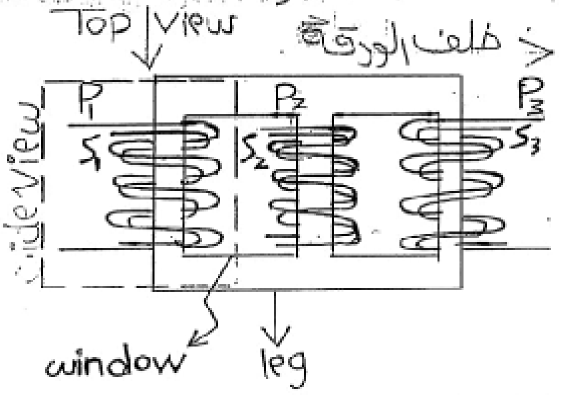
Three Single phase Transformer.

each unit in the bank could be replaced individually in the event of trouble.



Single three phase Transformer.

خلف الورقة ->



لازم نعمل عزل بين كل ϕ والأخرى.

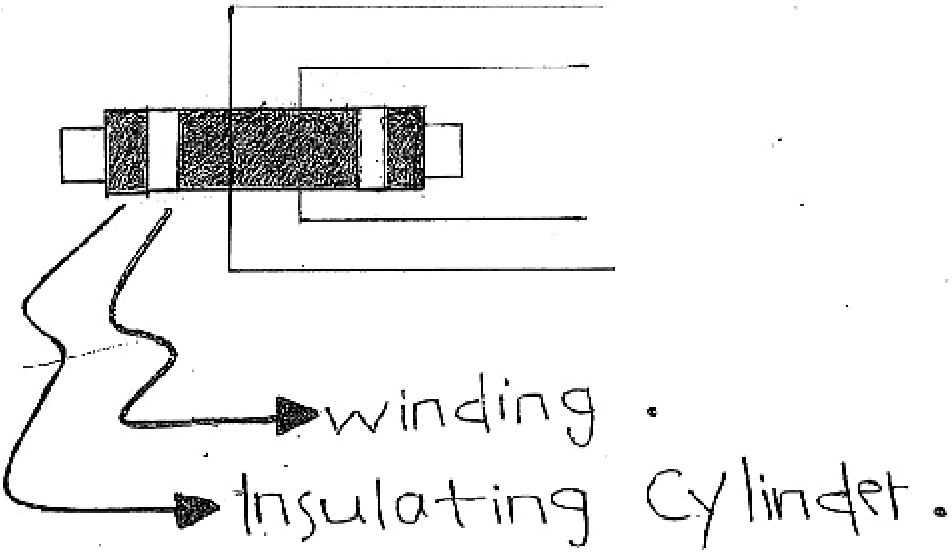
$\hookrightarrow \mu_r$ (2000-6000).

R very small. $\left[R=\frac{l}{\mu_o \mu_r A}\right]$.

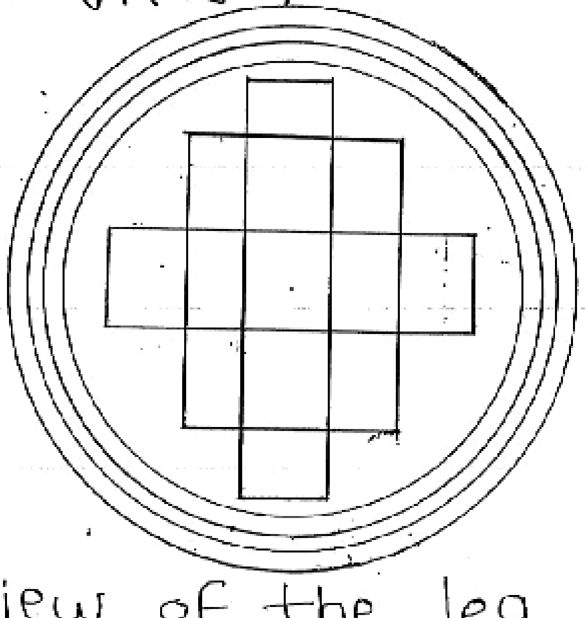
Flux flow through the path easily.

Energy ↓

→ Side view :-



→ Top view :-



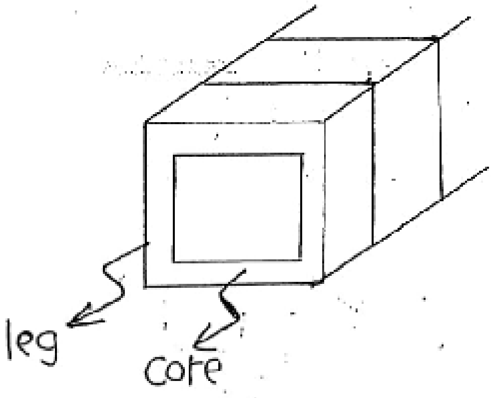
الدائرة الشكل الهندسي التي لها أقل محيط عند نفس المساحة لباقي الأشكال الهندسية .

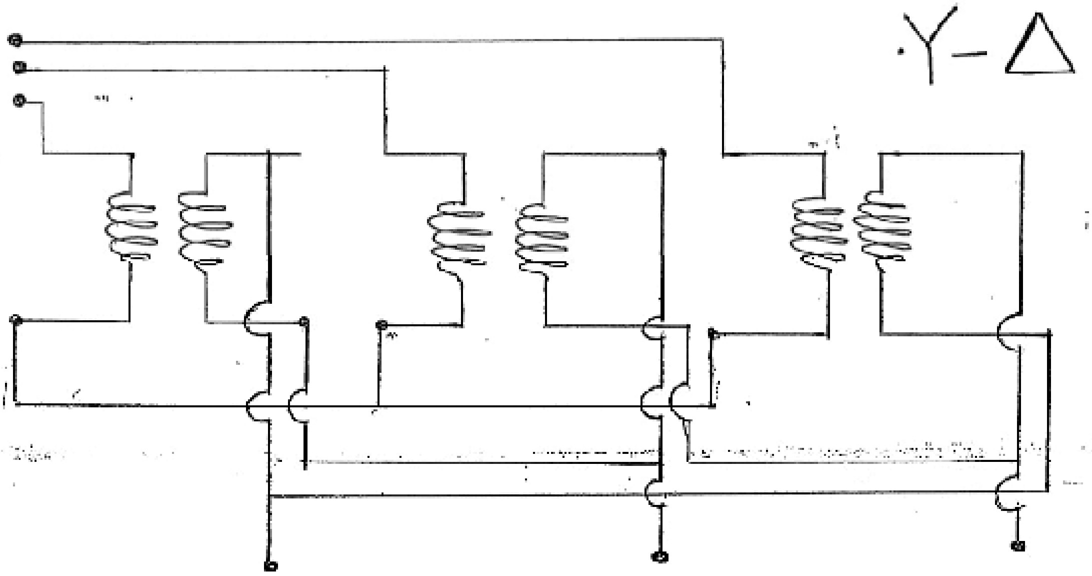
$$R = \frac{\rho L}{A} .$$

Top view of the leg is very closed Circular , because the circle has the lowest Circumference Compared with Square and triangle .

note: limination: to reduce eddy current losses.

↳ $\rho \uparrow$.





note: discrebed of Step up and Step down based on phase voltages

$V_{P-\phi}$ Y – Δ $V_{S-\phi}$

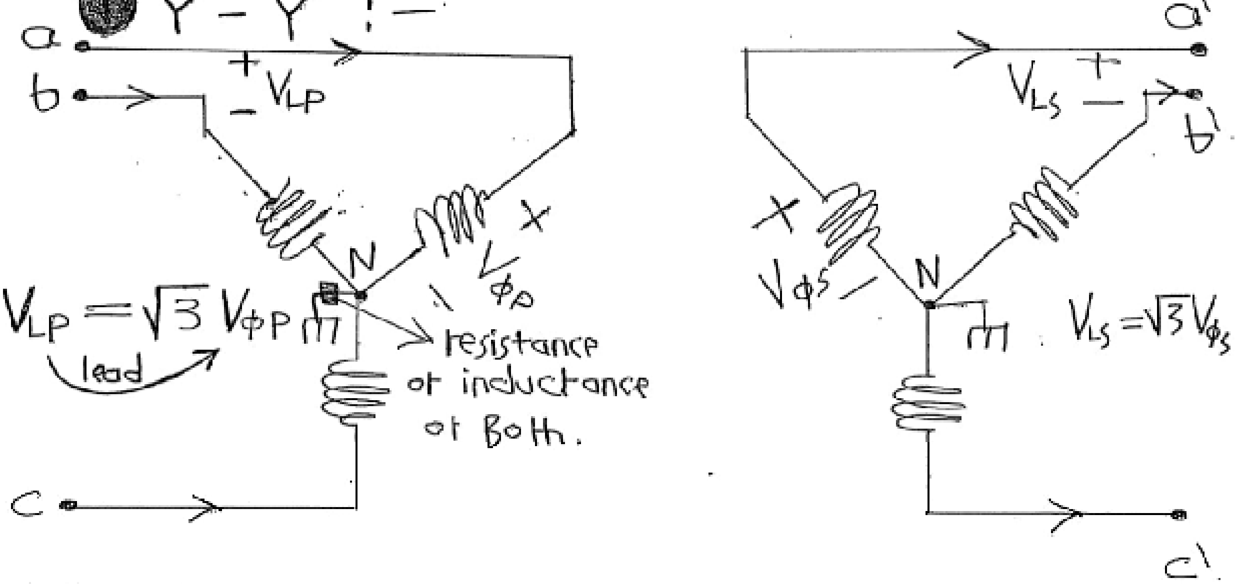
$$a = \frac{V_{P-\phi}}{V_{S-\phi}} = \frac{\#\text{ of terms P.}}{\#\text{ of terms S.}} = \frac{N_{P-\phi}}{N_{S-\phi}}$$

= turns ratio

Three phase Transformer

Connections :-

● Y-Y :-



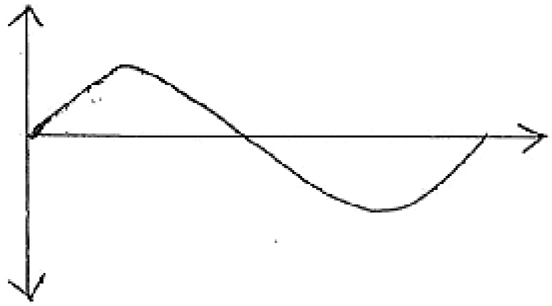
Y-Y connection has 2 problems :

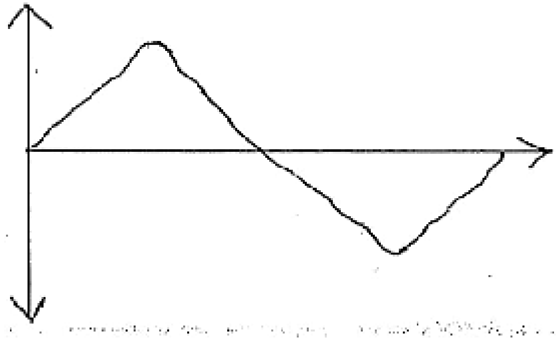
1- unbalanced problem :-

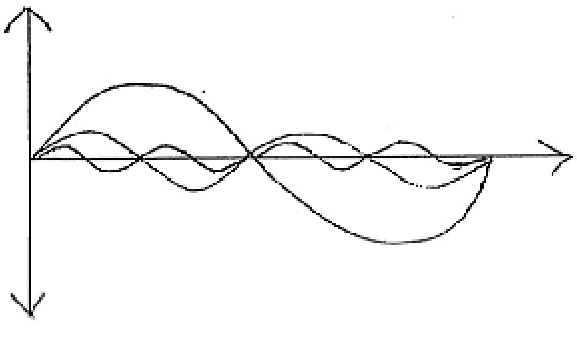
(Source unbalanced
Load unbalanced)

if the load is unbalanced, then the voltages in the phases become largly unbalanced .

2- Third - harmonic Voltages :-


pure sinusoidal .





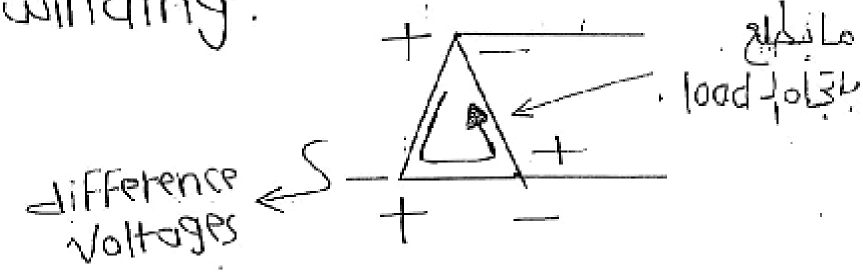
$$\left.\begin{array}{l} V_{3ha} = \hat{V}_{3h} \sin 3\omega t . \\ + \\ V_{3hb} = \hat{V}_{3h} \sin\left(3\left(\omega t - \underset{-360^\circ}{\underset{\sim\sim\sim}{120^\circ}}\right)\right) . \\ + \\ \underline{V_{3hc} = \hat{V}_{3h} \sin\left(3\left(\omega t + \underset{360^\circ}{\underset{\sim\sim\sim}{120^\circ}}\right)\right)} . \\ \hat{V}_{3h} \neq 0 . \end{array}\right\} \text{In Phase}$$

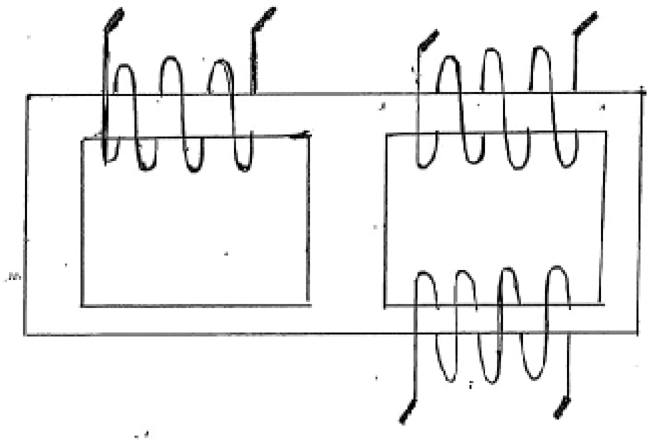
* due to nonlinearity of the material of the Core, their are 3^{rd} harmonic components in the phase voltages, Which are in phase.

→ Solution of 2 problems;

1- Solidly grounding the neutral Points. (with zero impedance).

2- Add third (tertiary) winding connected in delta, where the third harmonic components circlote inside this winding.

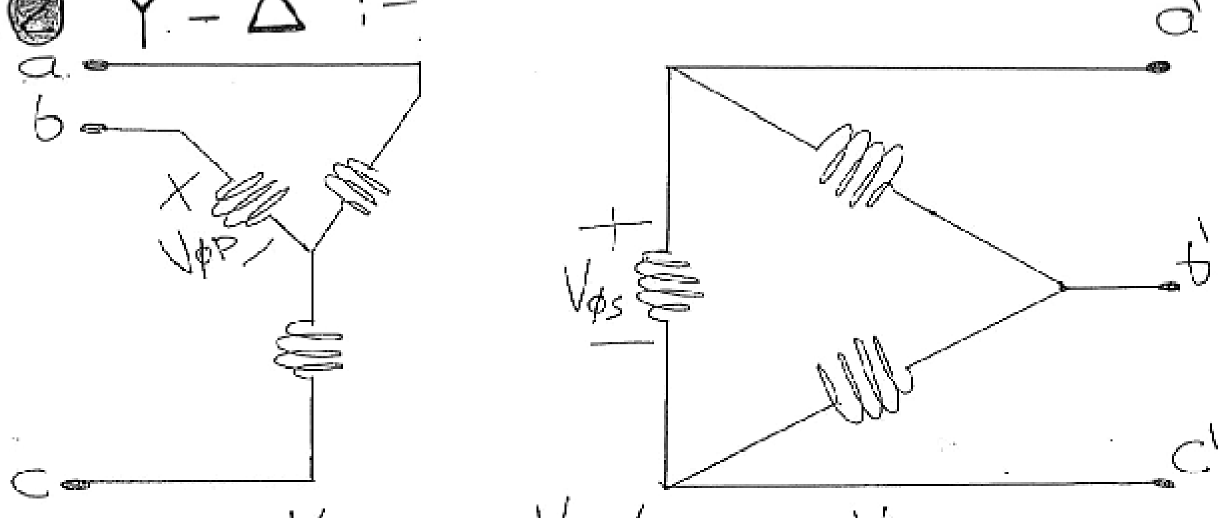




tertiary winding is used to supply light قليلة loads like, the lights of substation or the cooling fans :.

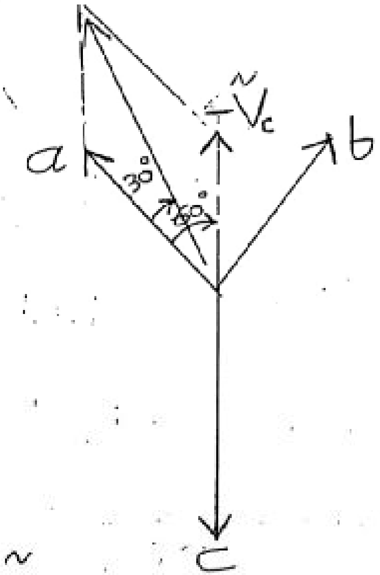
---

② Y - Δ :-



$$a = \frac{V_{\phi P}}{V_{\phi S}} = \frac{V_{LP}/\sqrt{3}}{V_{LS}} \rightarrow \frac{V_{LP}}{V_{LS}} = a\sqrt{3}$$

This connection has No problem with third harmonic component due to the Δ-connection of the Secondary.

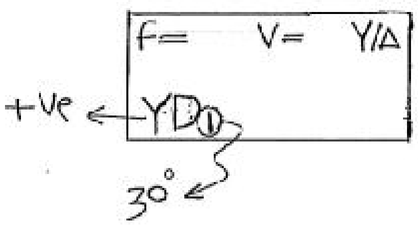


abc +ve
acb -ve

$\therefore \tilde{V}_{ac} = \tilde{V}_a - \tilde{V}_c$

$\therefore V_{ac}$ lags V_a by 30°.

Group Connection Y-Δ Y-Δ



-ve Seq. :-
V_{ac} leads V_a by 30°.

YD⑪ 330° lagging

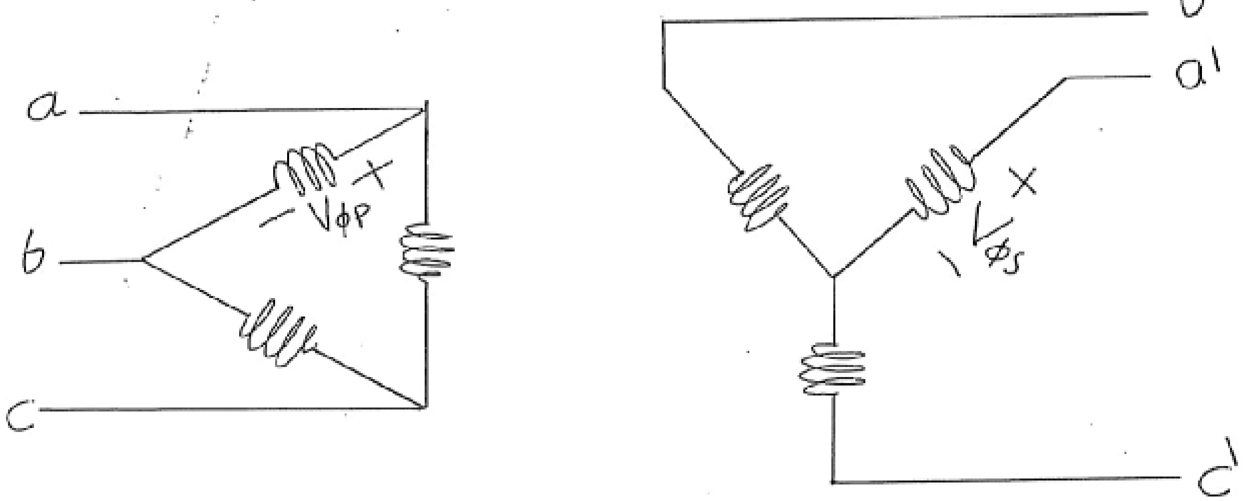
The Group Connection is important if the Transformers are to be parallel. The Phase angles of the transformers Secondary voltage must be equal.

note:

DC → Current if difference Voltage.

AC → Current if difference Voltage
or difference phase
or both .

③ Δ - Y :-



$$a = \frac{V_{\phi P}}{V_{\phi S}} = \frac{V_{LP}}{V_{LS}/\sqrt{3}} \rightarrow \frac{V_{LP}}{V_{LS}} = \frac{a}{\sqrt{3}} .$$

for +Ve Seq. : V_{ac} leads V_a by 30°.

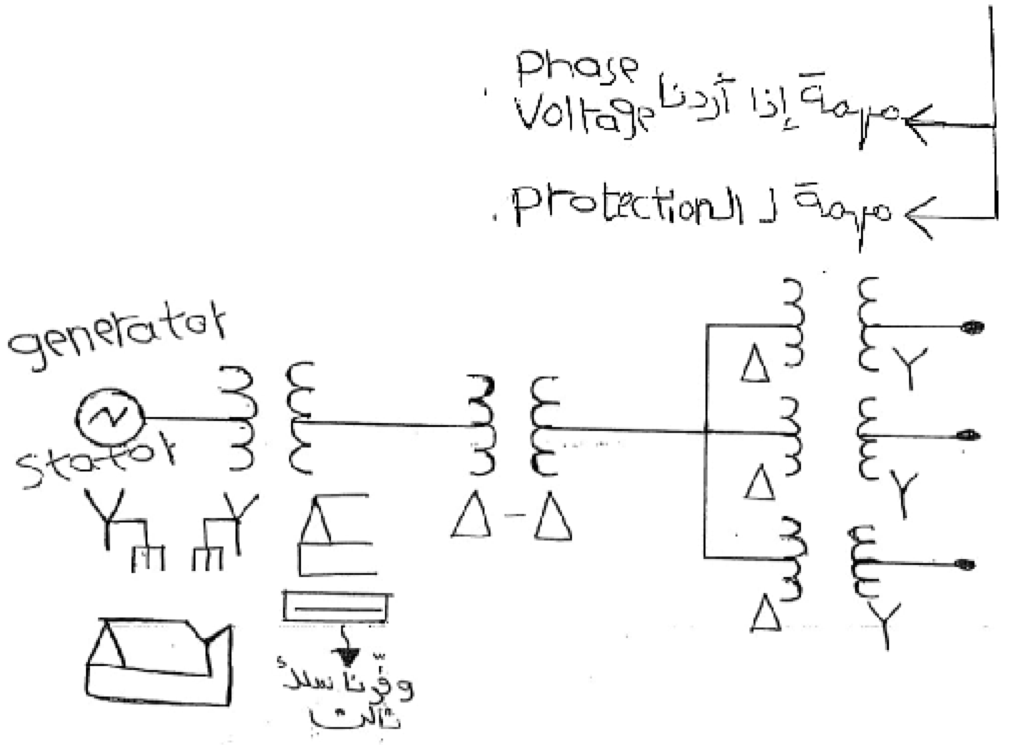
---

④ Δ - Δ :-

- * Third harmonic. X
- * Circulate current. X
- * Group connection. X

⟹ nutral point. ✓

This connection has no unbalanced or Third harmonic problems, but has no Neutral point.



* The Per-Unit System of 3ϕ Transformers :-

S_{base} = total Voltamper Value of transformer Bank.
(MVA/KVA/VA)

$$S_{1-\phi_{base}} = \frac{S_{base}}{3} .$$

$$I_{1-\phi_{base}} = \frac{S_{1-\phi\, base}}{V_{1-\phi\, base}} = \frac{S_{base}}{3V_{1-\phi,\, base}} .$$

$$Z_{base} = \frac{V_{1-\phi,\, base}}{I_{1-\phi,\, base}} = \frac{(V_{1-\phi,\, base})^2}{S_{1-\phi,\, base}} = \frac{3(V_{1-\phi\, base})^2}{S_{base}}$$

* دائماً الحل على ال Phase quantity سواء كانت Voltage current Power

$$V_{L,\, base} = V_{1-\phi,\, base} \quad \Delta .$$

$$V_{L,\, base} = \sqrt{3}\, V_{1-\phi,\, base} \quad Y .$$

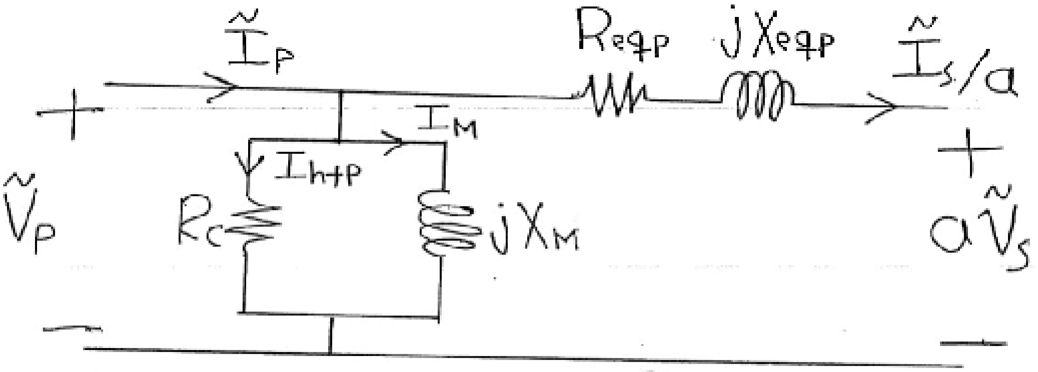
Example :- $\underbrace{50\text{ KVA}}_{\text{rated }3\text{-}\phi\text{ apparent power.}}$, $\underbrace{13800\ /208V,}_{\text{line voltages}}$

Δ-Y distribution transformer

$R = 1\% = 0.01$ pu
$X = 7\% = 0.07$ pu
} for both Sides.

ⓐ What is the phase impedance referred to primary (high voltage) Side. ?

$$\tilde{Z}_{eqp} = \underset{\overset{\downarrow}{R_1 + a^2 R_2}}{\underline{R_{eq.p}}} + j\,\overset{\overset{X_1 + a^2 X_2}{\uparrow}}{\underline{X_{eqp}}} \rightarrow \text{actual values} \ ?$$



Per-Phase equ. cct. of Transformer referred to primary side.

$$Z_{base} = \frac{3(V_{1-\phi,base})^2}{S_{base}}$$

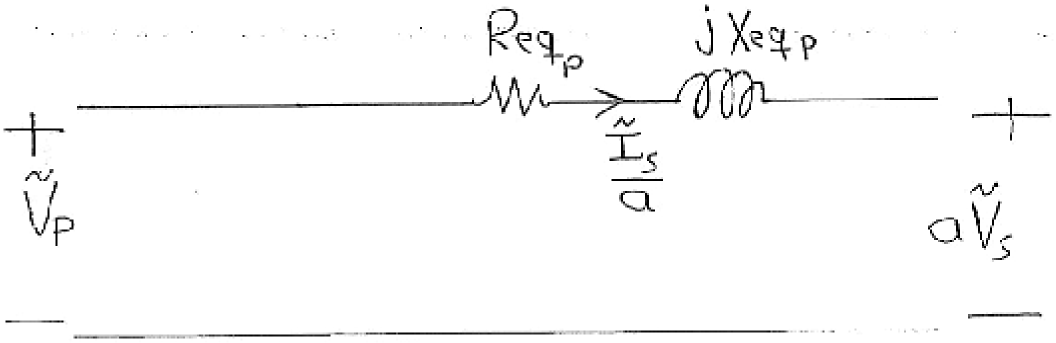
$$= \frac{3(13800)^2}{50k} = 11426\ \Omega.$$

$$\tilde{Z}_{eq} = 0.01 + j0.07\ pu.$$

actual value (per unit) (base)

$$\tilde{Z}_{eq_p} = (0.01 + j0.07)(11426)$$

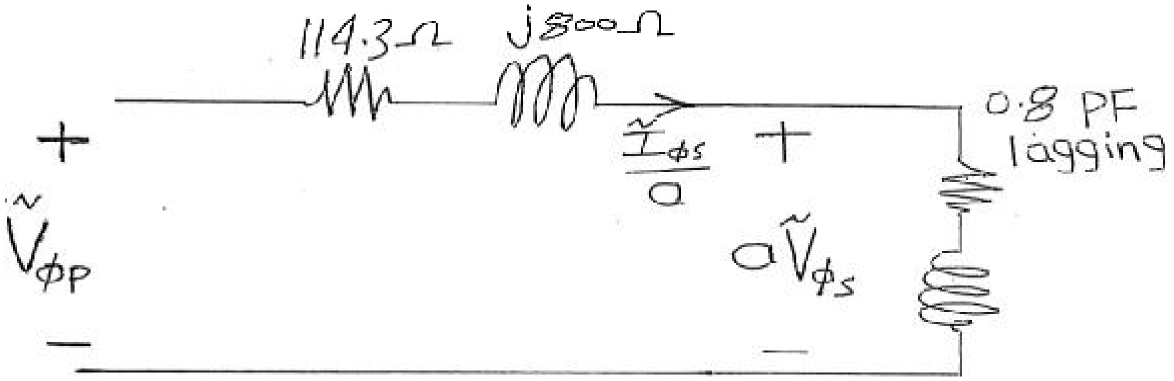
$$= 114.26 + j800\ \Omega.$$



R_c and $X_m \gg R_{eq}$ and X_{eq}.

∴ neglected. #

⑥ $V_R\,\%$ at full load and $\underset{\text{load}}{\underline{0.8\ PF}}$ <u>lagging</u> using actual Values.



*Per-phase equ. cct. referred to primary

$$V_R\,\% = \frac{|\overset{|a\tilde{V}_{\phi s\,\text{no load}}|}{\tilde{V}_{\phi P}}| - |a\tilde{V}_{\phi s}|}{|a\tilde{V}_{\phi s}|} * 100\%$$

$$\tilde{V}_{\phi P} = a\tilde{V}_{\phi s} + \left(\frac{\tilde{I}_{\phi s}}{a}\right)\left[114.3 + j800\right]$$

$$a = \frac{V_{\phi P}}{V_{\phi s}} = \frac{13800}{\left(\frac{208}{\sqrt{3}}\right)} = 114.8$$

$$S = \sqrt{3}\, V_L\, I_L$$

$$\underset{\text{rated}}{50*10^3} = \sqrt{3}\,(208)\,\overset{\text{rated}}{\underline{I_{\phi s}}}$$

$\rightarrow I_{\phi s} = 139\,A. \rightarrow$ at full load.

$\rightarrow$ at $\frac{1}{2}$ load $\rightarrow$ على $\frac{I_{\phi s}}{2}$ (تصبح) ، وهكذا

$\rightarrow$ at no load $\rightarrow I_{\phi s} = 0.$

$$\tilde{V}_{\phi S} = \frac{208}{\sqrt{3}} \angle 0 .$$ → دائماً خذه ال reference

$$\tilde{V}_{\phi P} = (114.8)\left(\frac{208}{\sqrt{3}}\right)\angle 0 + \left(\frac{139 \angle 0-\cos^{-1}0.8}{114.8}\right) * [114.3 + j800]$$

$$= 14500 \angle 2.73^{\circ} \ V .$$

$$\rightarrow V_R \% = \frac{14506 - 13800}{13800} * 100$$

$$= 5.1\% .$$

Ⓒ Repeat part ⓑ using Per-unit.

$$\tilde{V}_P = \tilde{V}_s + \tilde{I}_s (R + jX) .$$

$$= 1 \angle 0 + (\underset{\underset{\text{at full load}}{\uparrow}}{1} \angle -\cos^{-1}0.8)(0.01 + j0.07)$$

$$* \text{ if } \tfrac{1}{2} \text{ load} \rightarrow \tfrac{1}{2} \angle \cos^{-1}0.8$$

$$= 1.051 \angle 2.73 \ \text{PU} .$$

$$V_R \% = \frac{1.051 - 1.0}{1.0} * 100 \%$$

$$= 5.1\% .$$

*Advantages of per-unit :-

1- Reflected impedance has no meaning.

2- line and phase Voltages has no meaning.

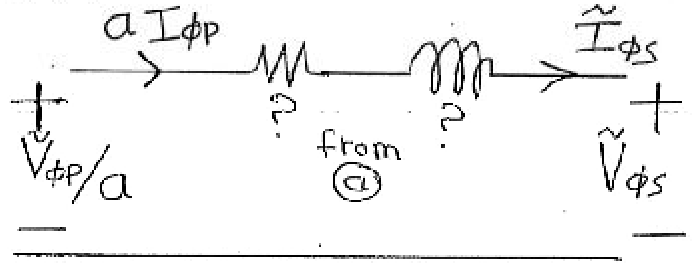
3- Square root of 3 has no meaning.

4- Δ and Y connections has no meaning.

5- more **Sense** in numbers.

∴ Simplifying Analysis.

$\boxed{b}$ if referred to Secondary :



→ Y- connection → $V_{LL} = \sqrt{3}\, V_\phi$.
$I_L = I_\phi$.

→ Δ - Connection → $V_{LL} = V_\phi$.
$I_L = \sqrt{3}\, I_\phi$.

Example :- 100 MVA , 230/115 kV ,

Δ - Δ , 3-ϕ , power transformer

$R = 0.02$ pu.

$X = 0.055$ pu.

$R_c = 120$ pu.

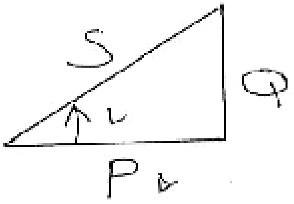
$X_M = 18$ pu.

$\boxed{1}$ if the transformer Supplies 80 MW at 0.85 P.F lagging load. draw the phaser diagram in pu ?

$S_{rated} = S_{base} = 100 * 10^6$ VA.

$P = \frac{80}{100} = 0.8$ pu.

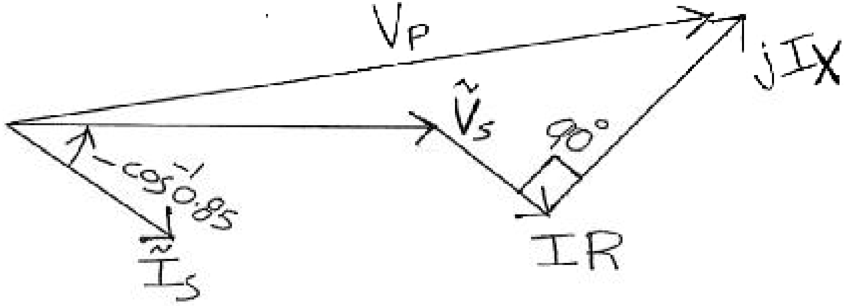
$P = V I \cos\phi$ pu.



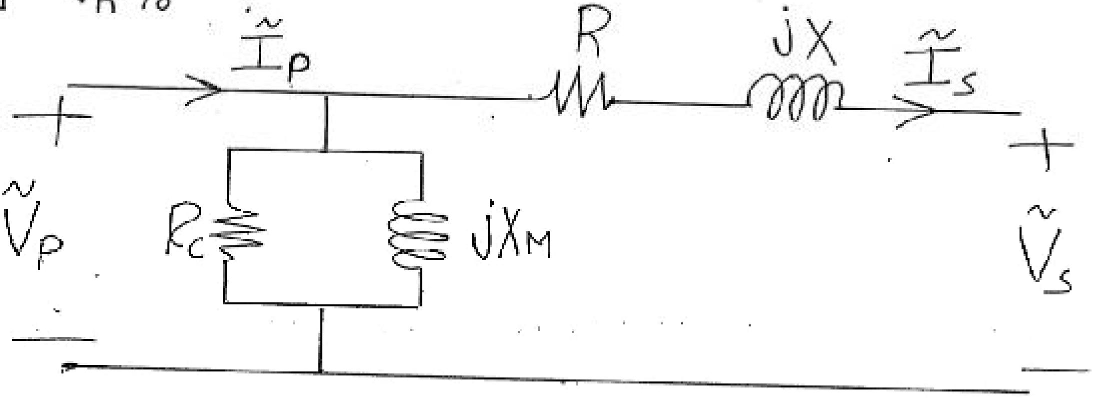
$0.8 = (1) I (0.85)$

$\rightarrow I = 0.94$ P.u.

"Phaser diagram"



$\boxed{b}$ $V_R\%$?



$$\tilde{V}_P = \tilde{V}_s + \tilde{I}(0.02 + j0.055)$$

$$= 1\angle 0 + (0.94\angle -\cos^{-1}0.85)(0.02 + j0.055)$$

$$= 1.0476 \text{ pu.}$$

$V_R\% = 4.76\%$.

R_c , X_M ليس لها

علاقة بحسابات الـ V_R

ولها علاقة بحسابات الـ η .

$\boxed{c}$ $\eta\%$?

$$\eta\% = \frac{P_{out}}{P_{in}} * 100$$

$$= \frac{0.8}{0.8 + P_{losses}} * 100$$

$$= \frac{0.8}{0.8 + |\tilde{I}_s|^2 R + \frac{|\tilde{V}_P|^2}{R_c}} * 100\%$$

$$= 96.75\% .$$

$\boxed{d}$ actual impedance values referred to primary ?

$\rightarrow$ Z_{base} at primary Side.

$$Z_{base} = \left. \frac{V_{\phi,\ base}}{I_{\phi,\ base}} \right|_{primary}$$

$$\left. V_{\phi,\ base} \right|_{primary} = 230 * 10^3 V .$$

$$S = \sqrt{3}\ V_L\ I_L$$

$$100 * 10^6 = \sqrt{3}\,(230 * 10^3)\, I_L \rightarrow I_L = 251.02 A .$$

$$I_{\phi,\,base} = \frac{I_L}{\sqrt{3}}$$

$$= \frac{251.02}{\sqrt{3}} = 145\ A.$$

$$Z_{base} = \frac{230 * 10^3}{145} = 1586.2\ \Omega.$$

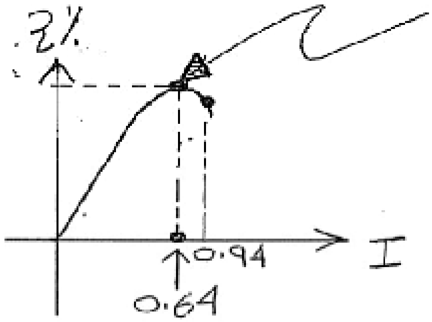
$$R_{eq,p} = (0.02)(1586.2\ \Omega) = \underline{\underline{31.7\ \Omega}}.$$

$$X_{eq,p} = (0.055)(1586.2\ \Omega) = \underline{\underline{87.2\ \Omega}}.$$

$$R_c = (120)(1586.2\ \Omega) = \underline{\underline{190.3\ k\Omega}}.$$

$$X_M = (18)(1586.2\ \Omega) = \underline{\underline{28.5\ k\Omega}}.$$

$\boxed{e}$ Calculate the load when the Transformer run at the max. η condition ?



η is max. if

$$\boxed{P_{iron} = P_{cu}}$$

P_{iron} → constant losses.

P_{cu} → Variable losses.

$$\rightarrow \quad P_{iron} = P_{cu}$$

$$\frac{|V_P|^2}{R_c} = |\tilde{I}|^2 (R_{eq})$$

$$\frac{(1.0476)^2}{120} = |\tilde{I}|^2 (0.022)$$

$$\rightarrow I = 0.64 \text{ A}$$

جبنا قيمة ال load
اللي بتعطيني ال max η
وال η max نفسها.

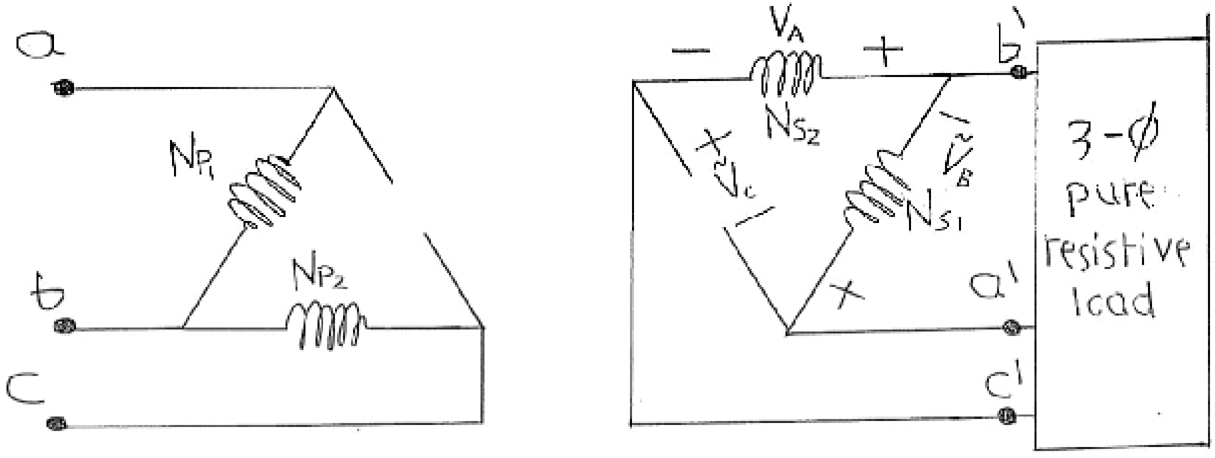
$$\eta\% = \frac{0.8}{0.8 + (2)\left(\frac{(1.0476)^2}{120}\right)} * 100\%$$

$$= 97.7\% .$$

Three-Phase Transformations using Two Transformers :-

1. Open - Δ (or V-V) Connection.
2. Open - Y - Open - Δ Connection.
3. Scott - T Connection.
4. The Three-phase T Connection.

Open - Δ (or V-V) Connection :-



$$-\tilde{V}_c - \tilde{V}_A - \tilde{V}_B = 0$$

$$\tilde{V}_c = -\tilde{V}_A - \tilde{V}_B = V\underline{/120^\circ}\ (V)$$ → balanced as Voltage, but not balanced as current.

$$P_1 = \frac{\sqrt{3}}{2} V_\phi I_\phi$$

$$P_2 = V_\phi I_\phi \cos 30^\circ = \frac{\sqrt{3}}{2} V_\phi I_\phi$$

$$P_1 + P_2 = \sqrt{3}\, V_\phi I_\phi \, .$$

if System is healthy :

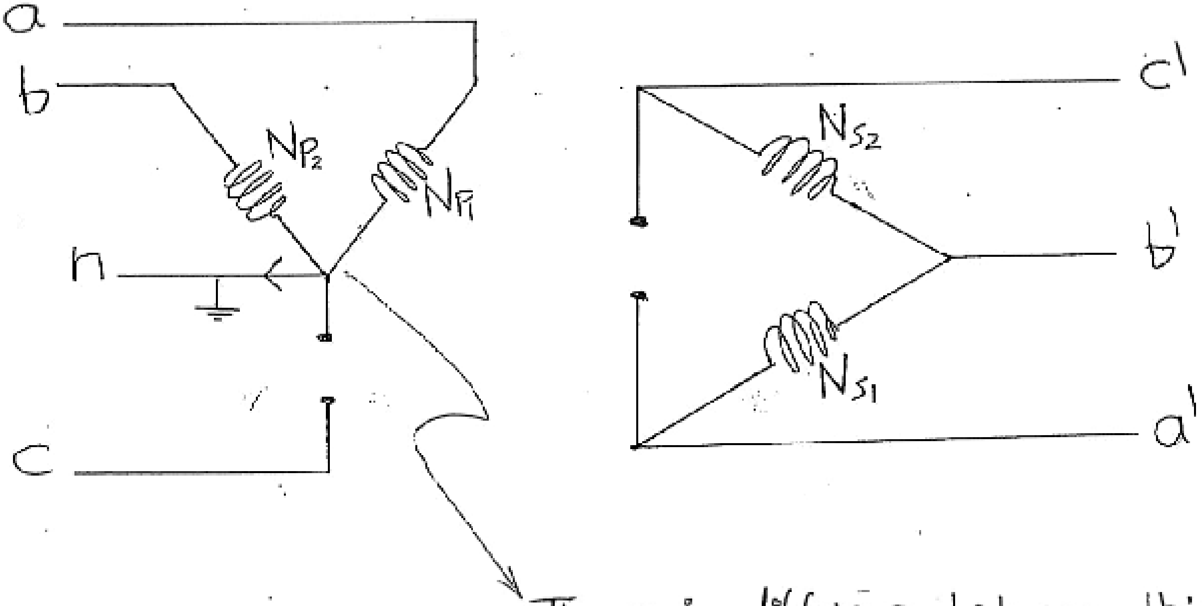
$$P = \sqrt{3}\, V_L I_L$$
$$= 3\, V_\phi I_\phi$$

$$\frac{P}{P_1+P_2} = \frac{3V_\phi I_\phi}{\sqrt{3}\, V_\phi I_\phi} = \sqrt{3} \, .$$

$$P_1 + P_2 = \underset{\overset{\uparrow}{57.7\%}}{\frac{1}{\sqrt{3}}} P \, .$$

⟶ This connection is used when one of the phases needs maintanance, And if we have 2 Transformers and we want to connect them as 3-ϕ System.

Open - Y - Open - Δ Connection :



The main difference between this connection and the previous one is : The current will not be equal zero.

→ The 3-φ Voltages are balanced.

→ The 3-φ Currents are not balanced.

→ $P_1 + P_2 = \frac{1}{\sqrt{3}} P$

$\uparrow$
57.7 %.

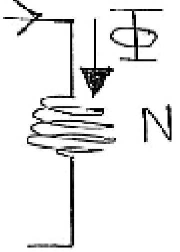
⟶ The same usage of the open - Δ connection

Transformer Ratings and Related Problems:

$\underline{S}$, $\underline{V}$, $\underline{I}$, and $\underline{f}$ → Basics.

* The Voltage and freq. Ratings of a Transformer :-

$$E_{rms} = 4.44\,\Phi f \underset{\substack{\uparrow \\ \#\text{ of} \\ \text{terms}}}{N}$$



$$E_{rms_1} = 4.44\,\Phi_1 f_1 N$$

$$E_{rms_2} = 4.44\,\Phi_2 f_2 N$$

assuming $E_{rms_1} = E_{rms_2}$:

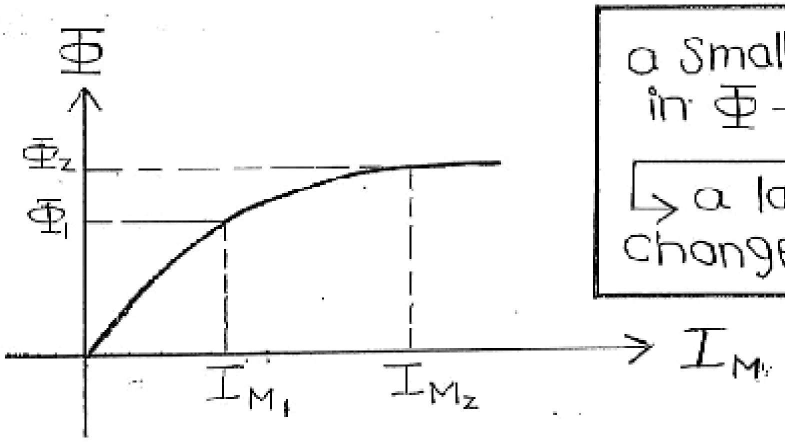
$$\Phi_1 f_1 = \Phi_2 f_2$$

$$\rightarrow \Phi_2 = \frac{f_1}{f_2}\,\Phi_1$$

$f_1 = 60\,Hz$ (american Sys.).

$f_2 = 50\,Hz$ (europe Sys.).

$$\Phi_2 = 1.2\,\Phi_1$$



a Small Change in Φ → a large change in I_M

$I_{M_2} \gg I_{M_1}$

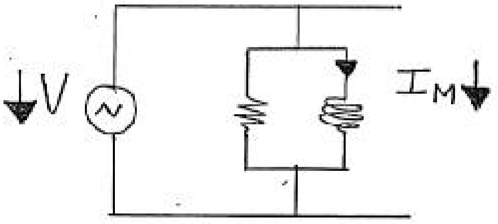
→ Change from high freq. to low freq. is very dangerous, because the Saturation of the magnetic cct.

→ Change from low freq. to high freq. is not dangerous.

→ To over come this problem, derate the apply Voltage with the Same ratio of the two frequencies.

$$\boxed{E_{rms_2} = \frac{50}{60} E_{rms_1}}$$

→ we have to reduce the voltage on the primary winding in order to reduce I_M.



---

* The apperant power and Current Ratings of a Transformer :

→ Transformer with 100 MVA .

↑ rated : max. power that the trans. can produce .

→ Most loads are RL loads.

$$\boxed{\hat{S} = P + jQ}$$

if $P.F_{load} = 1$.
→(pure resistive).

$$S = P = \sqrt{3}\, \underset{\underset{\text{const.}}{\uparrow}}{V_L}\, I_L \, .$$

→(pure Inductive).
→(pure capacitive).

$$Q = S = \sqrt{3}\, \underset{\underset{\text{const.}}{\uparrow}}{V_L}\, I_L \, .$$

→ load
واصل ع
Trans.
↳ قّر بال current → the value of the current indicates the kind of the load (Full load , over load , ...) .
↓
→ half load → half current.
→ Full load → Full current.

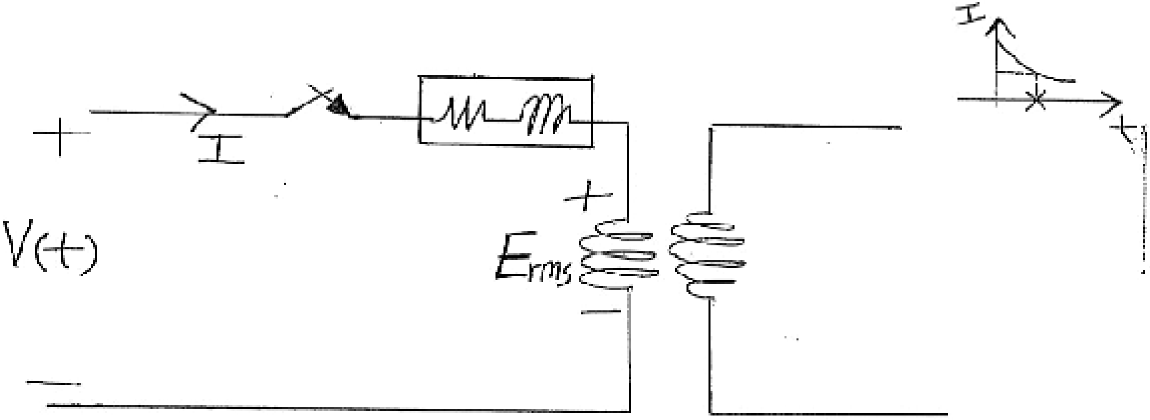
→ load ↑ , current consumed ↑ ,

P_{losses} (I^2R) ↑ , $P_{\text{Series impedance}}$ ↑ , heat ↑ ,

→ then Cooling is needed .

* Inrush Current :-

the current drawn by the transformer at Starting. (5-7 times load Current).



$$I = \frac{V - E_{rms}}{R + jX}$$

→ At the moment of the Switching there is no E_{rms} , So there is no Φ , and the current is very large.

No current → No Φ → No E_{rms} .

→ Inrush current depends on :

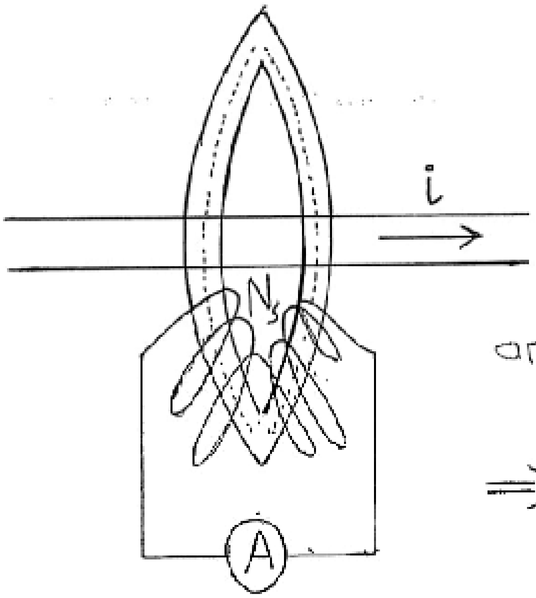
$$V(t) = V\cos(\omega t + \Phi)$$

↳ depends on the instant of switching.

the Φ Shift of the Voltage.

Instrument Transformers

V.T	C.T
1- Step down.	1- Step down.
2. accurate.	2- accurate.
3. Very low power rating (Small Size).	3- Very low power rating (Small Size)
4- Used for measurments.	4. Used for measurments



Very high current and Very high Voltage,

⇒ من الصعب تركيب Ⓐ

لذلك يتم استخدام # .
VT و CT

* V.T → Short cct. on Secondary → Very dangerous.

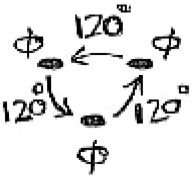
* C.T → Open cct. on Secondary → Very dangerous.

Notes On AC Machines :-

The effect of coil pitch on AC machines

Stators :-

→ phase shift between 3ϕ in space, gives 120° phase shift in time.



* In General ; the air gap flux density distribution is never pure sinusoidal.

Because :-

1. Saturation of ferromagnetic material.
2. Unbalanced load, Stator Y, non grounded.

→ reflection on flux.

→ never püre sinusoidal.

→ To reduce the unwanted harmonics Several techniques are used of these: techniques ,"fraction pitch winding"

↑

. effect of من خلالها بدنا نقلل ال
3rd harmonic

The pitch of the pole :-

The angular distance between two adjacent poles on a machine.

$$\rho_p = \frac{360^\circ}{P} \quad \text{(mechanical degrees)}.$$

The pitch of the Pole.

#. of poles.

* Regardless the #. of poles on the machine, the pole pitch is always equals 180° electrical.

ex.:- $P = 4$:-

→ mechanical : $\rho_P = \frac{360^\circ}{4} = 90^\circ$.

→ electrical : always $= 180^\circ$.

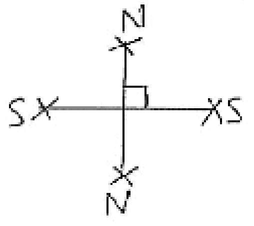
* Full pitch coil :- the Stator Coil Spans (extends) across the Same angle of the Pole pitch.

* Fractional pitch Coil : the Stator Coil Spans across an angle less than the Pole pitch.

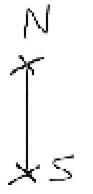
$\xrightarrow{ex}$ (coil pitch is $\frac{5}{6}$ of the pole pitch). in respect of the #. of poles : (P=2)

→ $\rho_P = \frac{5}{6} * 180°$ electrical = 150

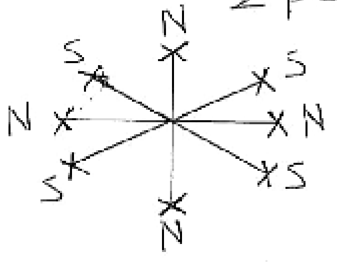
→ ρ_P = 150 * # of poles = 150 *2 = 300 mechanical.



2 poles



1 pole

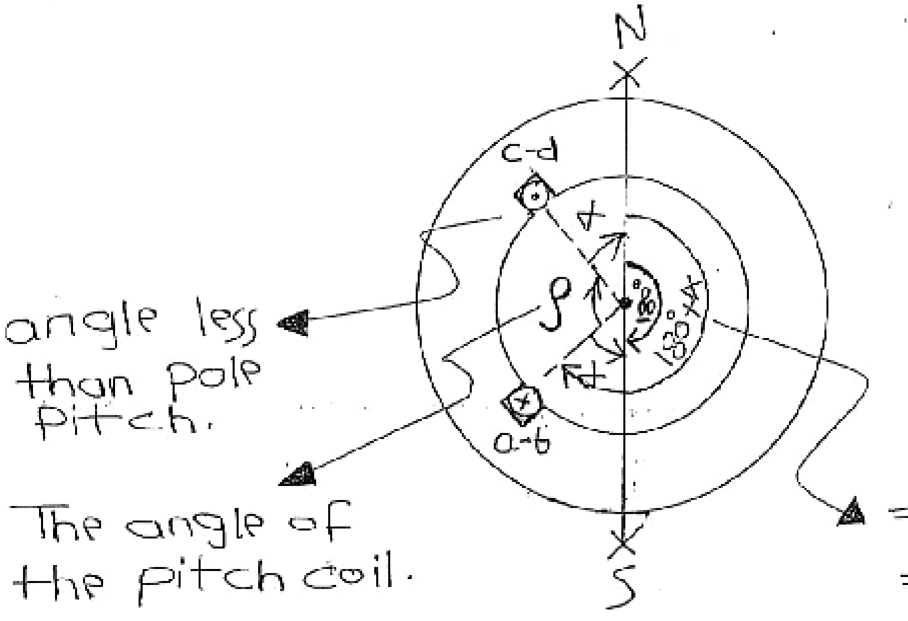


8 Poles

* Windings with fractional pitch Coils are known as Chorded windings.

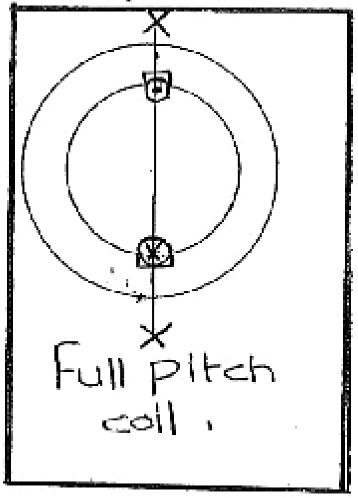
---

* The Induced Voltage of a fractional Pitch coil :-



$= 180° + 90° - \frac{\rho}{2}$

$= 270° - \frac{\rho}{2}$.

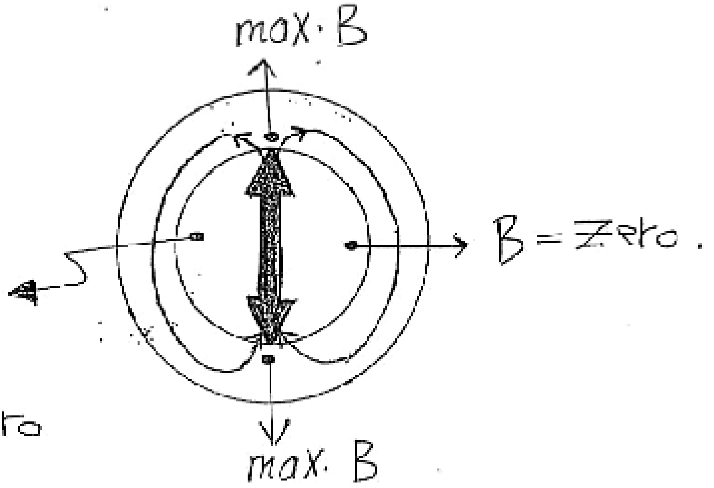


Full pitch coil .

$$\rho + 2\alpha = 180° \rightarrow \alpha = 90° - \frac{\rho}{2} \; .$$

→ Flux density (from rotor to Stator)

$\vec{B}$

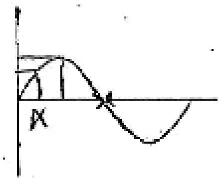


→ $\cos\alpha$

$\cos 90$

zero

→ $B = \text{zero}$



$$\boxed{B = B_M \cos\alpha}$$

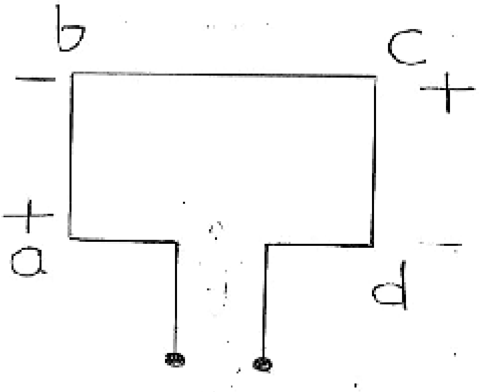
$$B = B_M \cos(\underset{\overset{\uparrow}{\text{time}}}{wt} - \alpha)$$ ---- travelling wave.

$$e_{ind} = (\vec{v} \times \vec{B}) \cdot \vec{l}$$ → length of the wire. (with current direction).

e_{ind} ↑ Voltage induced in any Coil

$\vec{v}$ ↑ velocity of the Conductor relative to the magnetic field

$\vec{B}$ ↑ magnetic flux density.



Segment ab ;

$$e_{ba} = (\vec{V}\times\vec{B})\cdot\vec{I} = VBl = VB_M\cos\alpha\, l$$

$$= VB_M\cos(\omega t-\alpha)\, l$$

$$= VB_M\cos(\omega t-(90-\tfrac{\rho}{2}))\, l$$

Segment bc and ad :-

$e_{cb} = e_{da} = 0$, $\vec{V}\times\vec{B} = 0$. $(\vec{V}\perp\vec{B})$.

Segment cd :-

$$e_{dc} = VB_M\cos(\omega t-(90-\tfrac{\rho}{2}))\, l .$$

→ $e_{ind} = e_{ba} + e_{cd}$

$$= 2VB_M \cos(wt - (90 - \frac{\rho}{2}))l$$

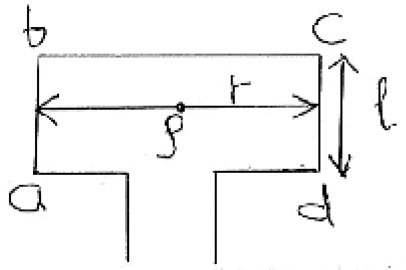
$$\Downarrow$$

$$e_{ind} = 2\underline{\underline{V}}B_M l \cos wt \sin \frac{\rho}{2} .$$

$\downarrow$

* $V = rw$

* $\phi = Brl$



$$\Rightarrow E_{ind} = 4.44 \Phi f N k_p$$

$\uparrow$

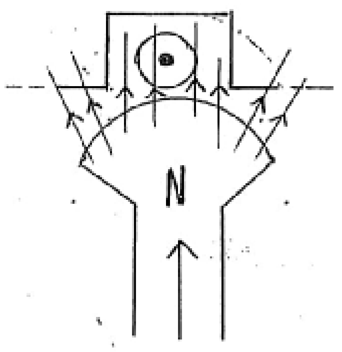
$k_p = \sin \frac{\rho}{2}$

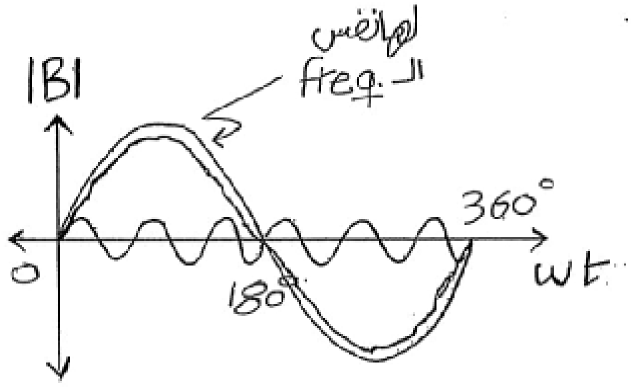
$\uparrow$

coil pitch factor.

if $k_p = 0.9$ → this will reduce the induced voltage (disadvantage).

Harmonic problems and fractional pitch windings :





* The waveform of Flux follow the waveform of Voltage.

* Voltage lags flux by 90° .

$$e_{ind} = \underset{\uparrow}{-}N \frac{d\Phi}{dt}.$$

ال Φ هو سبب ال induced Voltage .

ظهر في البداية ال (Φ) وبعدها بـ 90° ظهر ال (V)،
إذا صار في Load (يعني وصلت C, L, R) بده
يصير في I ، وال I بعمل Φ اتجاهه يعاكس
اتجاه ال Φ الأصلي.

at no load → no current . → only one flux.

Only odd harmonics exist in the waveform of the induced Voltages.

Why ? because Signals are Symmetric on X-axis.

→ 3rd , 5th , 7th , ...

The 3rd harmonic Components and its <u>multiples</u> do not appear in the <u>O/P</u>

3 × 2 = 6 ✗
3 × 3 = 9 ✓
3 × 4 = 12 ✗

⟹ تصبح ال 5th و ال 7th أخطرهم → لازم نقللهم أو نلغيهم .

<u>Voltage</u> in case of Solidly grounded Y and Δ Stator windings.

Only 5th, 7th, 11th, 13th, .. harmonic Components are there.

*[As the index of harmonic increases, the magnitude decreases.]

* The Pitch factor of the Coil at the harmonic frequncy is : $k_\rho = \sin \frac{\nu \rho}{2}$

where ν : index of the harmonic to be examined.

Example :- 3ϕ -2 Poles . Stator has Coiles with a 5/6 pitch, what are the pitch factors for the harmonics presented in the Coils of the machine?

$K_{\rho_1} = \sin\frac{\rho}{2}$ ⇒ fundamental (first harm. component)

$K_{\rho_3} = \sin\frac{3\rho}{2}$ ⇒ 3rd

$K_{\rho_5} = \sin\frac{5\rho}{2}$ ⇒ 5th

$K_{\rho_7} = \sin\frac{7\rho}{2}$ ⇒ 7th

⋮

$$* \rho_p = \frac{360^\circ}{2} = 180^\circ.$$

$$\rho = \frac{5}{6} * 180^\circ = 150^\circ.$$

⇒

$k_{p_1} = \sin \frac{150^\circ}{2} = 0.966$ ⇒ reduced by 3.4%

$k_{p_3} = \sin \frac{3(150^\circ)}{2} = -0.707$ ⇒ do not exist.

$k_{p_5} = \sin \frac{5(150^\circ)}{2} = 0.259$ ⇒ reduced by 75%.

$k_{p_7} = \sin \frac{7(150^\circ)}{2} = 0.259$ ⇒ reduced by 74%.

⋮

k_{p_9} ⇒ do not exist.

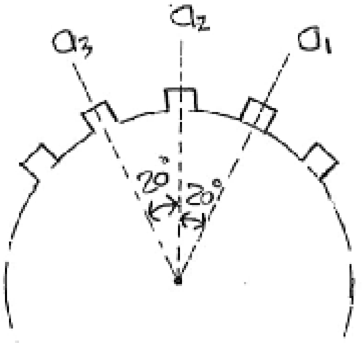
⋮

The advantage of fractional pitch winding is to reduce the magnitude of the most dangerous harmonic component (5th and 7th) ⇒ to get more sinusoidal wave form.

The disadvantage is slightly reduce the magnitude of the fundamental component.

Distribution windings and Distribution factor :-

Slot pitch $= \frac{360^\circ}{18} = 20^\circ$.



$\frac{360^\circ}{20^\circ} = \underline{18 \text{ Slots}}$.

$\div 3 = \underline{6 \text{ Slots/phase}}$.

$\rightarrow$ $\boxed{\text{Each coil needs } 2 \text{ slots}}$ Single layer

$\# \text{ of coils} = \frac{6}{2} = \underline{3 \text{ Coils}}$.

لو فرضنا

$\rightarrow$ each coil have 10 terns ! :-

$\# \text{ of terms per phase} = 10 * 3$

$= \underline{30 \text{ terns/phase}}$

$\theta = \omega t$

$20^\circ = 2\pi f t$

$t = \frac{20^\circ}{2\pi f} * \frac{\pi}{180^\circ}$

. douple layer $\rightarrow$ # of slots = # of coils.

$\tilde{E}_{a_2} = E\angle 0^\circ$ → referance.

$\tilde{E}_{a_1} = E\angle -20^\circ$

$\tilde{E}_{a_3} = E\angle 20^\circ$

$\rightarrow \tilde{E}_a = \tilde{E}_{a_1} + \tilde{E}_{a_2} + \tilde{E}_{a_3}$

$= E\angle -20^\circ + E\angle 0^\circ + E\angle 20^\circ = \text{---}\angle\text{...}$

$|\tilde{E}_a| = 2.879\ E$ → reduction

$\frac{2.879}{3} = 0.95 = k_d$: distribution Factor.

* توزيع ال winding في Slots يقلل ال induced Voltage .

* #.of Slots أكبر ← angle (بين كل slot و slot) أصغر ← k_d أقل .

$\rightarrow k_d = \frac{\sin(n\gamma/2)}{n \sin(\gamma/2)}$, where :

n : no. of slots per pole per phase.

γ : angle between each two Successive Slots.

→ If $n = 3$, $\gamma = 20^\circ$:

$$k_d = \frac{\sin(3 * 20^\circ/2)}{3\sin(10^\circ)} = 0.96$$

* $k_w = k_p k_d$ ⟹ winding factor.

* $E_{rms} = 4.44\,\Phi f N k_w$

→ $k_p \approx 0.96 \approx k_d$: typical.
(0.94 → 0.98)

AC Machines power flows and losses:

* Machines Convert $P_m \xrightarrow{generator} P_e$ through the action of magnetic field.

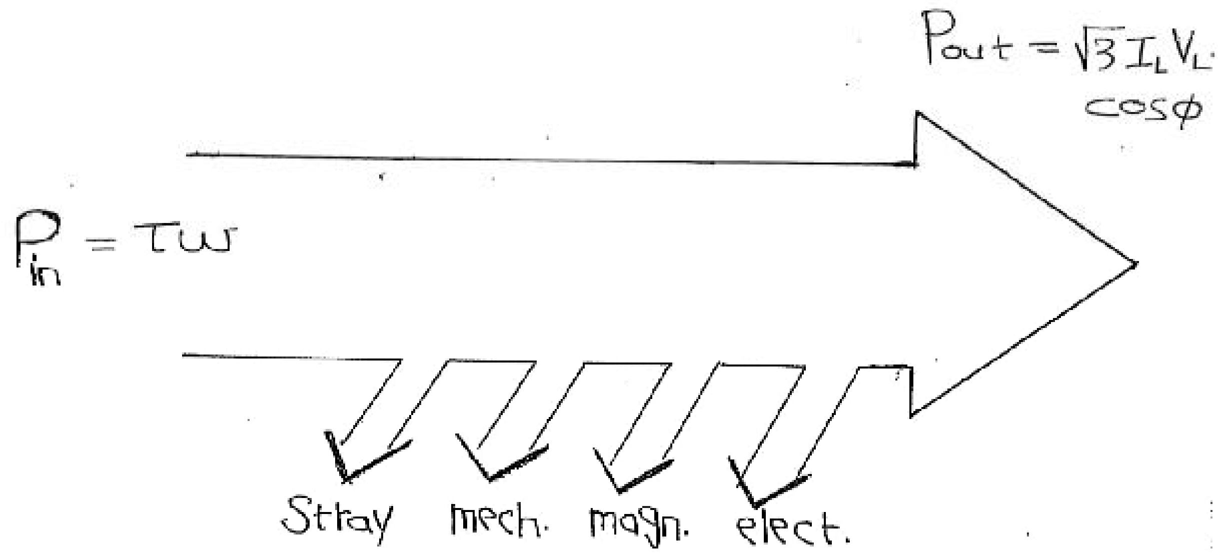
$P_e \xrightarrow{motor} P_m$

→ magnetic losses → hysteresis losses and eddy current losses. → at Core, Stator and Rotor. (Mostly at Stator)

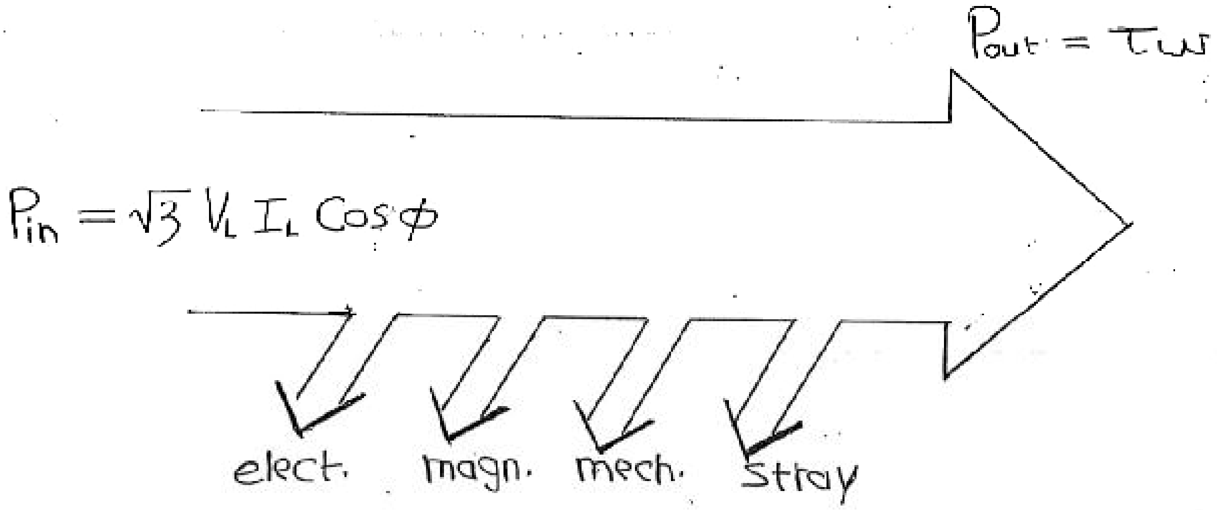
→ electtical losses → at rotor and Stator. ($I^2 R$).

→ mechanical losses → ftiction
- → with air → windegs losses.
- → with Bearings → frictio losses.

→ Sttay losses → difference in calculations, Some-times cases by aging.



* Power flow of generator.



* Power flow of motor.

* كلما زاد Size of the machine ← يزداد ال ؟

#. typical Practical ↵

Example : $P = 2$, 3-ϕ , Y-connected Synch. generator , Double layer , 4 Coils/Phase , 10 turns/Coil , Coil pitch $= 150^\circ$

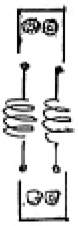
$n_s = 3000$ rpm , $\Phi = 0.019$ Wb/Pole .

a) Slot pitch ?

<u>Double layer</u> : #. of Slots = #. of Coils .

$= \underline{\underline{4 \text{ Slots/phase}}}$

in 3-ϕ $\rightarrow 4 \times 3 = \underline{\underline{12 \text{ Slots.}}}$



$$* \frac{360}{12} = 30^\circ \text{ elec.}$$

$\rightarrow 30^\circ$ mech.

b) How many Slots do the Coil Span

Coil pitch in terms of Slots ?

$$\rightarrow \frac{150^\circ}{180^\circ} = \frac{5}{6} \rightarrow \therefore 5 \text{ Slots.}$$

Coil pitch

elect. angle

# of Slots per pole.

C) E_A ?

$$E_A = 4.44\,\Phi f N k_w$$

$$= 4.44\,\underset{\text{flux per pole.}}{\underline{\underline{\Phi}}}\, f N k_p k_d$$

$$f = \frac{n_s P}{120} = \frac{(3000)(2)}{120} = 50\,\text{Hz}.$$

#. of turns per phase = N

$$= 4 \frac{\text{coils}}{\text{phase}} \times 10 \frac{\text{turns}}{\text{coil}}$$

if single layer ←
$\rightarrow 2 \frac{\text{coils}}{\text{phase}}$

$$= 40 \text{ turns/phase.}$$

$$k_p = \sin\frac{\rho}{2} = \sin\frac{150^\circ}{2} = 0.966.$$

$$k_d = \frac{\sin(n\gamma/2)}{\underline{n}\sin(\gamma/2)} = \frac{\sin(2(\frac{30^\circ}{2}))}{2\sin(\frac{30^\circ}{2})} = 0.966.$$

n = #. of slots per pole per phase $= \underline{\underline{2}}$.

6

$\frac{6}{3} = 2$

$$E_A = (4.44)(0.019)(50)(40)(0.966)(0.966)$$

$= 157$ V → phase voltage.

(Y-connected).

d) Line Voltage ?

$$\rightarrow V_T = \sqrt{3}\, V_\phi = \sqrt{3}\,(157)$$
$$= 272\,V .$$

e) How much suppression does the fractional pitch winding give for the 5^{th} harmonic component ?

$$\rightarrow k_{p_5} = \sin\frac{(5)(150)}{2} \doteq 0.259 .$$

سؤال 4 Poles, 80 Slots , 5^{th} harmonic pitch factor = zero

→ coil pitch in terms of Slots ?

$$\sin\frac{5\rho}{2} = 0$$

$$\frac{5\rho}{2} = 180n \rightarrow n = 1 : \rho = 72$$

$$\rightarrow \frac{X}{20} = \frac{72}{180}$$

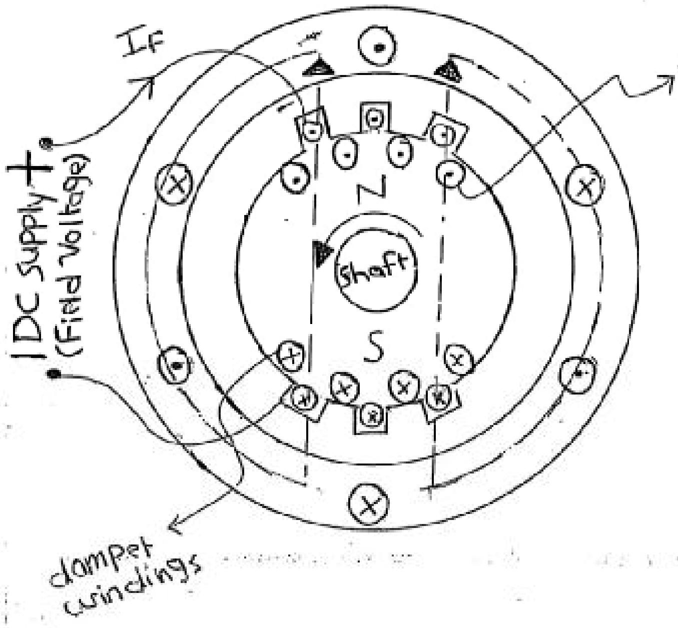
$$\frac{80}{4} \leftarrow 20$$

$$X = 8 \checkmark$$

$$\rightarrow n = 2 : \rho = 144$$

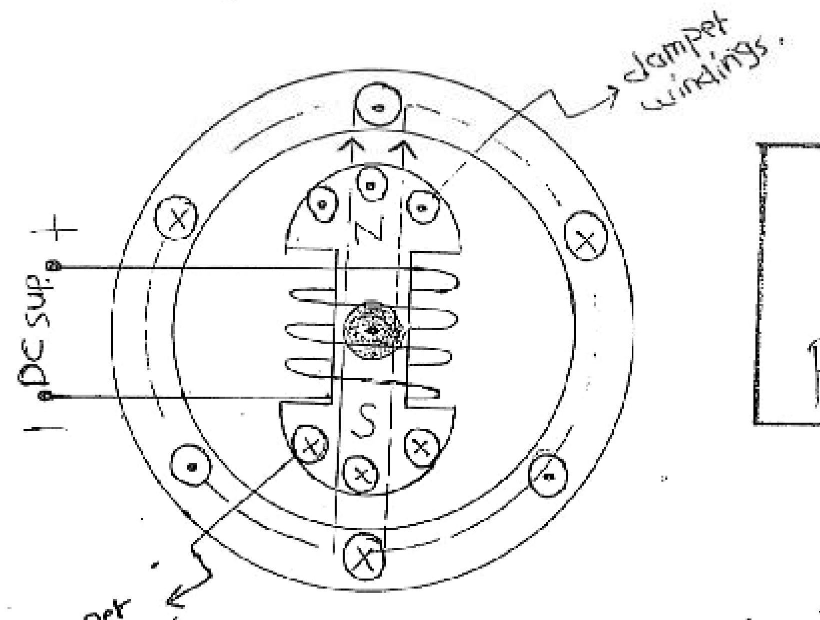
$$\rightarrow \frac{X}{20} = \frac{144}{180} \rightarrow X = 16 \checkmark$$

Chapter 4 :- Synchronous Generators :



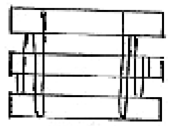
Cylindrical Rotor Type.

* Two electrical cct.s :
DC → rotor. , AC → Stator.



Salient Pole Type.

damper windings → copper bars Short circuited From the two ends at the Pole faces.



another elec. cct in rotor.

Damper windings : are windings placed in Slots curved at the pole face of the rotor of Synchronous generator, they are used to damp oscillation in case of transients,

In Steady-State the induced Voltage and current inside them are Zero.

* Why we use damper windings ?

① In transient case the current induced in them produces Anti-torque which damp Oscillation of the Rotor.

② To Start-up Synchronous Motor.

* There are two common approaches to supply dc power to field windings on the rotor :-

1) Supply dc power from an external dc source to the rotor by means of slip rings and brushes

2) Supply dc power from dc power source mounted directly on the shaft of the synch. generator .

* Slip rings and brushes problems :-

1) They increase the amount of maintenance required on the machine, since the brushes checked for wear regulary.

2) Brush voltage drop can be the cause of significant power losses on machines with large amount of field currents.

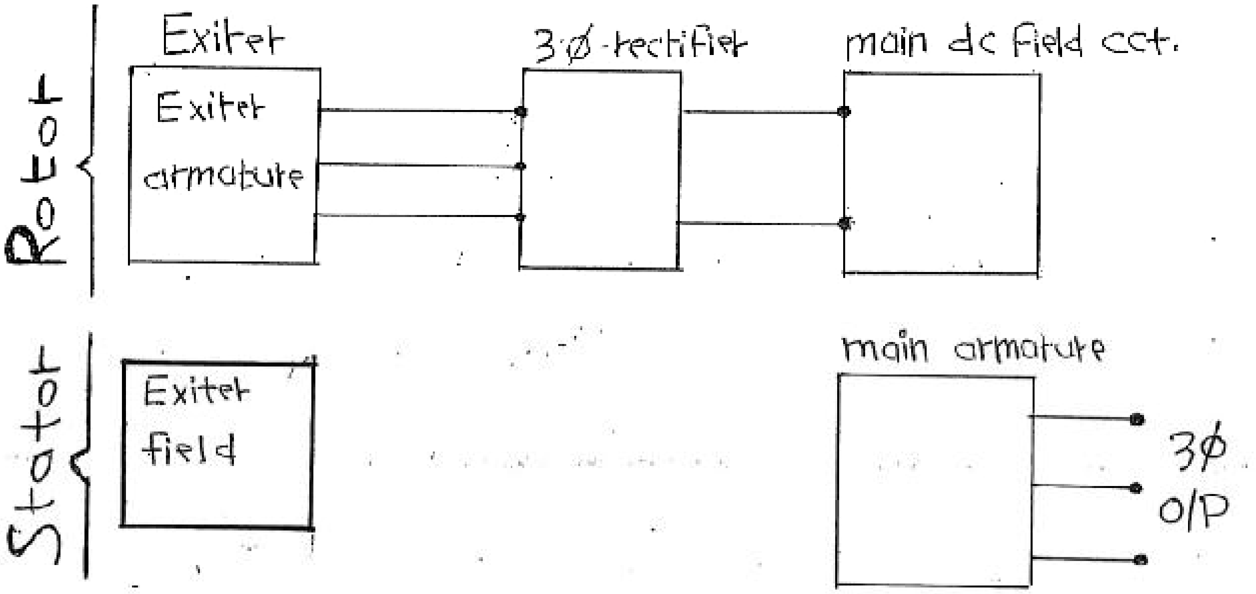
⇒ So, they are used in smaller synch. machines, because no other method of suppling dc - field current is cost-effective

Brushless exiter is a small ac generator,

↳ it's field cct. mounted on the Stator.

↳ it's armature cct. mounted on the rotor.

1 main exiter :-



* By controlling the small dc field current of the exiter generator (located on Stator), we can adjust the field current on the main machine without slip rings and brushes.

* brushless exitor requires much less maintenance than slip rings and brushes, since no mechanical contacts between rotor and stator.

$\boxed{2}$ pilot exciter :- Small ac generator.

↳ permanent magnets mounted on the rotor

↳ 3ϕ winding on the stator.

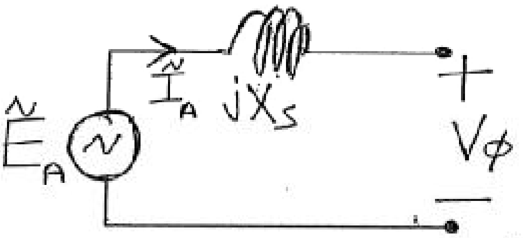
Why we use pilot exciter ?

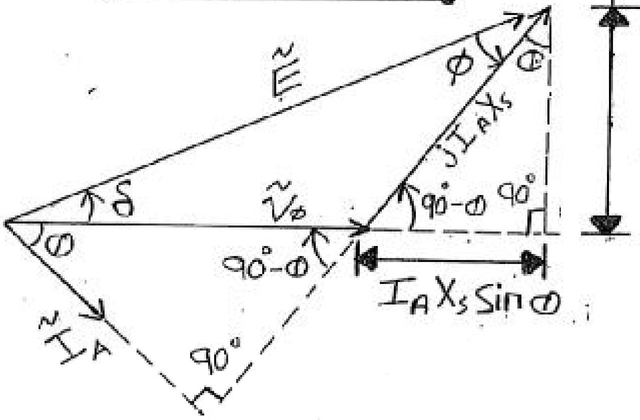
1) To make the excitation of a generator completely independent of any extrnal Power Sourc

2) It produces Power for the field cct. of the exciter, which in turn controls the field circuit of the main machine.

* IF the pilot exciter is included on the generator Shaft, then no external electric Power is required to run the generator.

* Power and Torque of Synch. gen. :-





$E_A\sin\delta = I_AX_s\cos\Phi$

$= I_A X_s \sin(90-\Phi)$

$$\boxed{I_A\cos\Phi = \frac{E_A\sin\delta}{X_s}}$$

$$P_{out} = 3V_\phi I_A\cos\Phi$$

$$= 3V_\phi \frac{E_A\sin\delta}{X_s}$$ --- Power angle equ.

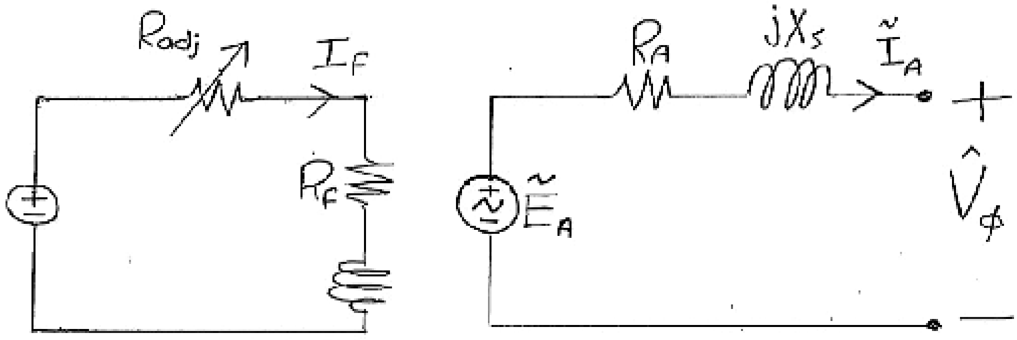
$$P_{out} = \frac{3V_\phi E_A}{\underbrace{X_s}_{\text{static stability limit.}}} \sin \underline{\delta}$$

↳ delta angle / Rotor angle (15° → 65°).

$$\tau_{ind} = \frac{3V_\phi E_A\sin\delta}{\omega_s X_s}$$

→ when $\boxed{R_A = 0}$.

Synchronous Generator Equivalent Circuit :

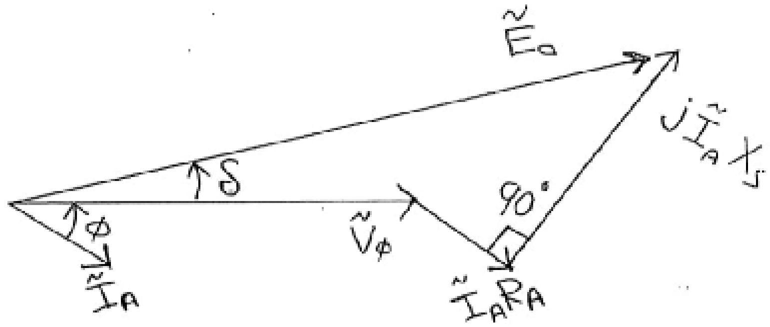


Field CCt.   Armature CCt.

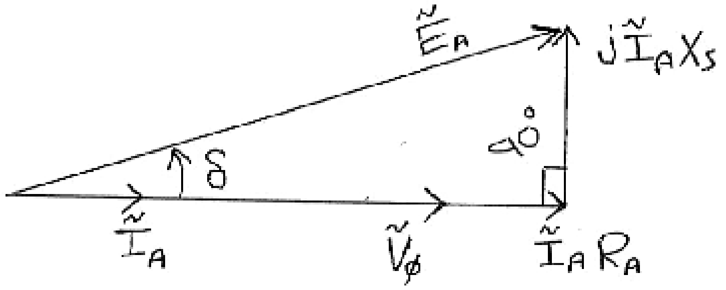
Per-phase Equ. CCt.

$$\tilde{E}_A = 4.44\, \Phi f N k_w$$

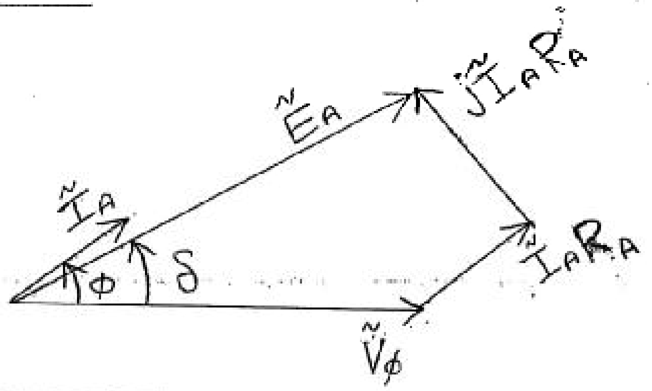
* Lagging PF Load :



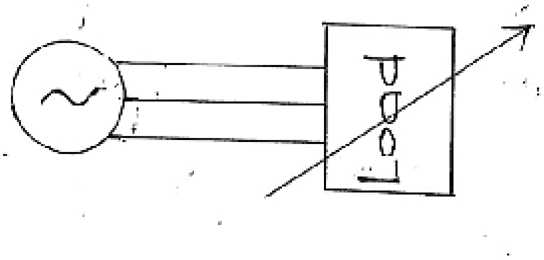
* Unity PF :



* Leading PF :-



Synchronous Generator Operating Alone :



⇒ operating alone : not connected to the net work, (Separate Power System).

Assumptions :

① Fixed $\tilde{E}_A$ (Fixed Φ).
  $\hookrightarrow I_F$ must be const.

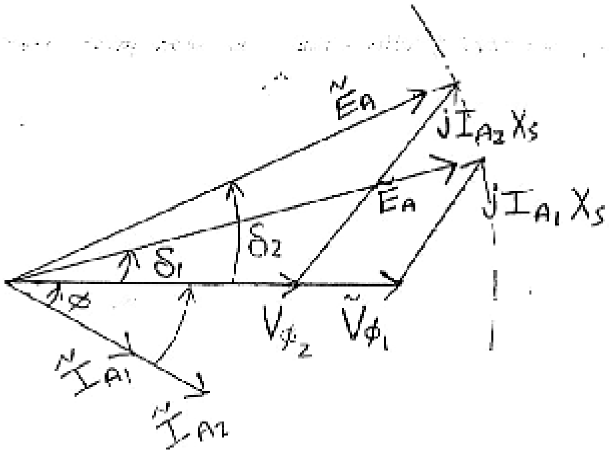
② No Change in the P.F of the load.

③ Constant ω. ④ R_A is neglected.

* Variable load.

← زيادة الـ load تعني زيادة الـ current.
$\underbrace{\text{زيادة الـ load}}$ ||| (Parallel loads)

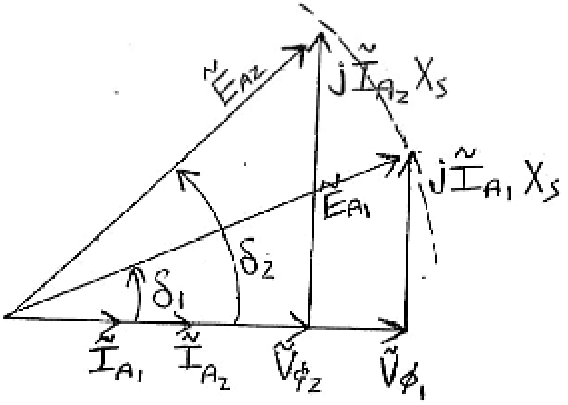
$\boxed{1}$ with lagging P.F Load :



$$V_R\% = \frac{|\tilde{E}_A| - |\tilde{V}_\phi|}{|\tilde{V}_\phi|} 100\% > 0$$

$\delta\uparrow, V_\phi\downarrow, I_A\uparrow \Longrightarrow$ if the load increase.

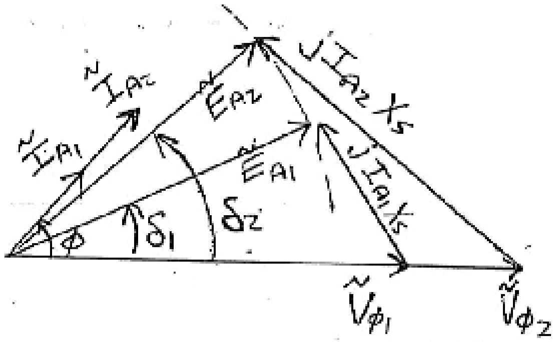
$\boxed{2}$ Unity P.F load :



$V_R\% > 0$.

$\delta \uparrow$, $V_\phi \downarrow$, $I_A \uparrow$.

$\boxed{3}$ with leading P.F load :



$V_R\% < 0$.

$\delta \uparrow$, $I_A \uparrow$, $V_\phi \uparrow$.

*If the load is capacitive → $V_R\% < 0$.
*If the load is Inductive → $V_R\% > 0$.

#How to keep $\underset{\substack{\uparrow \\ \text{terminal} \\ \text{Voltage}}}{V_\phi}$ constant ?

This is done by Automatic Voltage Regulator (AVR) : (negative feedback Control System) which changes the field Current (Φ) in order to keep V_ϕ constant , by $\underbrace{\text{Changing}}_{\substack{\text{increasing and} \\ \text{decreasing.}}}$ the R_{adj} .

$$\left.\begin{array}{l} \text{if } V_\phi\uparrow \longrightarrow I_f\downarrow \\ \\ \text{if } V_\phi\downarrow \longrightarrow I_f\uparrow \end{array}\right\} \text{due to } R_{adj} .$$

Example: 480V, 60Hz, Y-connected Stator, P=6., $X_s = 1\,\Omega$, $\underset{\text{Full load}}{I_{A|}} = 60A$, 0.8 P.F lagging load,

$\underset{\text{mech. losses.}}{P_{F\&W}} = 1.5\,kw$, $P_{core} = 1kw$, $R_A = 0$,

I_f is adjusted Such that the terminal Voltage is 480 V at no load.

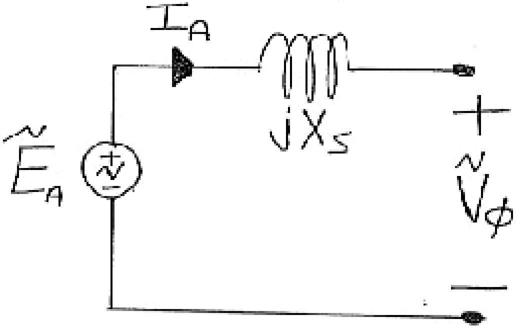
→ operating point.

a) $n_s = ?$

$$f = \frac{n_s P}{120} \rightarrow 60 = \frac{n_s(6)}{120}$$

$$n_s = 1200\ rpm.$$

b) ① $\tilde{V}_\phi = ?$ if it is loaded with Full-load and 0.8 lagging P.F ?



$$\rightarrow \tilde{E}_A = \tilde{V}_\phi + j\,\tilde{I}_A X_s$$

at phase

$$\frac{480}{\sqrt{3}}\angle\delta = V_\phi\angle 0 + j\left(60\angle -\cos^{-1}0.8\right)(1)$$

$$\frac{480}{\sqrt{3}}\cos\delta + j\,\frac{480}{\sqrt{3}}\sin\delta = V_\phi + j\left[60\times0.8 - j60\times0.6\right]$$

$$= V_\phi + j\,60\times0.8 + 60\times0.6$$

$$\rightarrow \frac{480}{\sqrt{3}}\cos\delta = V_\phi + 60 * 0.6 \quad ---- ①$$

$$\rightarrow \frac{480}{\sqrt{3}}\sin\delta = 60 * 0.8 \quad ---- ②$$

from ② :- $\sin\delta = 0.17 \rightarrow \delta = 9.97^\circ$.

from ① :- $V_\phi = 236.9\,V$.

حلّينا بهيك الطريقة لأنه المعطى E_A
والمطلوب حساب V_ϕ .

② $\tilde{V}_\phi = ?$ if it is loaded with full-load at unity P.F Load ?

$$\frac{480}{\sqrt{3}}\angle\delta = V_\phi\angle 0 + j\left(60\angle 0\right)(1)$$

$$\frac{480}{\sqrt{3}}\cos\delta + j\frac{480}{\sqrt{3}}\sin\delta = V_\phi + j\,60$$

$$\rightarrow \frac{480}{\sqrt{3}}\sin\delta = 60 \rightarrow \delta = 12.5^\circ$$

$$\rightarrow \frac{480}{\sqrt{3}}\cos\delta = V_\phi \rightarrow V_\phi = 270.5\,V$$

③ $\tilde{V}_\phi = ?$, if it is loaded with leading P.F load ?

$$\frac{480}{\sqrt{3}}\cos\delta + j\frac{480}{\sqrt{3}}\sin\delta = V_\phi + j(48+j36)$$

$$\rightarrow \frac{480}{\sqrt{3}}\sin\delta = 48 \rightarrow \delta = 9.97^\circ$$

$$\rightarrow \frac{480}{\sqrt{3}}\cos\delta = V_\phi - 36 \rightarrow V_\phi = 308.9V$$

c) $\eta\%$ for the case b : ① ?

$$\eta\% = \frac{P_{out}}{P_{in}} * 100\%$$

$$P_{out} = \sqrt{3}\,\underset{\substack{\uparrow \\ \sqrt{3}V_\phi = 410V}}{V_L}\,I_L\cos\phi = \sqrt{3}(410)(60)(0.8)$$

$$= 34113.6\,W.$$

$$P_{in} = P_{out} + 3|\tilde{I}_A|^2 R_A + P_{F\&W} + P_{core}$$

$$= 34.1136\,kw + 3(60)^2(0) + 1.5\,kw + 1\,kw$$

$$= 36.6136\,kw.$$

$$\rightarrow \eta\% = \frac{34.1136k}{36.6136k} 100\% = 93.2\% .$$

d) calculate the (τ) applied by prime mover ?

$$\underset{\substack{\uparrow \\ P_{losses}/P_{in}/P_{out}}}{\tau_{\substack{prime \\ mover}}} = \frac{P_{in}}{\omega_s} = \frac{36.6136k}{125.6} = 291.5 \ N.m.$$

$$\omega_s = \frac{2\pi n_s}{60} = \frac{2\pi(1200)}{60} = 125.6 \ rad/s.$$

$$\tau_{counter} = \frac{P_{out}}{\omega_s} = \frac{34.1136k}{125.6} = 271.6 \ N.m$$

$\uparrow$

τ corresponding to load power ($\underset{\sim\sim}{P_{out}}$)

• الT اللي بعمل ال load

e) Voltage Regulation ?

$$V_{R_1}\% = \frac{\frac{480}{\sqrt{3}} - 236.8}{236.8} 100\% = 17\% .$$

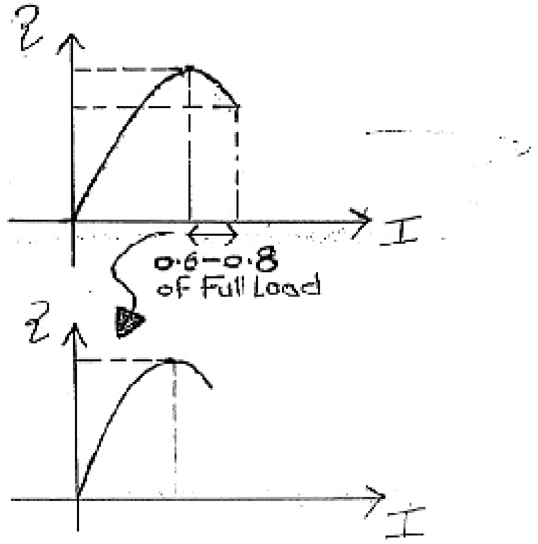
$$V_{R_2}\% = \frac{\frac{480}{\sqrt{3}} - 270.4}{270.4} 100\% = 2.48\% .$$

$$V_{R_3}\% = \frac{\frac{480}{\sqrt{3}} - 308.8}{308.8} 100\% = -10.25\% .$$

Parallel Operation of AC Generator :-

Why Connect generators in parallel ?

1. To Supply more Power if the demand increases.
   active & reactive
2. Increased Realiability of the Power System.
3. To have a more efficient Power System:



> operating pnt. الفكرة تكون ال
max. point عند ال generator
η

if η▲, losses▼

if only one generator is used and it is not operating at near full Load, then it will be inefficient. With several smaller machines in Parallel, it is Possible to Operate Only a fraction of them. The ones that do operate are Operating near full Load and thus more efficiently.

Conditions of Paralleling :-

$\boxed{1}$ The rated line Voltages, must be equal other wise, Circulating current flow between generators.

$\boxed{2}$ They must have the Same phase sequence, other wise, → Voltage difference → Circulating current

الأول ⇓ الثاني
generator , motor .

$\boxed{3}$ The Same phase angles, other wise, → Circulating current.

$\boxed{4}$ The frequency of the oncoming generator must be Slightly higher. [1 Hz, 1.5 Hz] than the freq. of the running System.

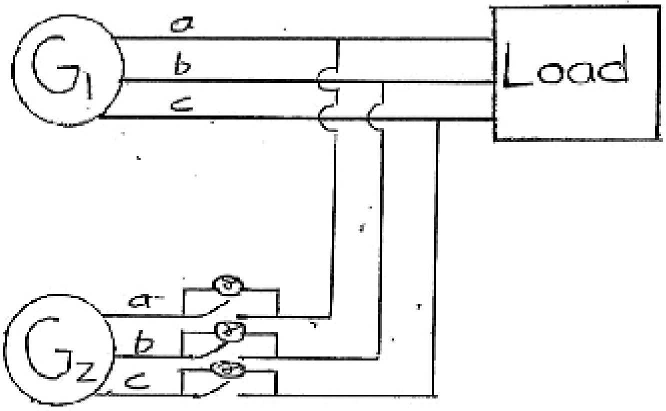
→ When the generator is loaded after Switching the cct. breakers on, the rotational Speed decreases (freq. decreases).

generator بحركه ال prime mover s لما نوصله ع إلشبكة بصير loaded وعليه 50Hz

تنزل سرعة ال prime mover ← وكاستجابة لازم يرجع السرعة ← بس ما راح يقدر اذا كان ال

delay كبير ← فبنعطي ال gener. الثاني 51Hz or 52Hz ※

Paralleling procedure :-



When the three light-bulb become dark [difference voltages = 0],

↳ G_1, G_2 have the Same Voltages, Same freq, Same phase Shift, Same Seq.

↳ Then Switch the cct breaker (G_2) ON.

at Small systems or PV's Systems.

#

→ Big Stations → Big cct. breakers

↓

we use Synchroscope as a switch for G_2 When 4 conditions are met.

*automated
*need high Power.

Frequency-Power and Voltage-Reactive Power Characteristics of a Synchronous Generator:

Prime movers → any Type of mech. engines,
→ wind turbines,
→ water turbines,
→ gas turbines ...

Speed ↓ When Load ↑ (freq. ↓) .

⇒ Variation in Speed with increasing load is non-linear .

ترجع تزوّد كميّة الـ Fuel ⇒ الحل .

---

demand ↑ , Reactive power from gen. ↑ ,

Load ↑ , Reactive comp. current ↑ ,

Voltage ↓ .

ترجع تكبّر الـ induced Voltage ⇒ الحل .

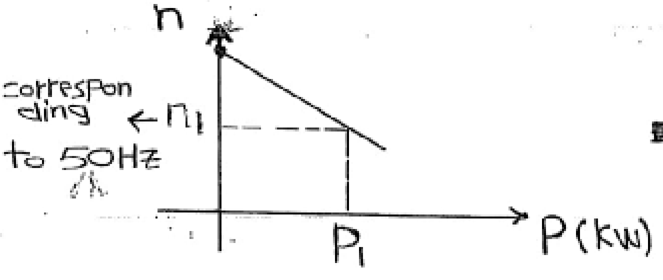
$$SD\% = \frac{n_{nl} - n_{Fl}}{n_{Fl}} * 100\%$$

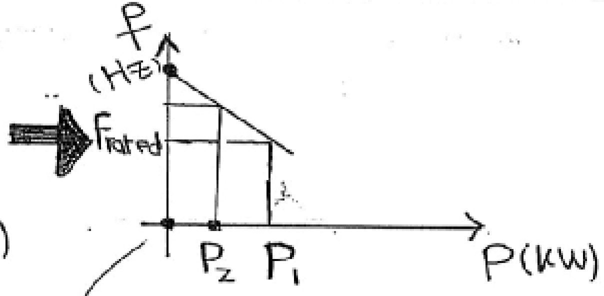
↑
Speed regulator.
Speed drop.

كلما اقتربت لل صفر بكون أحسن ✓

قطع ل Sync. motor بالطول SD = صفر ✓

$SD\% = 2\% - 4\%$





فجأة $P = 0$ (Short cct. or open cct.)

تتغير السرعة

كحل → تقلل السرعة
تقلل ال fuel الداخل لل engine

Tourbine governer

→ due to use feed back control speed
↳ Time delay → (1-2 second).

$P = S_P (f_{nl} - f_{sys})$ --- freq. Power Characteristic.

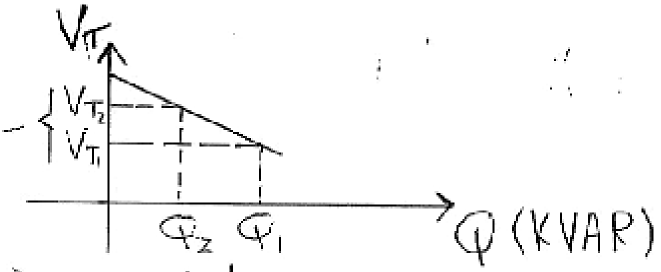
P : output power from generator.

S_P : Slope of the curve (KW/Hz) or (MW/Hz)

f_{nl} : no-load freq.

f_{sys} : System operating freq. (constant : 50 or 60 Hz).

A Similar relation for the Voltage as function of the output reactive power can be derived :



$\boxed{V_T \downarrow , Q \uparrow}$

→ parallel generator have the same V_T.

demand ↓ , Q ↓ ,

الحل ⇒ AVR → (−ve) feedback controler.

↳ Time delay (in msec.) → measuring process , order : Field current due to Φ

← والوقت لل Field curr. عشان يتغير . ✱

Note :-

In Synch. generators operating alone, P & Q supplied are the amount demanded by the load.

all the power generated must be consumed, other wise, → difference Voltage and losses

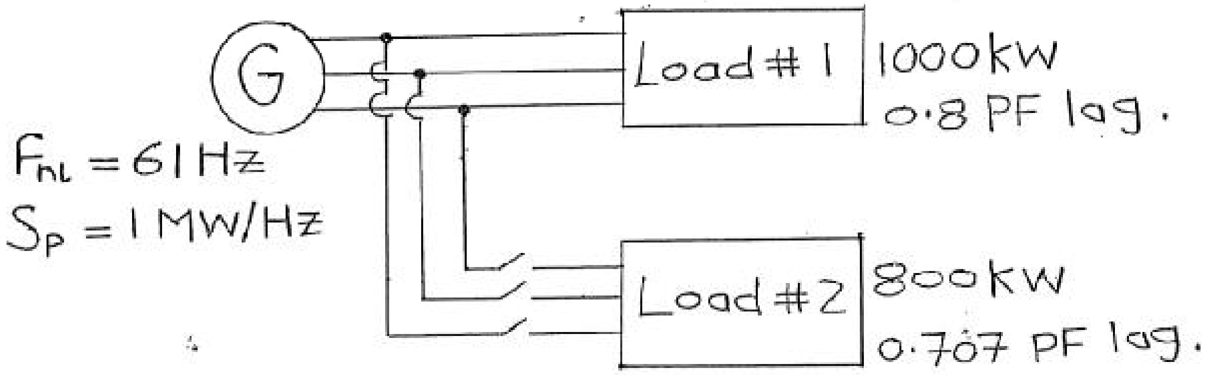
مبدأ حفظ الطاقة

$P\uparrow$, $S\downarrow$ $\xrightarrow{\text{الحل}}$ governer.

$Q\uparrow$, $V\downarrow$ $\xrightarrow{\text{الحل}}$ AVR.

} -ve control System.

Example :-



a) Before Switching ON, f_{sys} ?

$P = S_P(f_{nL} - f_{sys})$

$1\times10^6 = 1\times10^6(61 - f_{sys}) \rightarrow f_{sys} = 60Hz.$

b) with load # 2 $\underbrace{\text{connected}}_{\text{demand}\uparrow}$, f_{sys}?

$P = S_P(f_{nL} - f_{sys})$

$1\times10^6 + 0.8\times10^6 = 1\times10^6(61 - f_{sys})$

$f_{sys} = 59.2\,HZ.$

C) What action should be taken to restore the nominal freq. ?

The fuel input to the primover must increase, (no-load freq. must increase)

$\rightarrow 1 \times 10^6 + 0.8 \times 10^6 = 1 \times 10^6 (f_{nl} - 60)$

$f_{nl} = 61.8 \, Hz$.

---

* Summery for Generator operating alone:

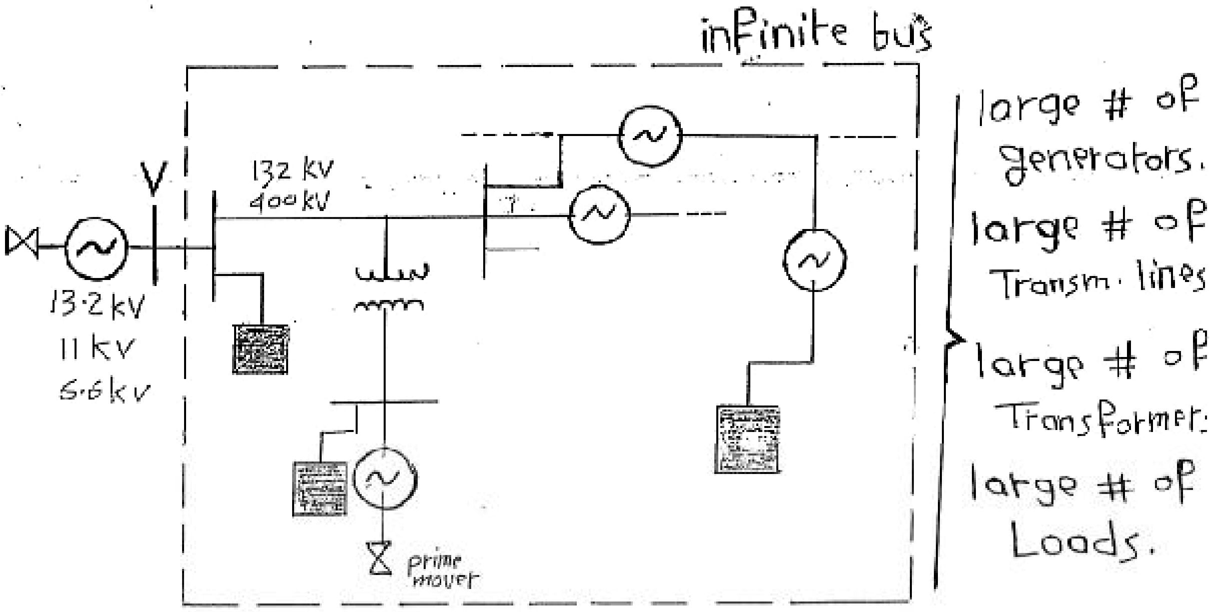
$\boxed{1}$ Real power and Reactive power must be equal demand of the load.
(the Same power generated by generator)

$\boxed{2}$ The Goverher Set point controls the operating freq.

$\boxed{3}$ The Field current controls the terminal Voltage.

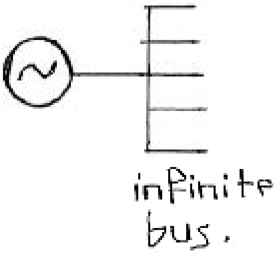
Operation of Generators in Parallel with large power System :

Infinite bus : So large power System where its Voltage and Frequency do not Vary regardless (بغض النظر) the amount of active and reactive Power consumed.

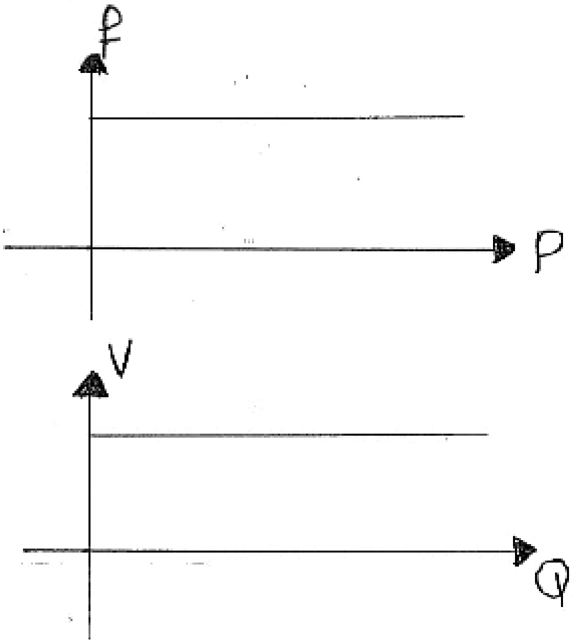


gen. يُجبر الـ الجديد إنه يشتغل بنفس الـ V و F .

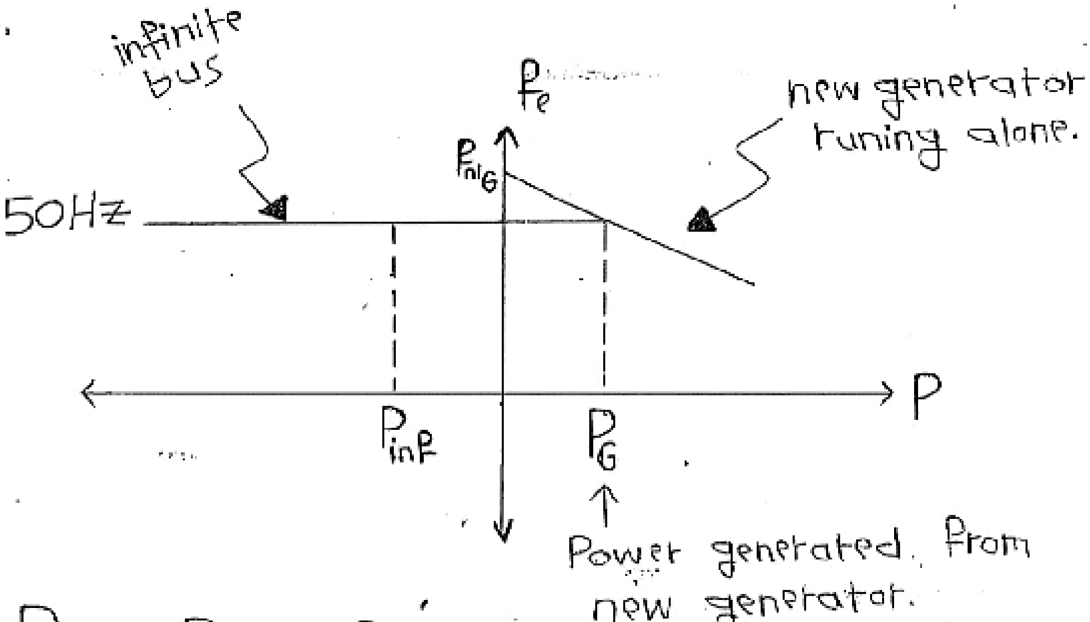
≡ constant V, constant F .



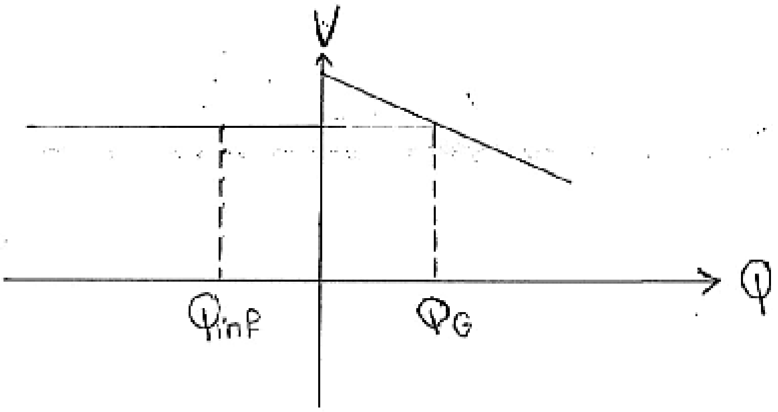
When we add a new generator by using Synchroscope, initially the original generator of the Power system is still bigger than the new one. Then the new one takes the <u>Same Voltage</u> and the <u>Same freq.</u> of the Power System becoming Similar to the original generator.

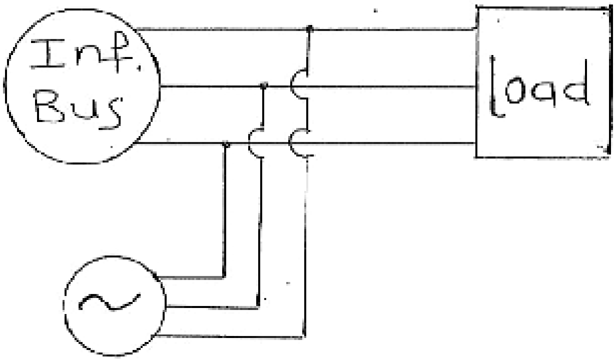


How the new generator takes the Same network's Voltage even though there are a lots of transformers inside the infinite bus? <u>* Becouse we use the per unit Values.</u>

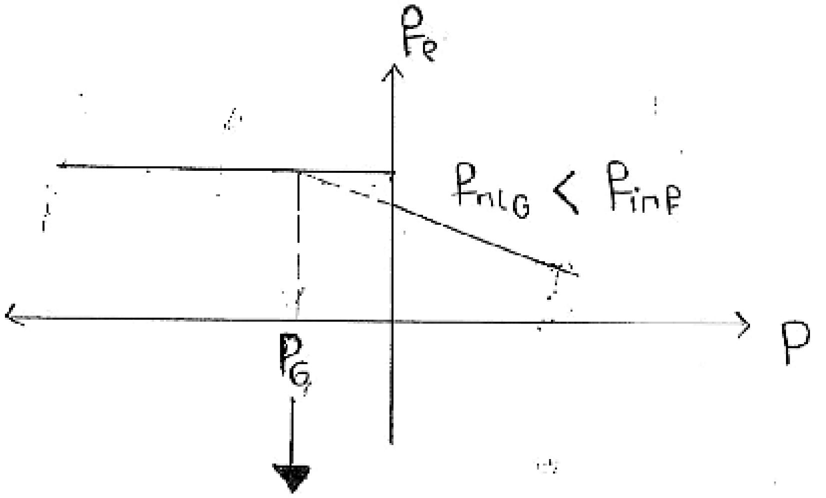

infinite bus
f_e
new generator runing alone.
P_{nlG}
50Hz
P
P_{inf}
P_G
Power generated from new generator.

$$P_{tot} = P_{inf} + P_G$$


V
Q
Q_{inf}
Q_G


Inf. Bus
load

if f_{nlG} was not Sligtly higer than f_{inf}:



↓

-ve (P_G<0)

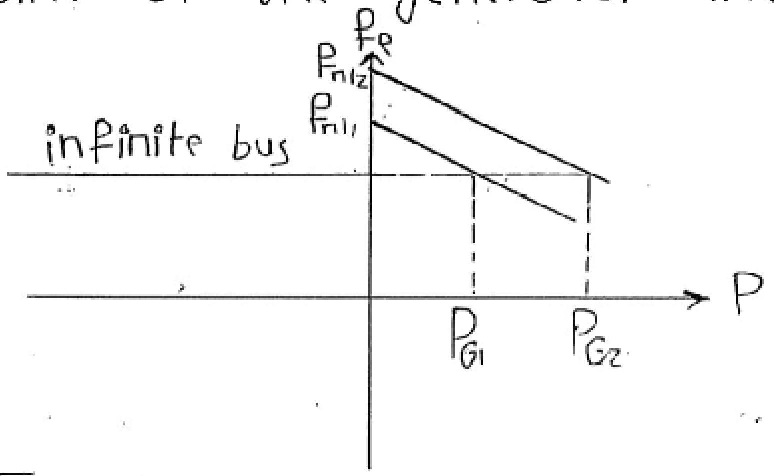
↓

The generator will
run as motor.
(consumed Power)

→ to turn ON protiction system;
due to → directional of the Power.
→ or due to current.

Power System ↑ → Voltage constant أكتر
→ cost بتقل

What happens when the governer Set point of the generator increase ?



"The effect of increasing the governer Set point."

→ valve of fule أكبر

→ no load freq. of the generator increases,

→ Power Contribution of the generator increases,

→ Runing freq. of the Power System remains Constant.

∗ at no load → the Speed of the generator greater than the Synchronous Speed.

= If you have a generator connected to infinite bus, and you need to increase the active power,

→ Provide the amount of fule in governer.

In phase diagram :-

assumptions :-

I_f is constant $\Rightarrow E_A$ is constant.

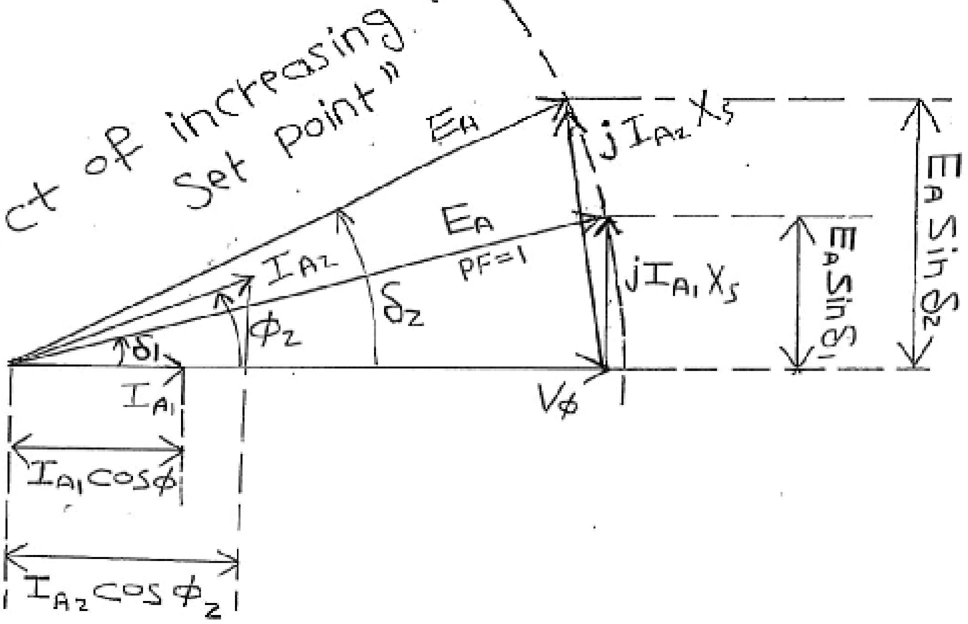
ω is constant $\Rightarrow$ runing freq. is const.

V_t is constant $\Rightarrow$ terminal Voltage is const.

} connection with infinite bus.

R_A is neglected.

"The effect of increasing the governer set point"



$$P\uparrow = 3\underset{const.}{\underline{\underline{V_\phi}}}\,\underline{I_A\cos\phi}\uparrow$$

$$P\uparrow = \frac{3\overset{const.}{\underline{V_\phi}}\,\underline{E_A}}{\underset{const.}{\underline{X_s}}}\underline{\sin\delta}\uparrow$$

*Conclusion:

$\boxed{1}$ I_A increases. (phase current ↑)

$\boxed{2}$ V_ϕ constant.

$\boxed{3}$ $\underline{I_A X_s}$ increases.
(Voltage drop)

$\boxed{4}$ E_A constant by assumption.

$\boxed{5}$ $E_A \sin\delta$ increases.

$\boxed{6}$ δ increases.

$\boxed{7}$ The p.F of the generator becomes more leading. ($\phi\uparrow$).

يتحرك باتجاه ال leading.

$\boxed{8}$ $I_A \cos\phi$ increases.

$\boxed{9}$ Power generated (P) increases.

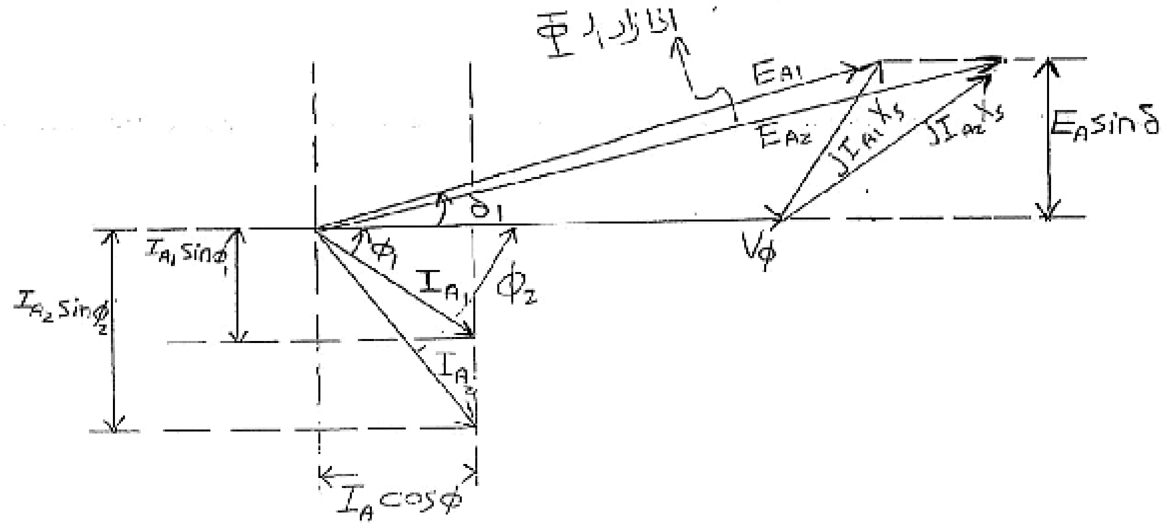
$\boxed{10}$ $Q = 3 V_\phi \underline{I_A \sin\phi} \downarrow$

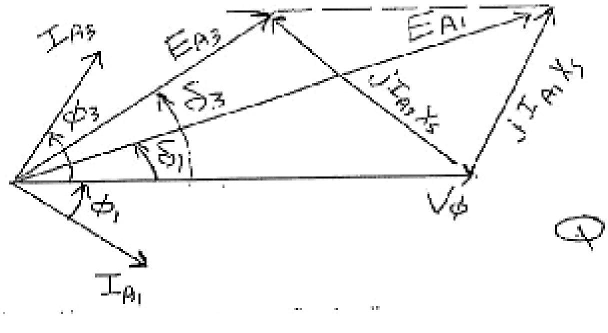
The variation of Q is very Small compared with P.

(Q cosumes Power) because the generator becomes more leading.

What happens if the field Current increases and the governer Set point remains Unchanged ?

- The input active power remains Constant ,
  - $\hookrightarrow I_A \cos\phi$ & $E_A \sin\delta$ are constant.
- $i_F \uparrow \longrightarrow \Phi \uparrow \longrightarrow E_A = 4.44\, \Phi f N k_\omega \uparrow$,
- V_ϕ remains Constant.
- f remains constant $\longrightarrow$ ω is Constant.





$Q = 3V_\phi I_\phi \sin\phi$

$\boxed{1}$ $I_f \uparrow$, $\Phi \uparrow$, $E_A \uparrow$,

PF becomes more lagging ,

$\delta \downarrow$, $I_A \sin \phi \uparrow$,

$Q_{output} \uparrow$

P_{output} remains constant.

$\boxed{2}$ $I_f \downarrow$, $\Phi \downarrow$, $E_A \downarrow$,

PF becomes more leading ,

$\delta \uparrow$, $I_A \sin \phi \downarrow$,

$Q_{output} \downarrow$

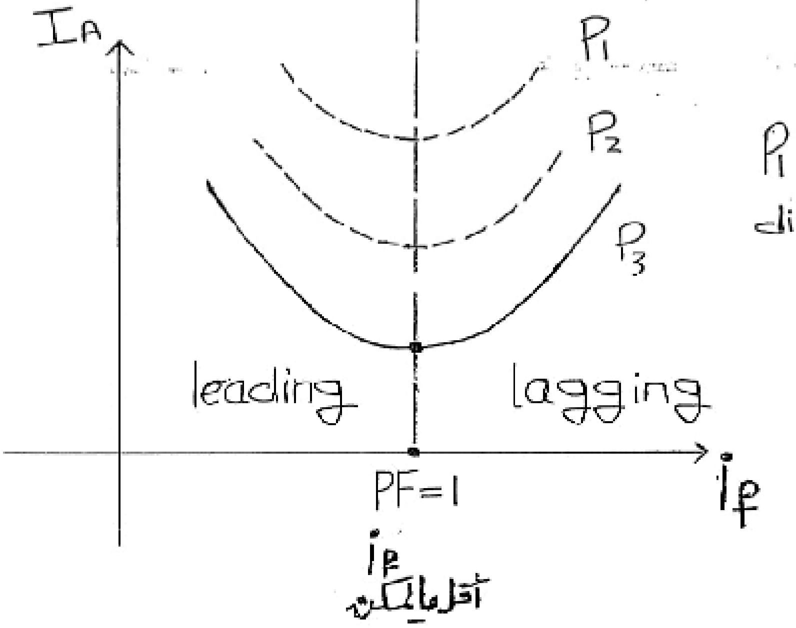
P_{output} remains constant.

$\boxed{3}$ @ Certain value of $I_f \rightarrow PF = 1$

$\downarrow$

I_f

أقل ما يمكن



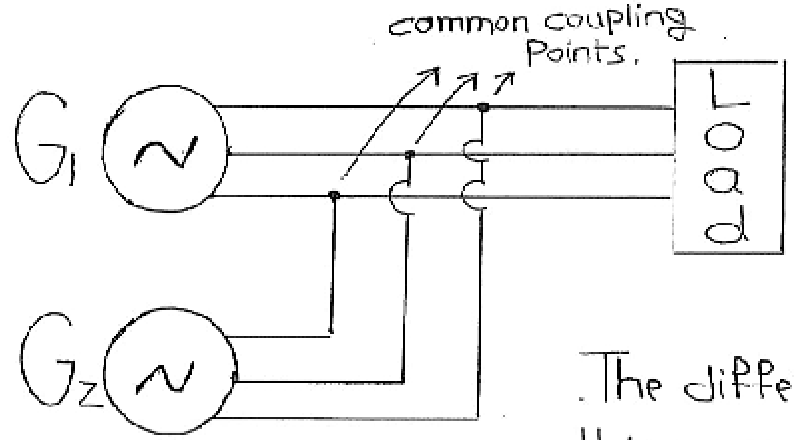
$P_1 > P_2 > P_3$
diff. operating points.

V-curves of
Synch. gen.

Summary:

1) When a generator is connected to an infinite bus; the frequency and terminal voltage are controlled by the power system (infinite bus).
2) The governor set point controles the active power generated by the generator.
3) The reactive power supplied by the generator is controlled by the field current.

Operation of Generators in parallel with Other generators of the Same Size:



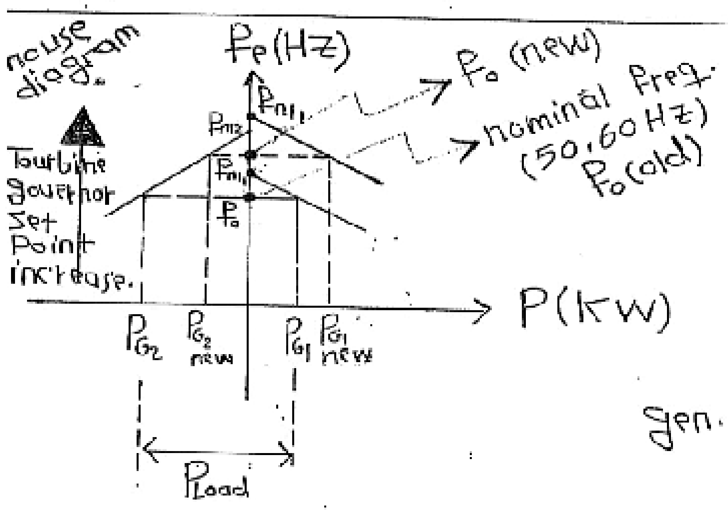
. The differance between this case and the previous cases is that here, the Voltage & freq. are not constant, While in the other cases they were Const

The most important point here, is the Power Sharing, which is the process of how the power is Shared between generators with the need to avoid the overload that exceeds the 10% at a certain period of time, as long as there is no over heat.

$$\underbrace{P_{Load}}_{consumed} = P_{Tot} = P_{G_1} + P_{G_2}$$

$$\underbrace{Q_{Load}}_{consumed} = Q_{Tot} = Q_{G_1} + Q_{G_2}$$

As the previous cases, this case has the same principle and the same equations (مبدأ حفظ الطاقة), but they differ in the load : here, the loads are lamped , and there the loads are distributed on large areas.



governor set point $\boxed{I}$ ↑

↓

f_{nl_1} increase

↓

بترتفع الـ C/C لفوق

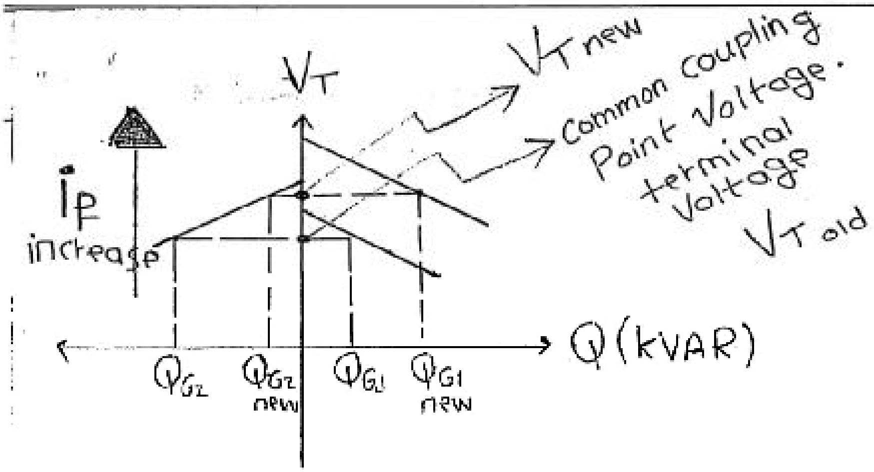
↓

بزيد الـ Power contribution الطالع من هذا الـ gen.

وبتقل الطالع من الثاني.

note: if the governer set point of the first generator increases , for the same load : P_{G_1} ↑ , P_{G_2} ↓ , f_{nl_1} ↑ .

* governor ⟷ P *

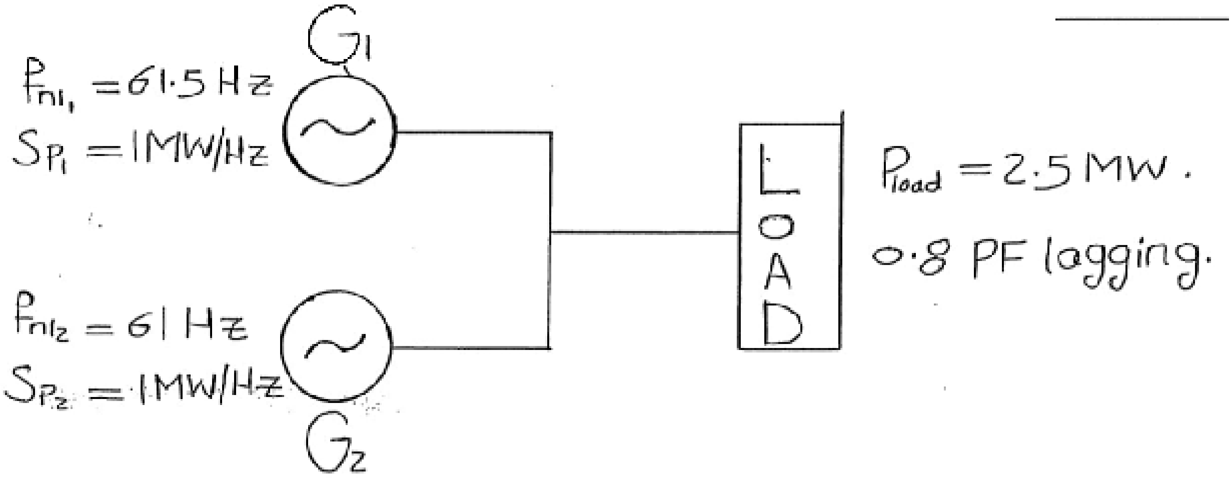


note: if the field current of the first generator increases, ∴ Q_{G1} ↑, Q_{G2} ↓, running Terminal Voltage ↑

Why we do this ?!

Because of the overload : So, if we have two generators, one of them running at the 20% of the overload and the other at 40%, then one turns off and the other runs at 60% of the over load. (توزيع أتوفي)

- Example :



a) $f_{sys} = ?$

$$P_{Tot} = P_1 + P_2$$

$$= \underbrace{S_{P_1}(f_{nl_1} - f_{sys})} + \underbrace{S_{P_2}(f_{nl_2} - f_{sys})}$$

$$2.5\times10^6 = 1\times10^6(61.5 - f_{sys}) + 1\times10^6(61 - f_{sys})$$

$$\rightarrow f_{sys} = 60\text{Hz}.$$

$$P_1 = 1.5 \times 10^6 \text{ W}.$$

$$P_2 = 1 \times 10^6 \text{ W}.$$

b) If an additional 1MW is connected

$$P_{Tot} = P_1 + P_2$$

$$3.5 \times 10^6 = 1 \times 10^6 (61.5 - f_{sys}) + 1 \times 10^6 (61 - f_{sys})$$

$\rightarrow f_{sys} = 59.5$ Hz. $\boxed{f \downarrow, \text{ as load} \uparrow}$

$P_1 = 2$ MW.

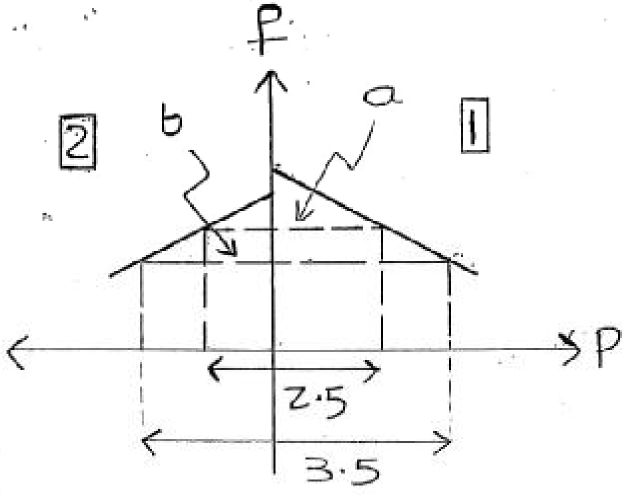
$P_2 = 1.5$ MW.

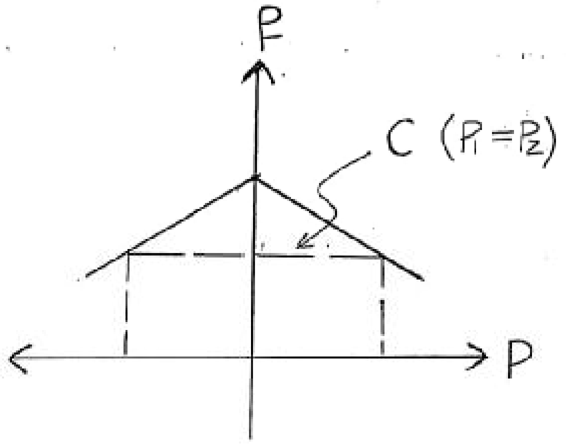
c) If the governor Set point of G_2 is increased by Such that to have f_{nl_2} equals to 61.5 Hz.

$$3.5 \times 10^6 = 1 \times 10^6 (61.5 - f_{sys}) + 1 \times 10^6 (61.5 - f_{sys})$$

$\rightarrow f_{sys} = 59.75$ Hz.

$$\left.\begin{aligned} P_1 &= 1.75 \text{ MW.} \\ P_2 &= 1.75 \text{ MW.} \end{aligned}\right\} \begin{aligned} &\text{Same } S_P \text{ , Same } f_{nl} \\ &\Rightarrow \text{Same } P. \end{aligned}$$





d) How to restore the nominal freq.?

→ increase the (no load freq.) of the first generator or the second generato or the Both.

e) How to restore the nominal freq. keeping the power Sharing equally ?

$$3.5 \times 10^6 = \left[1 \times 10^6 (f_{nl_1} - \underset{\overset{\uparrow}{60Hz}}{\underline{f_{sys}}})\right] * \underset{\overset{\uparrow}{\text{equals Power}}}{\underline{2}}$$

$$f_{nl_1} = f_{nl_2} =$$

→ two generators connected in Parallel have the Same f_{sys}.

$\boxed{1}$ The Total Power consumed by the load is supplied by the generators.

$\boxed{2}$ The System freq. and the teminal Voltage (Common Coupling Point Voltage) depends on the Power demands.

$\boxed{3}$ To adjust the real Power Sharing between the generators without Changing f_{sys} :

a- if the load increases, the governor set point of the first or the second or the both of two generators should increases.

b- if the load decreases, the governor set point of the first or the second or the both of two generators should decreases.

$\boxed{4}$ To adjust f_{sys} without Changing the real Power Sharing between the generators :

a- if the f is to be increases, increase the governor Set Point of two generators.

b- if the f is to be decreases, decrease the governor Set Point of two generators.

$\boxed{5}$ To adjust the Reactive Power Sharing between generators without Changing V_T :

a- if the Q demand increases, increase the Field current of the First generator or the Second or the both b- if the Q demand decreases, decrease the field current of the first generator or the Second or the both.

$\boxed{6}$ To adjust the V_T between generators without Changing the reactive Power Sharing :

a- if the V_T is to be increased, increase the field Current of the two generators.

b- if the V_T is to be decreased, decrease the field Current of the two generators.

Synchronous Generator Transients :

* Transients Come as a result of :

$\boxed{1}$ Shaft torque is applied .

(i/P mech. power Changed) .

↑ or ↓ .

$\uparrow P_m = \uparrow \tau_m \underset{\underset{\text{const.}}{\uparrow}}{\omega}$

↳ by governor set point. (Rule).

$\boxed{2}$ Output load Suddenly Changes .

* demand Changes on P or Q .

* Switching : P or Q↓ , and
[illegible]

Connecting : P or Q↑ .
[illegible]

$\boxed{3}$ Connecting generator in Parallel with a running power Sys. (or disconnecting)

↳ * Changes in the power Sharing .

$\boxed{4}$ Short circuits in any part of the power system.

$P=0$

* during fault → S.C between 3 lines or 2 lines or line-ground.

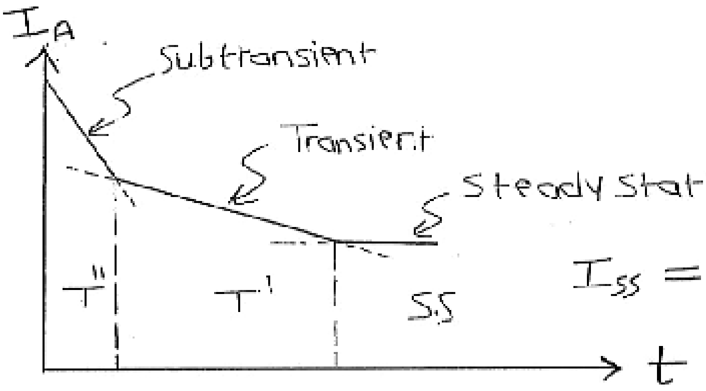
↳ Changing the power flow.

$\boxed{5}$ Field current or Field voltage is applied. → [Field power is applied].

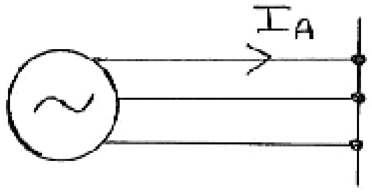
Also, ~~loss of excitation~~ → rotor of the syn. gen. is open.
($I_f = 0$)
(fault).

Short CCt. Transient :-

(See the figure in book Pages :- 246 - 249 , 5th Ed.)



$$I_{ss} = \frac{E_A}{X_s}$$



كل ما كان ال rated power
لل generator أكبر ،
كان ال time أقل .

4

Synchronous Generator Ratings :

Ratings (Design Specifications) : Certain basic limits like speed and power that maybe obtained from the machine.

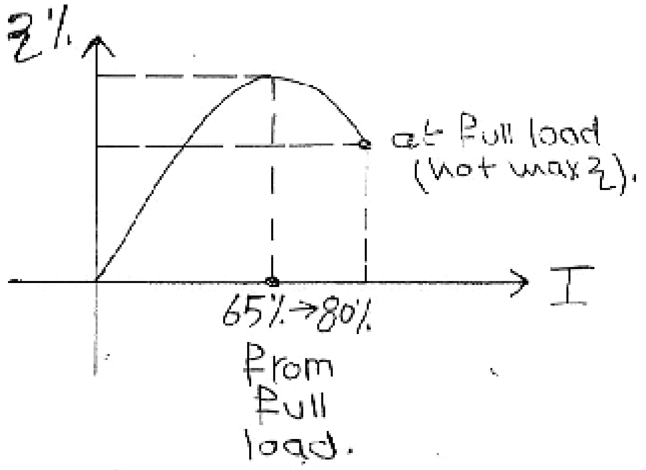
The purpose of the Ratings is to protect the machine from important operation.

Rated Power ↑ , Size & weight ↑

Rated Voltage ↑ , Size & weight ↑

Current ↑ , Size , cost , weight & Volume ↑

Rated Power ↑ , η ↑ , losses ↓ , as a ratio of η ↑



* Typical Rated Values :

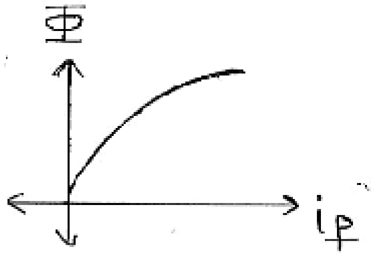
1. Voltage.
2. Frequency.
3. Speed.
4. Apperant Power.
5. P.F → ال load يحدده
6. Field current.
7. Armature Current.
8. Service factor.

→ most of them are coupled together.

$E = 4.44\,\Phi f N k_w$

$f = \dfrac{nP}{120}$

$S = \sqrt{3}\,V_L I_L$



• الفكرة ماتتعدى ال Full load Power ◄——

over load → Current ↑ → $\underline{\underline{I}}^2 R_A$ ↑

cooling ↑

V_{drop} on R and X on Stator.

1 * $F\uparrow \xrightarrow{\text{بتأثر على}}$ hysteresis losses → F^2 بتعتمد على ال

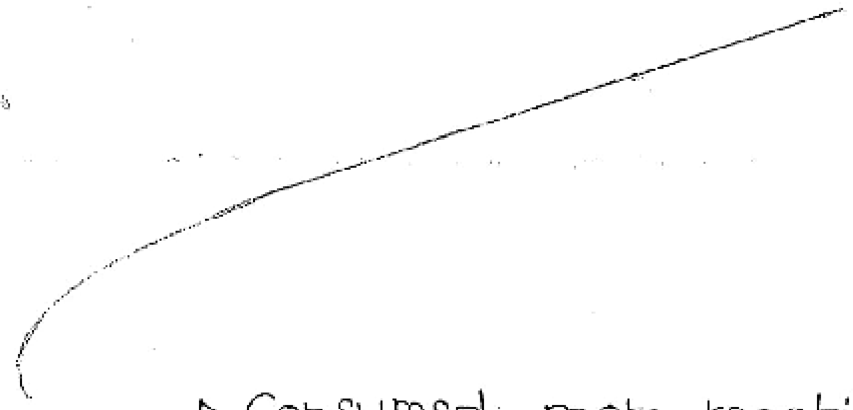
eddy current losses (copper losses).

↓

effect on the losses.

---

more reduction in P.F → Very bad.



بسبب وجود ال induc. part

→ Consumed more reactive Power.

active power is more important than Reactive.

Q

عبء → مجبورين عليها بسبب ال inductive parts.

$S = \sqrt{3}\, V_L . I_L$

@ full load:

$\rightarrow P = 0$: pure inductive or capacitive load.

أحسن حالة

$\rightarrow \varphi = 0$: pure Resistive load.

$[S = P]$

$* \ \varphi \uparrow \ \rightarrow \ I \uparrow\uparrow$ ─┬→ losses in T.L $\uparrow$

└→ losses in Trans. $\uparrow$

$\downarrow$

cost $\uparrow$

Service Factor : The ratio of actual max. Power to ~~it's~~ Name plate rating. a generator with Service factor of 1.1 Can run at 110 % of the rated load without damage (problems), if the overheat is accounted.

→ up normal conditions → underload بشغل ع
مثلاً موجة حر، وتبريد سيء ⇒ 90% full load.

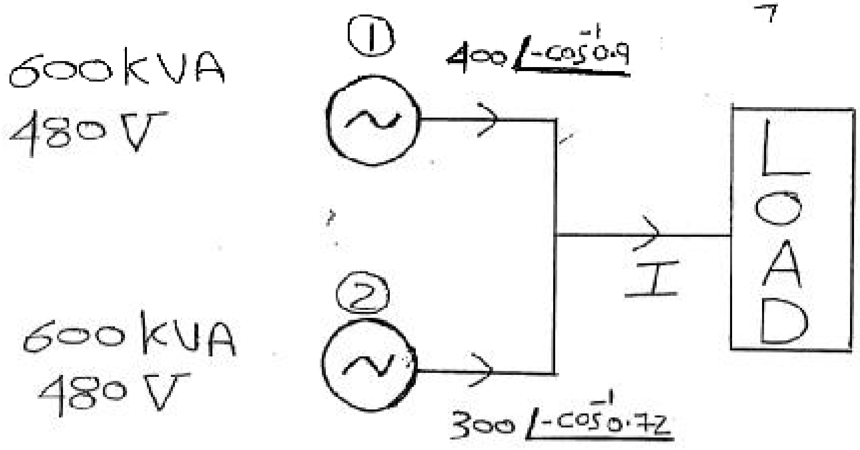
* because of that, Service factor related with Temp. #.

التبريد كويس وبدي اشغل ع 150% من full load ← SF=1.5

- → Transformer → due to Tap changers.
  change #. of terms
- → Generator → a problem is : saturation of the magn. cct.

Qustion :-

both have the same field current, and the same voltage.



Both Generator prime mover have difference Speed drop c/c.

a)

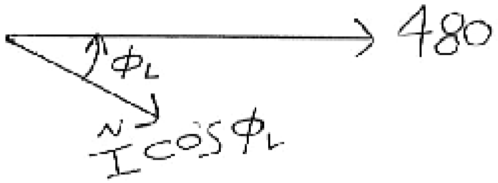
$P_1 = \sqrt{3}\ V_L I_L \cos\phi = 0.3$ MW.

$P_2 = \sqrt{3}\ V_L I_L \cos\phi = 0.18$ MW.

$Q_1 = \sqrt{3}\ V_L I_L \sin\phi = 0.14$ MVAR.

$Q_2 = \sqrt{3}\ V_L I_L \sin\phi = 0.173$ MVAR.

b) The overall P.F on the load .?



$$\tilde{I} = 400 \angle -\cos^{-1} 0.9 + 300 \angle -\cos^{-1} 0.72$$

$$= 691.5 \angle -33.6^\circ \text{ A.}$$

$PF_L = \cos(-33.6) = 0.833$ lagging.

C) Is the G_1 run in rated power. ?

$P_1 = 300k$. , $Q_1 = 144k$

$$\sqrt{(P_1)^2 + (Q_1)^2} \overset{?}{=} S_{rated}$$

$$\underbrace{332.7\,k} \neq \underbrace{600\,k}$$

* No, G_1 not run in rated power.

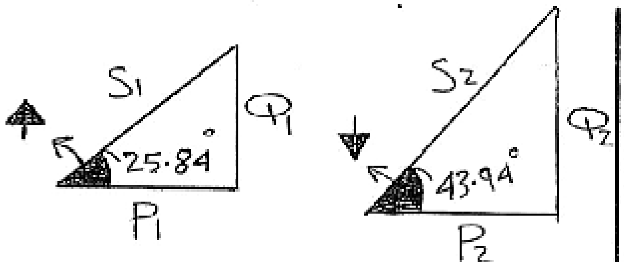
d) Is one Generator is enough.?

$$\sqrt{(P_1+P_2)^2+(Q_1+Q_2)^2} \overset{?}{=} S_{rated}$$

$$\underset{\sim\sim\sim}{581.9k} < \underset{\sim\sim\sim}{600\,k}$$

→ ∴ one G is enough.

e) In what direction must the field current on each generator be adjusted in order for them to run at the Same P.F ?



increase field current of the 1st gen. → Q_1↑

or:

decrease field current of the 2nd gen. → Q_2↓

$$\cos\phi_1 = \cos\phi_2$$

$$\cos\left[\tan^{-1}\frac{Q_1}{P_1}\right] = \cos\left[\tan^{-1}\frac{Q_2}{P_2}\right]$$

$$\frac{Q_1}{P_1} = \frac{Q_2}{P_2} \quad --- \boxed{1}$$

$$Q_1+Q_2 = 0.144+0.173$$

$$Q_1+Q_2 = 0.317 \quad --- \boxed{2}$$

⋮

Question :

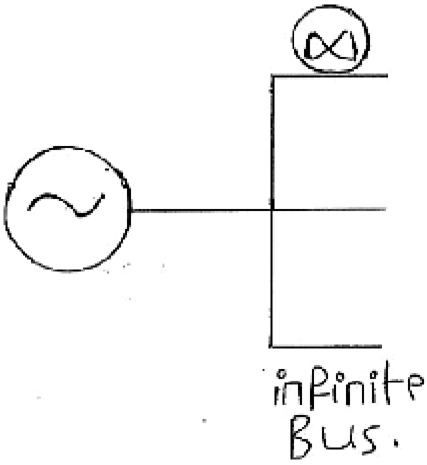
20 MVA , 13.8 kV , 0.8 PF lagging -

Y connected , Synch. gen. , $R_A = 0 , X_s = 0.7$ pu

rated Values

إزا ما أعطى

ال basis.



a)

$$S_{base} = \sqrt{3}\, V_{L,base}\, I_{L,base}$$

$$20 \times 10^6 = \sqrt{3}\,(13.8 \times 10^3)\, I_{\phi,base}$$

$$\rightarrow I_{base} = 836.74 \text{ A} .$$

$$Z_{base} = \frac{V_{\phi base}}{I_{\phi,base}} = \frac{13.8 \times 10^3 / \sqrt{3}}{836.74} = 9.5\, \Omega .$$

$$X_s = (0.7)(9.5) = 6.67\, \Omega .$$

b) $\tilde{E}_A = ?$ in p.u !

$$\tilde{E}_A = \tilde{V}_\phi + j\,\tilde{I}_\phi X_s$$

$$= 1\angle 0 + j(1\angle -\cos^{-1} 0.8)(0.7)$$

$$= 1.526\angle 21.52^\circ \text{ p.u.}$$

c) $|\tilde{E}_A| = (1.526)\,V_{\phi,\text{base}}$

$$= (1.526) * \frac{13.8\times10^3}{\sqrt{3}} = 12.15 \text{ kV.}$$

d) If the internal generated Voltage is reduced by 5% , Then calculate I_ϕ ?

or I_P

(نفس الشيء).

$$E_{A2} = 0.95\,E_{A1}$$

$$\rightarrow E_{A1}\sin\delta_1 = E_{A2}\sin\delta_2$$

$$E_{A1}\sin(21.52^\circ) = 0.95\,E_{A1}\sin\delta_2$$

$$\rightarrow \delta_2 = 22.71^\circ$$

$$* \ \tilde{E}_A = \tilde{V}_\phi + j\,\tilde{I}_\phi X_s$$

$$0.95 * 1.526 \angle 22.71^{\circ} = 1\angle 0 + j\,\tilde{I}_\phi (0.7)$$

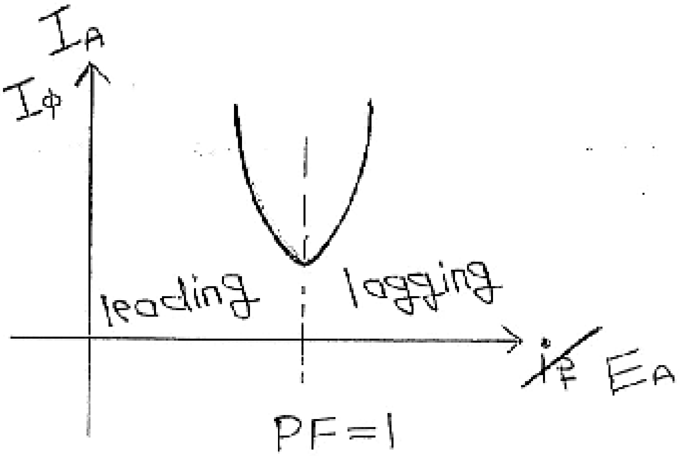
$$\rightarrow I_\phi = 0.93 \angle -31.1^{\circ} \text{ A.}$$

e) repeat the previous part (d), for

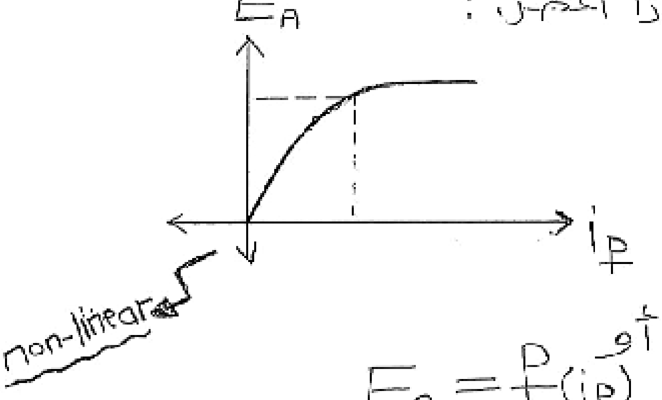
10%, 15%, 20%, 25%.

*reduction in E_A.

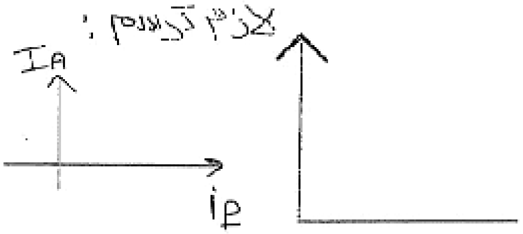
I_ϕ	E_A



إذا أعطى :



لازم ترسم :



$$E_A = f(i_F) \quad \text{أو}$$

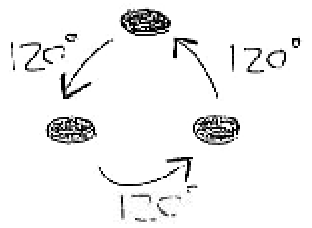
Synchronous Motors :-

Types:

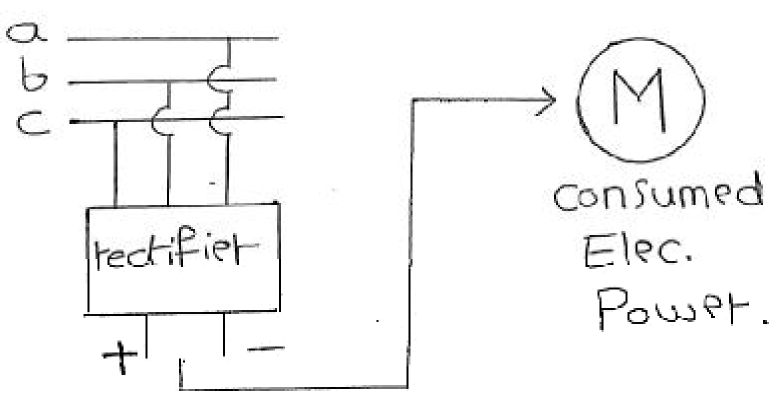
1] Salient pole rotor.

2] Cylindrical rotor.

* The Stator of Synch. motor is the same as that of the induction motor i.e three phase winding phase Shifted by 120° in Space.



* DC Power Supply is fed to the rotor.



3ϕ synch. machines → rotor → DC.

*Principle of Operation :-

in Induction motor:

3ϕ currents ⟶ 3ϕ windings

120° phase in time — 120° phase in space.

↓

Rotating mag. field
in synch. speed

$$f = \frac{n_s P}{120^\circ}$$

→ Φ → قطع ال conductors → V → لأنه short circuited

↓

يولّد I

لازم سرعة دوران Φ
أعلى من سرعة دوران rotor.
(diff. in speed).
(1-6)%

in Synchronous motor :

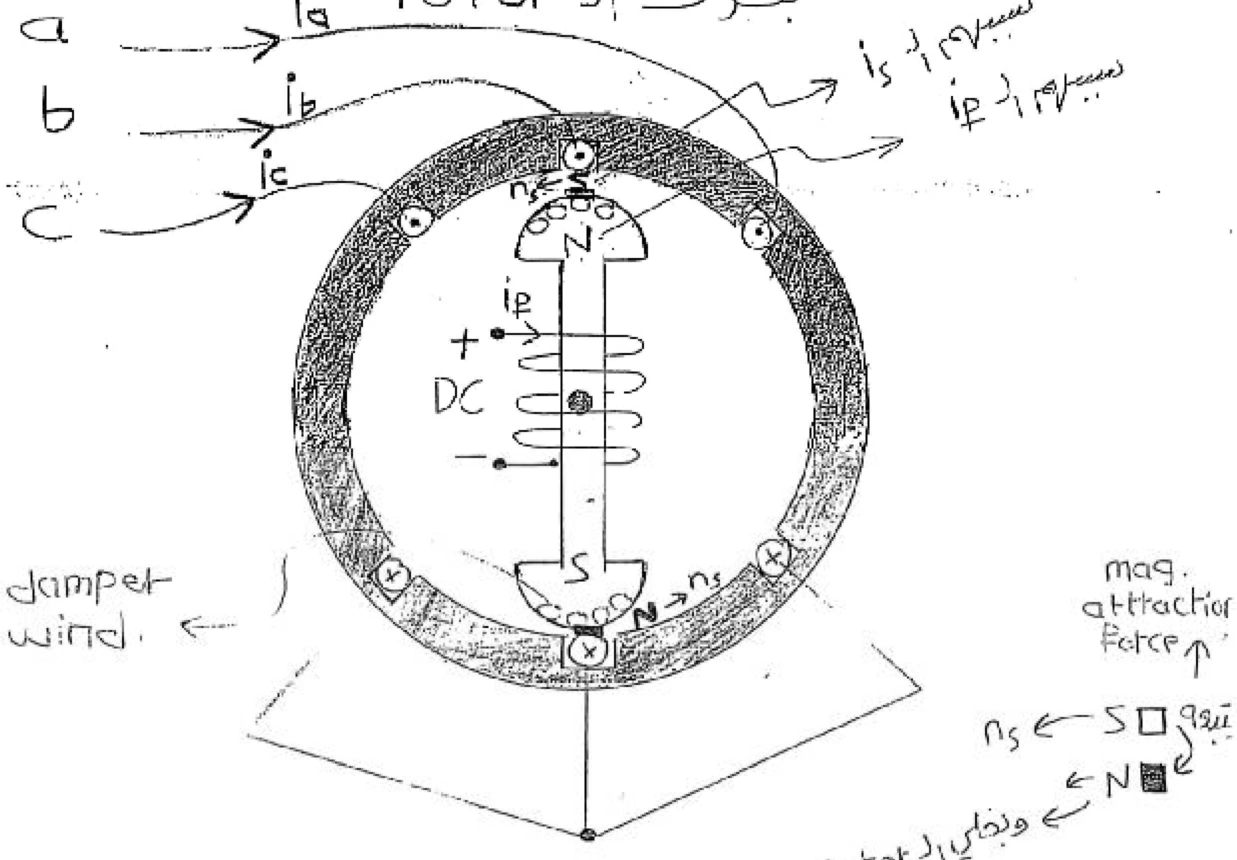
3ϕ currents ⟶ 3ϕ winding .

120° phase in time. 120° phase in space .

⇓

Rotating mag. field

بحرك ال rotor



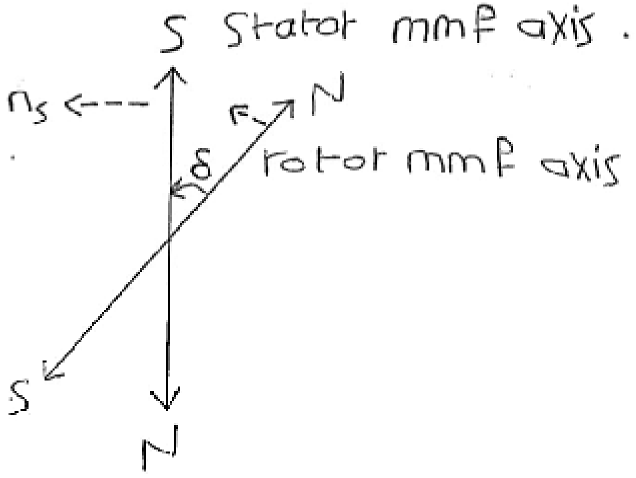
وبخلي ال rotor يدور .

n_s سرعة = سرعة دوران ال rotor

وبنفس إتجاه دوران ال rotating field .

S ■ → n_s

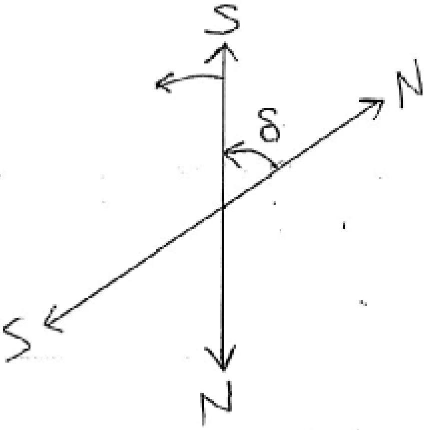
N □ →

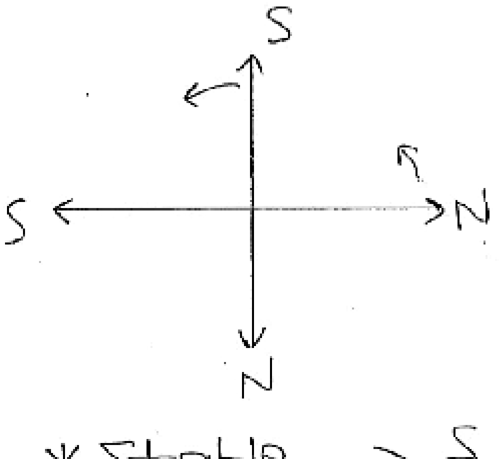


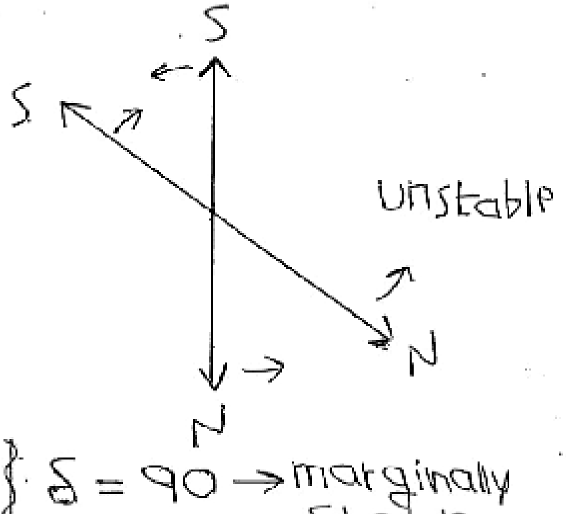
* $\delta = 0$ at no-load

$\uparrow\delta$ ← load كل ما زاد ال

والعلاقة بينهم sin :







* Stable → $\delta < 90$ } $\delta = 90$ → marginally stable

* unstable → $\delta > 90$ } uns. ← distrbance لو

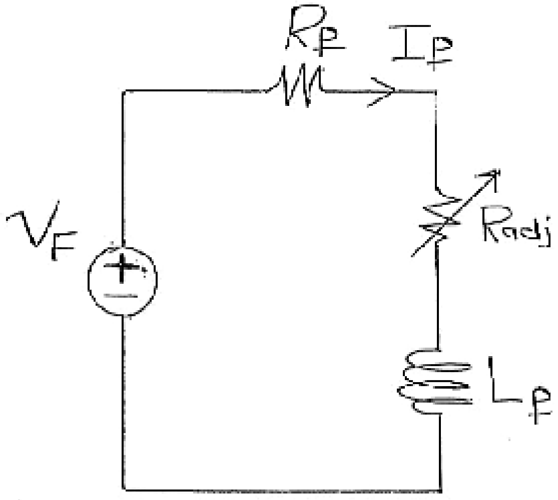
* This motor is not Self-Starting due to inertia of the rotor.

↑

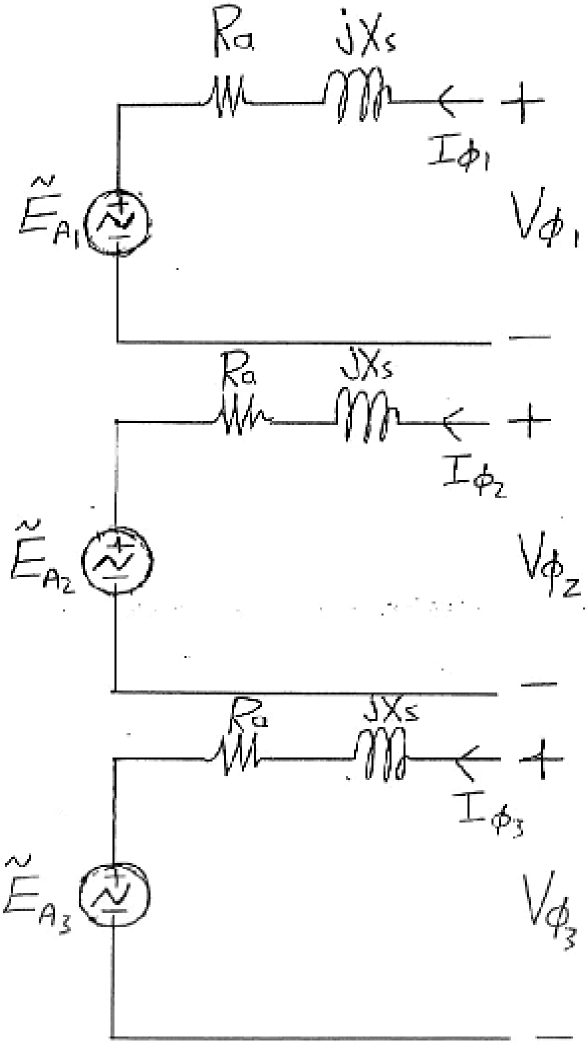
[mass + dimension]

(Step Change مفاجئ . of Speed)

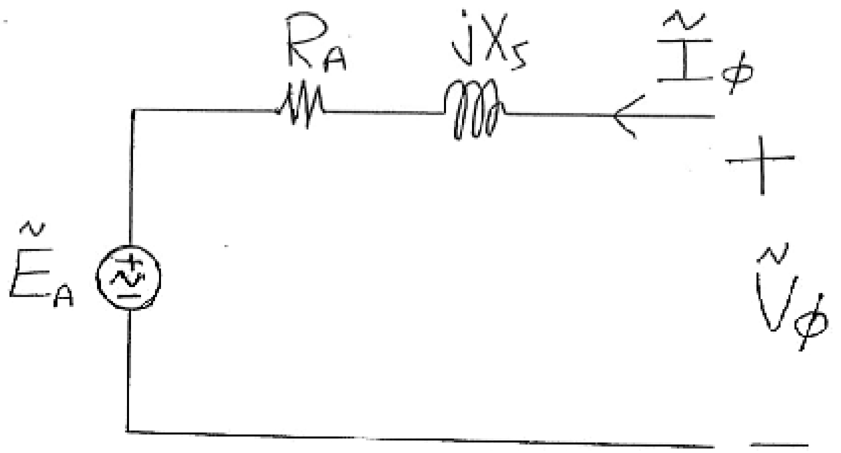
Equivalent circuit of Synch. Motor :-



Field cct.



Armature cct.

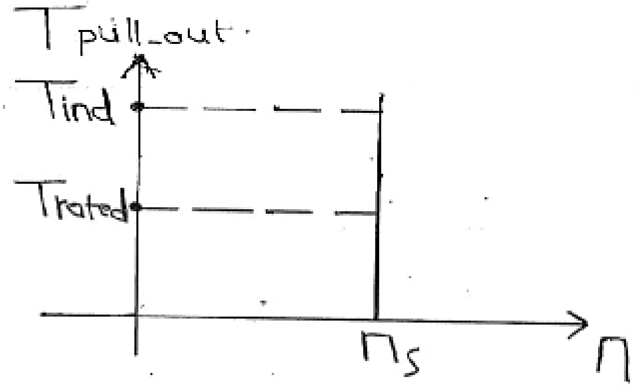


$$\tilde{E}_A = 4.44\,\Phi f N k_w$$

$$\tilde{V}_\phi = \tilde{E}_A + \tilde{I}_A (R_A + jX_s)$$

* Torque - Speed Charcterstics:

[Steady - state]

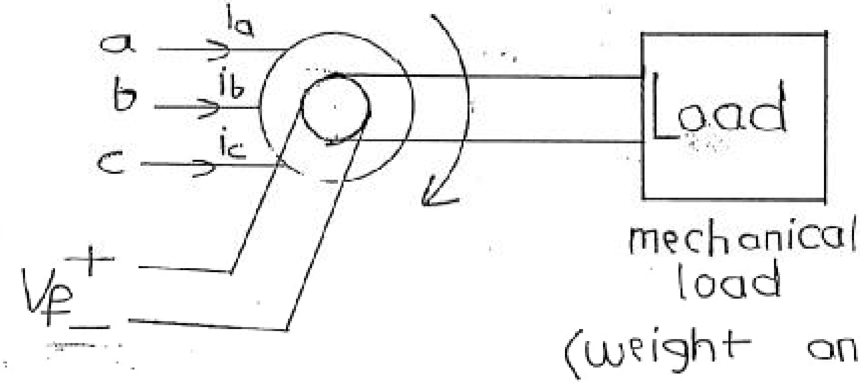


$$T_{pull\text{-}out} = T_{max}\Big|_{\underline{\delta = 90}} = \frac{3 V_\phi E_A}{\omega_s X_s}$$

marginally stable.

$$T_{ind} = \frac{3 V_\phi E_A}{\omega_s X_s} \sin\delta$$

* Effect of load Changes on Synch. motor :-



weight and/or friction ↑

↓

load ↑

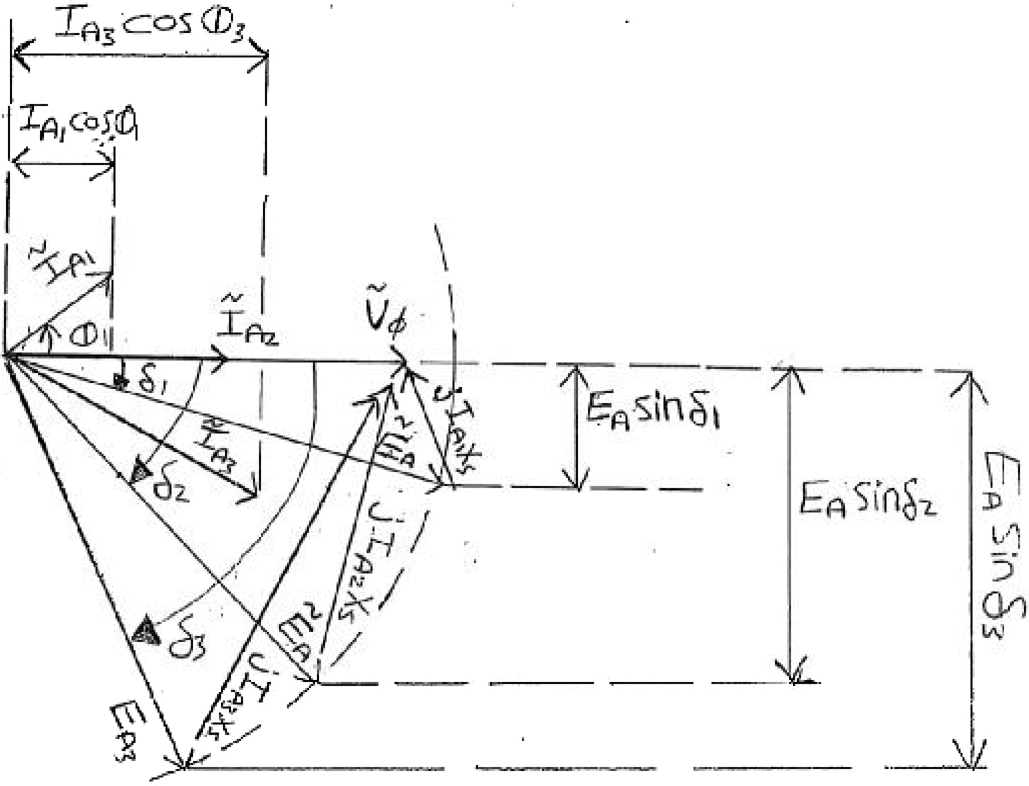
(weight and/or friction)

← مصعد/ رافعة/ دريل/ خط انتاج ...

1- E_A is constant → i_F is constant

2- V_ϕ is constant.

$$3\text{-}\ T_{ind}\uparrow = \frac{3 V_\phi \boxed{E_A} \boxed{\sin\delta}\uparrow}{\underbrace{\omega X_s}_{\text{const.}}} \longrightarrow E_A \sin\delta$$



as the load increases $[(T_L)\uparrow]$,

$T_{ind}\uparrow$, $\sin\delta\uparrow$, $I_A\uparrow$,

$E_A \sin\delta\uparrow$, $P.F_{motor}$ moves towards lagging .

* ممكن يبقى leading ولكن يقل .

Example : 208 V , 45 kVA , 0.8 PF leading , Δ- connected Stator 60Hz

$X_s = 2.5\ \Omega$, $R_A = 0$. $P_{F\&W} = 1500\,W$,

$P_{core} = 1000\,W$.

$P_{out} = 15$ hP at 0.8 PF leading . $\Big\}$ initial O.P

a) $\tilde{E}_A = ?$

$$P_{in} = P_{out} + P_{losses}$$
$$= 15 * 746 + 1500 + 1000$$
$$= 13.7\ kW .$$

$$P_{in} = \sqrt{3}\, V_L I_L \cos \theta$$

$$13.7 \times 10^3 = \sqrt{3} * (208)\, I_L (0.8)$$

$$\rightarrow I_L = 47.5 A \quad \div \sqrt{3}$$
$$\tilde{I}_\phi = 27.4 \angle \cos^{-1} 0.8$$

$$\tilde{E}_A = \tilde{V}_\phi - j \hat{I}_A X_s$$
$$= 208 \angle 0 - j \left[(27.4) \angle \cos^{-1} 0.8 \right] (2.5)$$
$$= 255 \angle -12.4^\circ\ V .$$

b) if the load Torque becomes 30 hP ?!

$$P_{in} = 30 * 746 + 1500 + 1000$$

$$= 24.9 \text{ kw.}$$

$$P_{in} = \sqrt{3}\, V_L\, I_L \cos \phi$$

$$24.9 \times 10^3 = \sqrt{3}\,(208)\, \underline{\underline{I_L}} \cos \underline{\underline{\phi}} \quad \times \text{ ---2 unknowns}$$

$$\rightarrow P_{in} = \frac{3 V_\phi E_A}{X_s} \sin\delta \quad \checkmark$$

$$24.9 \times 10^3 = \frac{3(208)(255)}{2.5} \sin\delta$$

$$\rightarrow \delta = \underset{\substack{\uparrow \\ \text{motor}}}{-}23^\circ$$

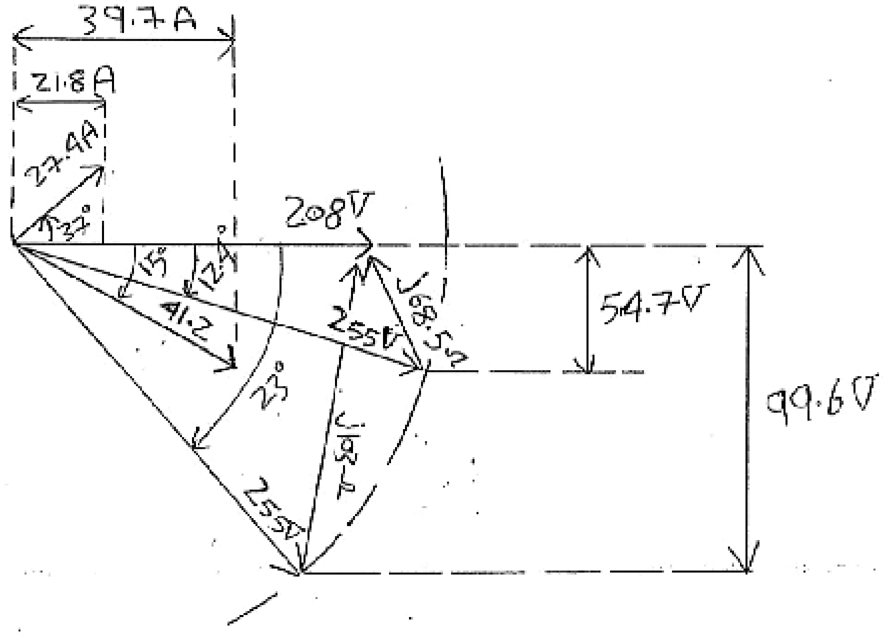
$$\tilde{E}_A = \tilde{V}_\phi - j\, \hat{I}_A X_s$$

$$255 \angle{-23^\circ} = 208 \angle{0} - j\, \tilde{I}_A (2.5)$$

$$\rightarrow I_A = 41.2 \angle{+15} \text{ A.}$$

PF = cos 15° = 0.96 leading.

C) draw the phasor diagram for the two cases , a , b ?



---

* The Effect of Field Current Changes :

1- V_ϕ is constant.

2- P_{out} & P_{in} constant.

3- ω_s is constant.

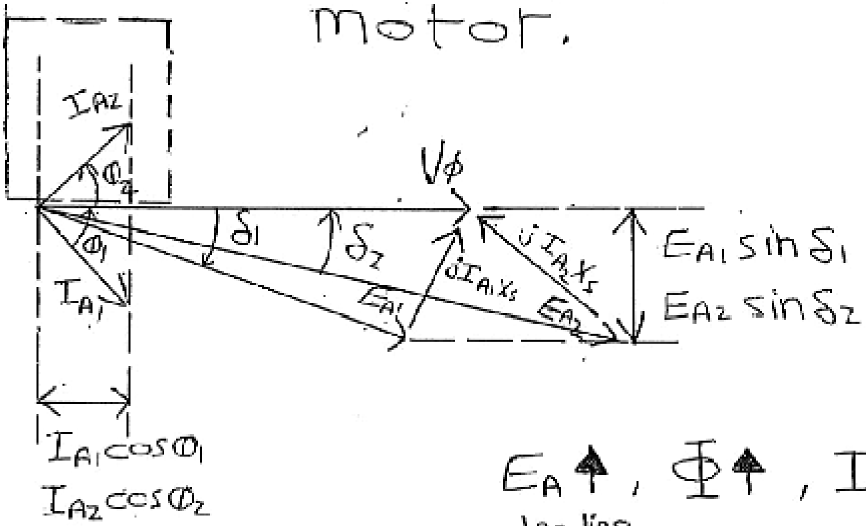
$I_F \uparrow \rightarrow \Phi \uparrow \rightarrow E_A \uparrow$

$$T_{ind} = \frac{3 V_\phi E_A \sin\delta}{\omega_s X_s} \rightarrow E_A \sin\delta \text{ : const.}$$

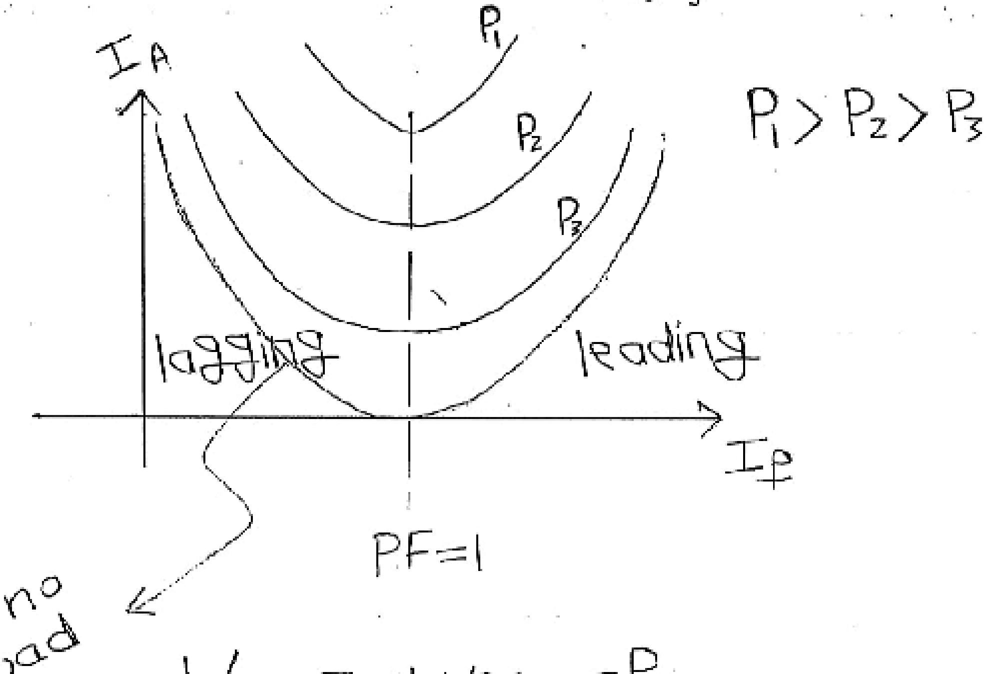
$P_{in} = 3V_\phi I_A \cos\theta$

↳ $I_A \cos\theta$: const.

overexcited synch. motor.

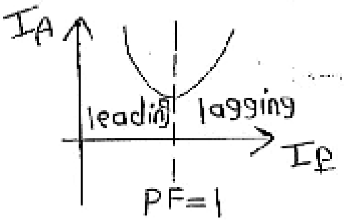


E_A↑, Φ↑, I_f↑
leading

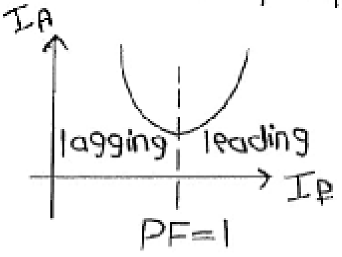


V-curves of Synch. motor.

* Synch. generators



* Synch. motors



→ PF of the motor can be controlled.

: adv. : leading ممكن يشتغل بال

→ * Can be used as P.F correction in overexcited Synch. motor.

motor

corrector

controlable

* To get V-curves :

- $\boxed{1}$ P_{out} const.
- $\boxed{2}$ V_T const.
- $\boxed{3}$ Speed Const.
- $\boxed{4}$ I_f Variable.

Example : The Same motor of the previous example.

$$\underbrace{P_{out} = 15\ hP\ ,\ pF = 0.85\ \text{lagging}}_{\substack{\uparrow \\ \text{initial} \\ \text{O.P}}}$$

a) $\tilde{E}_A = ?$

$$P_{in} = \sqrt{3}\ V_L I_L \cos \theta$$

$$(15 * 746) + 1500 + 1000 = \sqrt{3}\,(208)\ I_L\ (0.85)$$

$$\rightarrow \tilde{I}_\phi = 25.8 \angle{-31.8}\ A .$$

$\tilde{E}_A = 208 \angle 0 - j\left[(25.8) \angle -31.8^\circ\right](2.5)$

$= 182 \angle -17.5 \; V.$

b) If the flux is increased by 25%,

$\tilde{I}_A = ?$

$\rightarrow E_{A1} \sin \delta_1 = E_{A2} \sin \delta_2$

$E_{A1} \sin(-17.5) = 1.25 E_{A1} \sin \delta_2$

$\rightarrow \delta_2 = -14^\circ.$

$182 \angle -14^\circ = 208 \angle 0 - j \tilde{I}_A (2.5)$

$\rightarrow \tilde{I}_A = 22.5 \angle 13.2^\circ \; A.$

$PF = \cos 13.2 = 0.97$ leading.

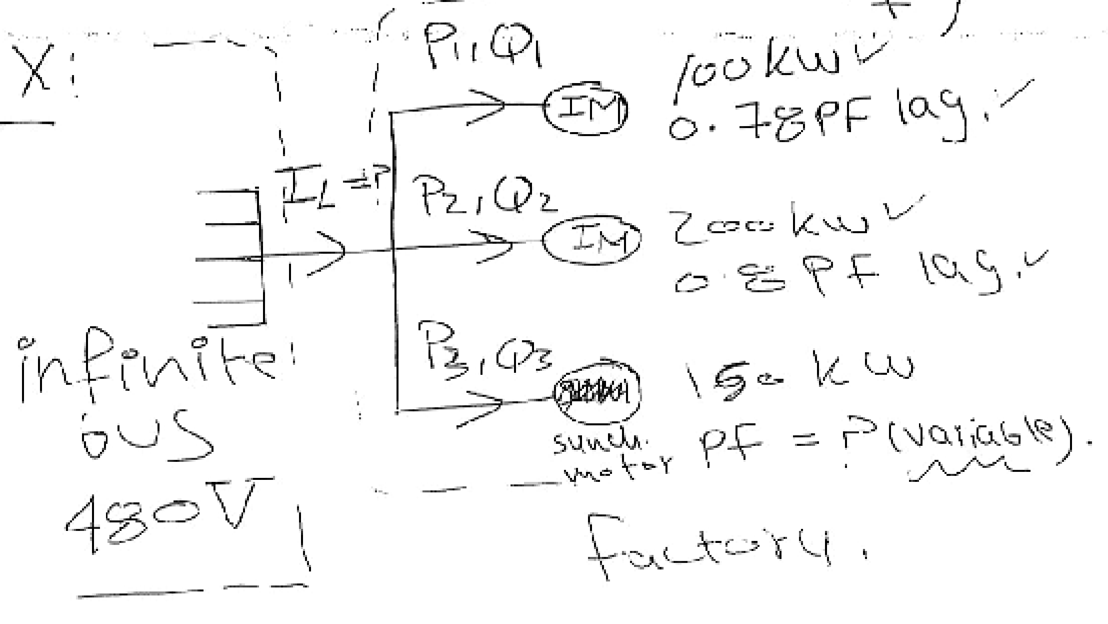
c) What is the minimum value of I_A?

@ unity PF :-

The Synchronous Motor and Power factor Correction:

* overexcited synch. motor runs with $\boxed{\text{leading}}$ Power factor therefore it can be used as Power factor corrector. The good thing is that its power factor is controllable (due to change i_f).

Ex:



a) if the synch. motor is adjusted to run at 0.85 PF lagging. I L E P

Q +ve

$Q_1 = \tan \phi_1 P_1$

$= \tan[\cos^{-1} 0.78][100]$

$= 80.2$ KVAR.

$Q_2 = \tan \phi_2 P_2$

$= \tan[\cos^{-1} 0.8][200]$

$= 150$ KVAR.

$Q_3 = 93$ KVAR.

$P_{tot} = P_1 + P_2 + P_3 = 450$ kW

$Q_{tot} = Q_1 + Q_2 + Q_3 =$.

$\phi_{tot} = \tan^{-1} \frac{Q_{tot}}{P_{tot}}$

$=$

$\cos \phi_{tot} = 0.812$ lag.

$\boxed{2}$

$$P_{tot} = \sqrt{3}\, V_L I_L \cos \Phi_{tot}$$

$$450 * 10^3 = \sqrt{3}\,(480)\, I_L (0.812)$$

$$\rightarrow I_L = 667\,A. \ \#$$

b) If the synch. motor is adjusted to run at 0.85 $\underline{\text{leading}}$ P.F $I_L = ?$

$\underline{Q \ -ve}$

No change in Q_1, Q_2

$$Q_3 = \tan \Phi_3 P_3 = -93\ KVAR.$$

$$\# P_{Tot} = P_1 + P_2 + P_3 = 450\ kW$$

$$\# Q_{Tot} = Q_1 + Q_2 + Q_3 = 137.2\ KVAR$$

$$PF_{tot} = 0.957 \text{ lags}$$

$$P_{tot} = 450 * 10^3 = \sqrt{3}\,(480)\, I_L\, (0.957)$$

$$I_L = 566A. \quad \sqrt{3}$$

* PF قليل ،

* current كبير → في المشكلات ،

↓

تتحمل الخسارات ← يجبروهم يحسنوا الـ PF

* احدى طرق تحسين ال P.F :

synch. motor

حسنات :

قلة الـ losses في الـ lines *

كبير reduction

لأنه I^2R ← بتفرق كتير في الـ current الـ loss.

#

تتم المراقبه من خلال # . PF meter

synch.
motor
cost ↑
bulky size

أيضاً :- تكلفته عالية :-

↓

Cap. banks
in parallel.

Starting of synch motor :-

~~rotor will follow up due to~~

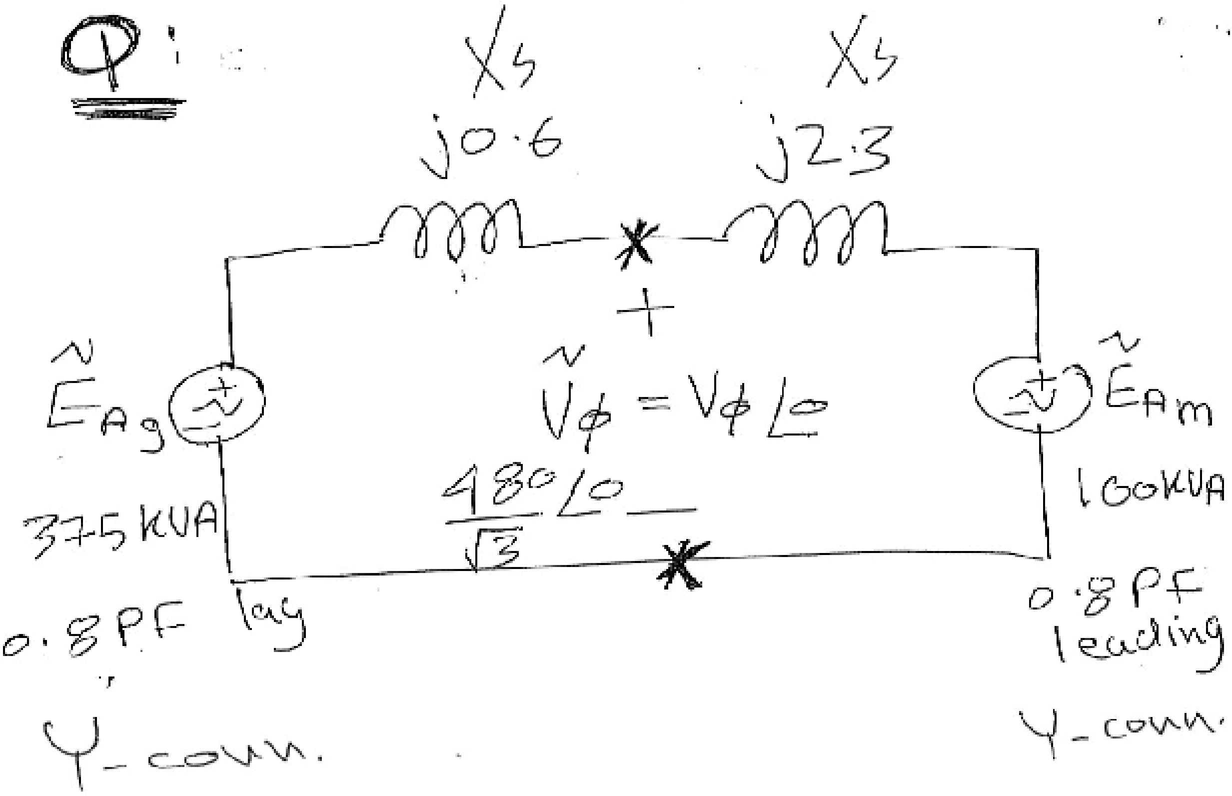
≡ starting of all types of mechanical engine

1. external primemover (motor)
2. rotating mmf ↓ speed ↓ due to f ↓ → f
   gradual inc. of freq.
   $f = \frac{n_s P}{120}$
3. Utilizing the damper windings. ⇒ شبه induc. motor

Starting @ as induction and running @ sync. motor
ns. lower, [illegible] motor

5

Q:



$\tilde{V}_\phi = \frac{480}{\sqrt{3}}\angle 0$ when the motor draws the rated power @ PF=1

→ O.P

→ $P_m = \sqrt{3}\, V_L I_L \cos\phi$

$100*10^3*\cancel{1} = \sqrt{3}\,(480)\, I_\phi\, \cancel{(1)}$.

$\tilde{I}_\phi = 120.3\angle 0\ A.$

$\tilde{E}_{Ag} = \tilde{V}_\phi + j\,\tilde{I}_\phi\, 0.8$

$= 286.4 \angle 14.6^\circ\ V$

$\Rightarrow V_\phi = \tilde{E}_{Am} + j\,\tilde{I}_\phi 2.3$

$\tilde{E}_{Am} = 391.6 \angle -44.9^\circ\ V.$

b) if the flux of the motor increases by <u>10%</u>, Then calculate the new terminal voltage.

$\Rightarrow E_{Am_1} \sin \delta_1 = E_{Am_2} \sin \delta_2$

$E_{Am_1} \sin(-44.9^\circ) = (1.1)(E_{Am_1}) \sin \delta_2$

$\delta_2 = -39.9^\circ$

$P_2 = P_1 = 100 \times 10^3 = \frac{(3)(V\phi_2)(1.1)(391.6)}{2.3} * \sin(-39.9^\circ)$

$V\phi_2 = 277.4\ V = \frac{480}{\sqrt{3}}$

$$I_\phi = \frac{277.4\angle 0 - (1.1)(391.6)\angle -34.9^\circ}{2.3}$$

$=$

$Pf_{new} = \cos \angle =$

* static stability power limite

$$= P_{max} = \frac{3 V_\phi E_A}{X_s} \quad \#$$

Permanent Magnet (PM) materials and Permanent Magnet (PM) machines:

* The flux in PM machines is establisec by permanent magnets. Both internal generated voltage and induced Torque depends on the value of the magnetic flux.

$E_A = k\Phi\omega$ --- internal generated Voltage.

$\tau_{ind} = k\Phi I_a$ --- induced Torque.

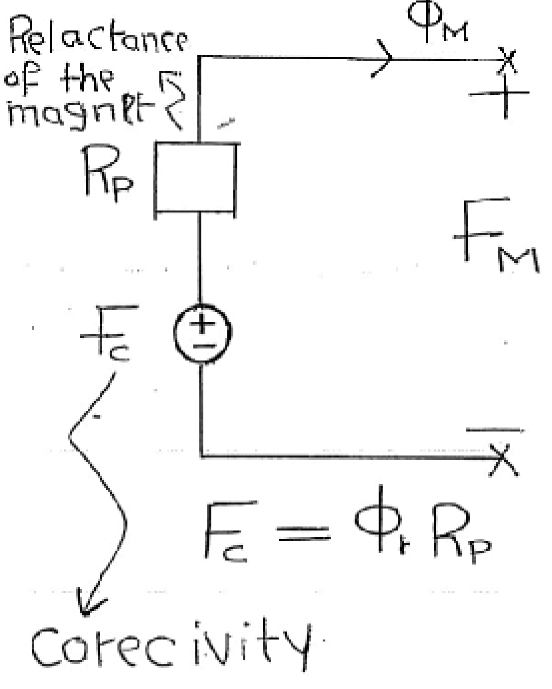
PM machine is considered as the source of the magnetic flux Φ.

Magnetic cct.	Electrical cct.
Flux (wb)	Current (A).
MMF (A.turns)	EMF (V).
Reluctance (A/wb)	Resistance (Ω).
$MMF = NI$ or $MMF = \Phi R$	

The main difference :
Electrical CCt. is linear.
Magnetic CCt. is non-linear.

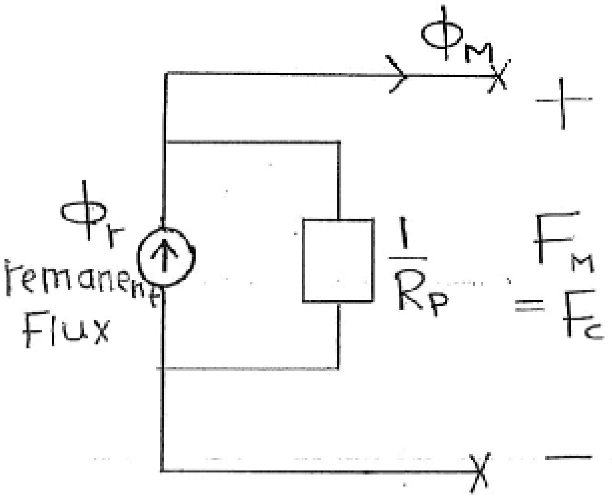
PM Can be represented by :

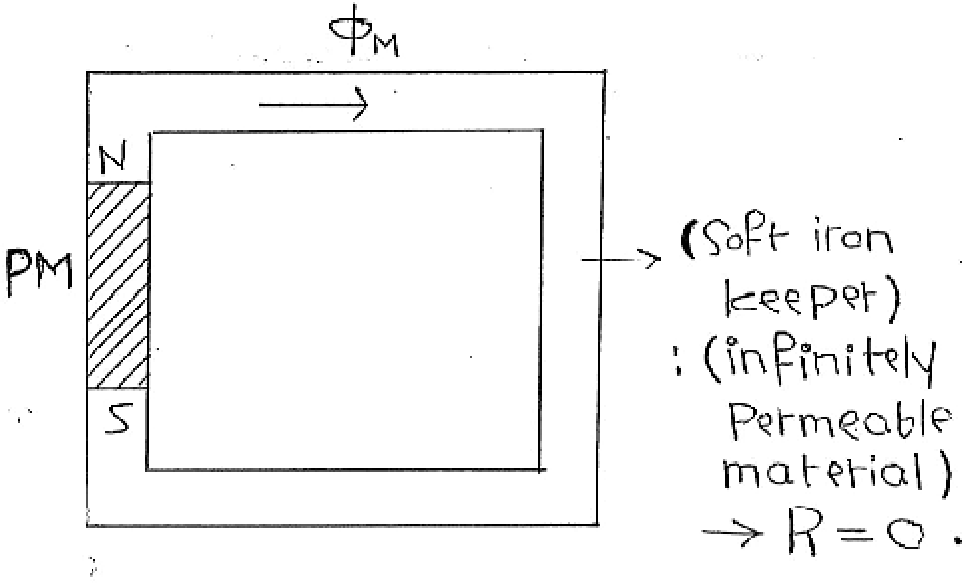
<u>Thevenin Eq.</u>



$$F_c = \phi_r R_P$$

<u>Norton Eq.</u>





The magnet Can be Short Circuited by connecting a material with infinite permeability (R = 0) .

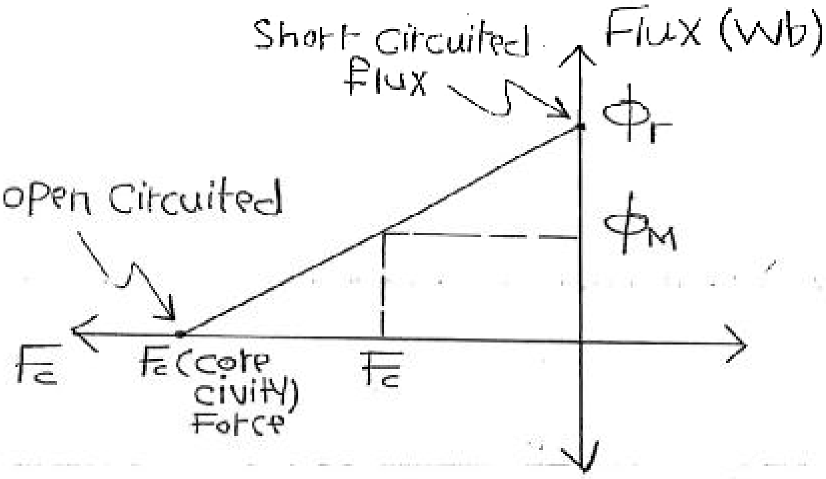
$$\longrightarrow \phi_r = \phi_M .$$

The magnet is Open Circuited if

$$\phi_M = 0 \longrightarrow R = \infty .$$

F_c is called Corecive MMF as it is MMF required to $\underline{\overset{\text{Force}}{\text{Coerce}}}$ the magnet to produce Zero flux. It directly expresses the resistance of the magnet against demagnetization.

* The Characteristics of PM :



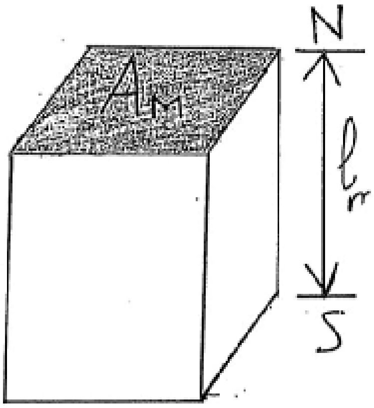
حسنات إستبـدال Field CCt. بـ PM :-

losses ↓, design ↓, Size ↓, η ↑, weight ↓, copper X, winding X.

سيئات :

cost ↑ , ϕ const: No Controlability.

The remanent Flux ϕ_r & Corecive MMF depend not only on the material properities but also on the dimensions of the magnet.



$$\phi_r = B_r \cdot A_M$$

B_r ↓ material properity

A_M ↳ magnet Cross Sectional area dimension.

$$F_c = H_c \cdot l_m$$

F_c ↓ Corectivity Force

H_c ↓ corectivity

l_m ↳ length of the materia in the direction of magnetization.

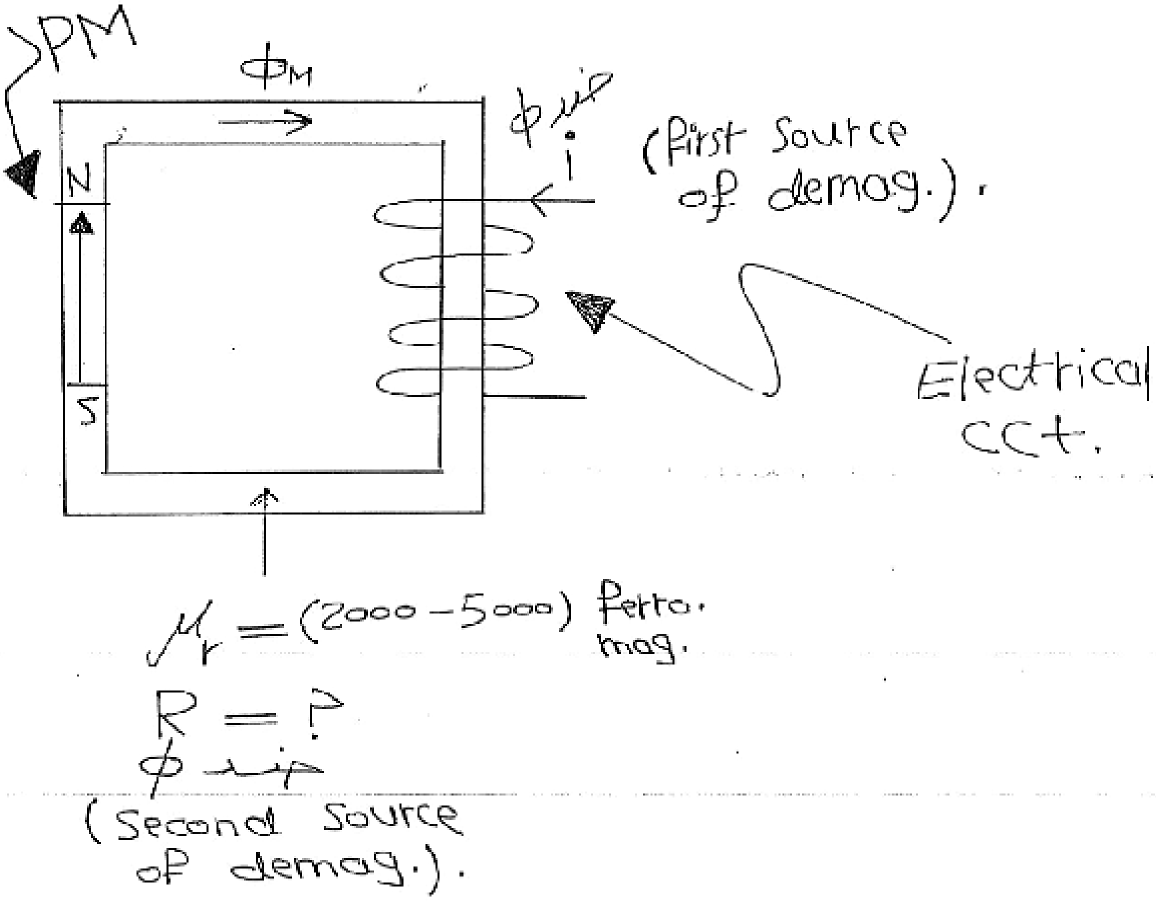
---

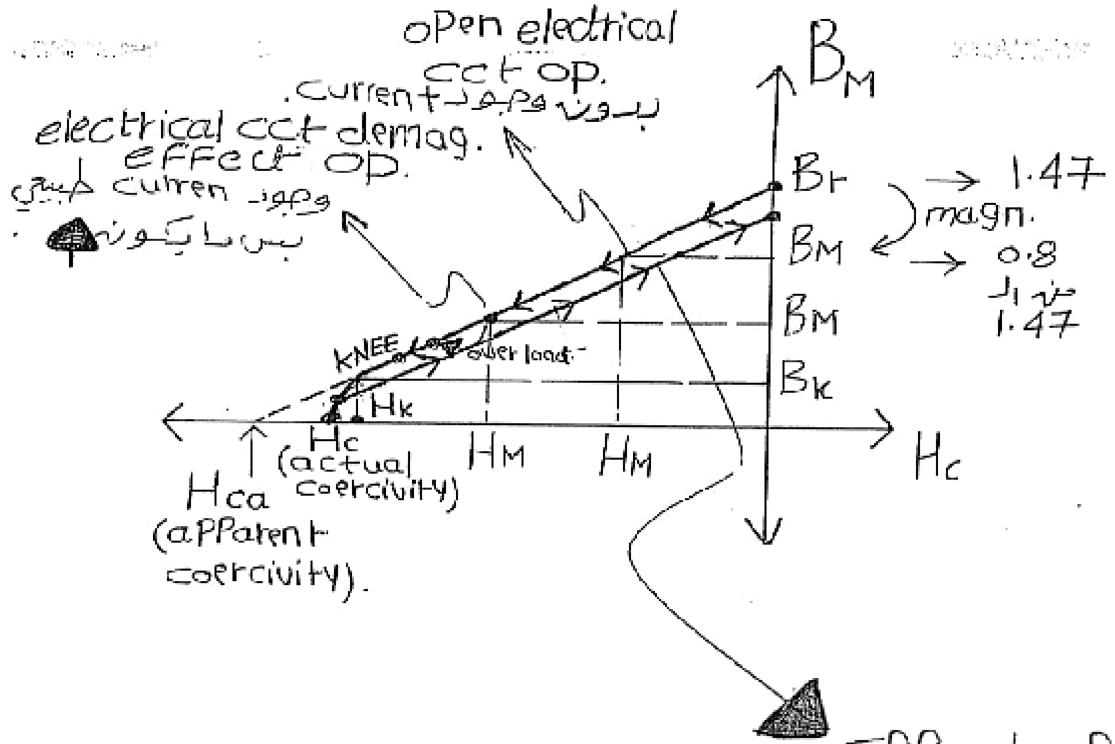
* Electrical cct. → current in Stator [diff in Voltage] ↓ $\phi \Rightarrow$ diff in MMF

; if Fault or Short cct. → current ↑

↳ First source of demag.

If the vertical axis is scaled by $1/A_M$ and the horizental axis by $1/L_m$, then the result will be a relation between B_M & H_M.





Effect of
demagnitizing
on the C/C
of PM mat.

في حالة short cct.

$$\underline{H_{sc} = NI}$$

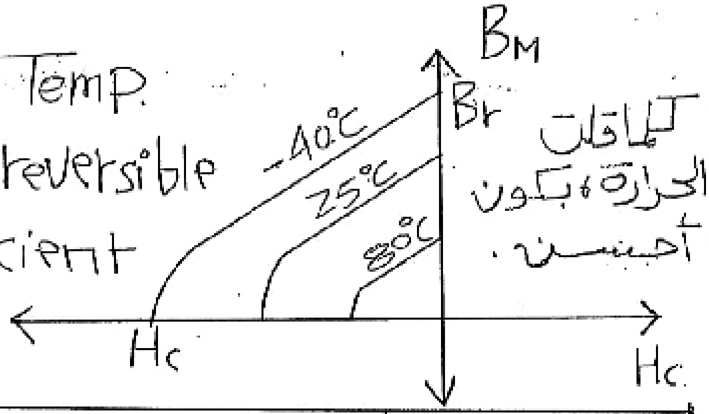
→ مش لازم توصل ال KNEE

$$B_M = \mu_{rec} H$$

↑

recoil permability
(PM it self)
(1.03 → 1.05)

The effect of Temp. is Specified by reversible temperature cofficient



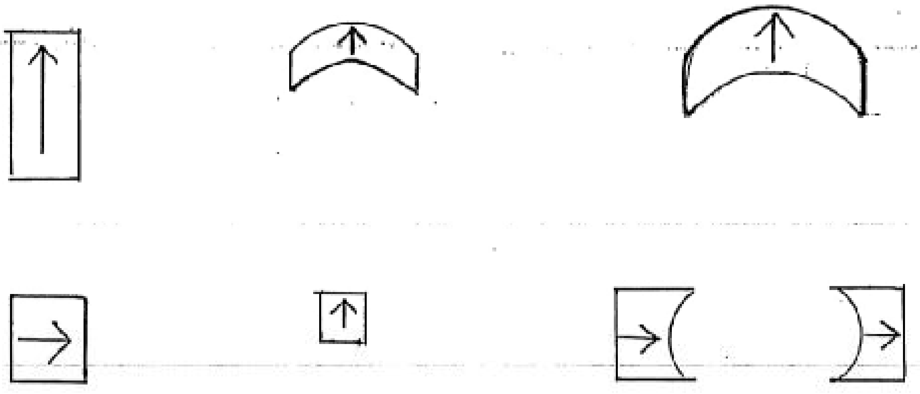
كلما قلت الحرارة ، يكون أحسن .

α_{Br} .

$$\boxed{B_r(T) = B_r(20^\circ) * \left[1 + \alpha_{Br} \frac{(T-20)}{100}\right]}$$

Provided by the manufacturer.

* Shapes of perment magnets :-



Coated by Al 0.5 mm $\Leftarrow$ لحمايته من الصدأ الذي يسبب ① التآكل . ② تقلل من الـ E المخزنة فيهم . $\Leftarrow$ بسبب وجودهم في أماكن رطبة .

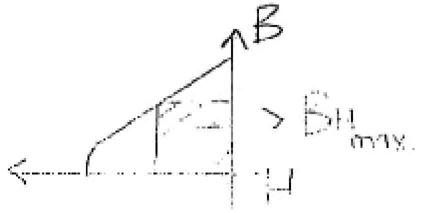
Types :-

Ferrites
AlNiCo
} inexpansive.

SmCo
NdFeB
} rare-earth materials.

NdFeB → highest $B_{H_{(max)}}$ → indicates to the energy stored in magnet.

↑ max. energy product.

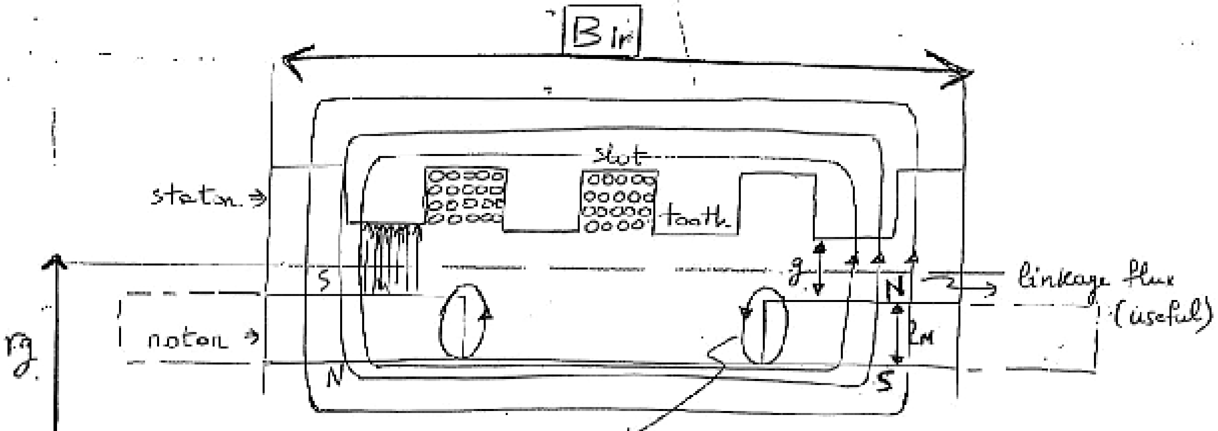


Al → aluminium.
Ni → nickel.
Co → Cobalt.
Sm → Samarium.
Nd → Neodymium.
Fe → iron.
B → Boron.

14/12/2016 لأربعاء

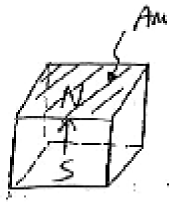
MACHINES 2

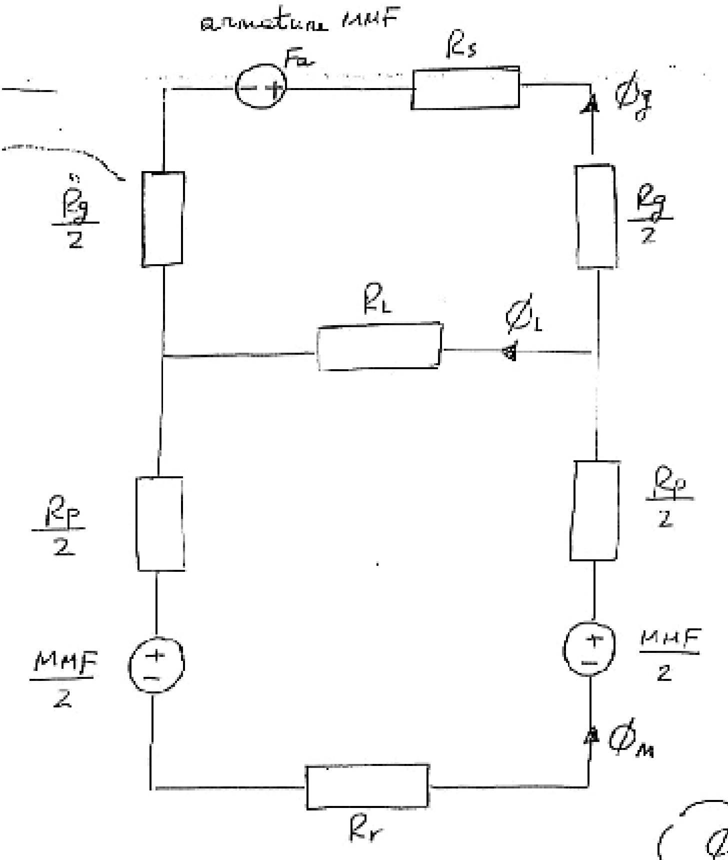
* Approximate calculations of flux



leakage flux

one pole-pitch of a PM machine





* R_s : stator reluctance

* R_g : air gap reluctance

* R_P : PM reluctance

* R_L : reluctance of the leak flux

* R_r : rotor reluctance

$$\phi_M = \phi_L + \phi_g$$

$$f_{LKG} = \frac{\phi_g}{\phi_M} = \frac{\phi_g}{\phi_g+\phi_L}$$

*f_{LKG} : leakage flux coefficient

$f_{LKG}<1$

- Typical $f_{LKG}=0.9$
- Practical $f_{LKG} = 0.7 \to 0.8$

$F_a = 0$ @ no electrical load

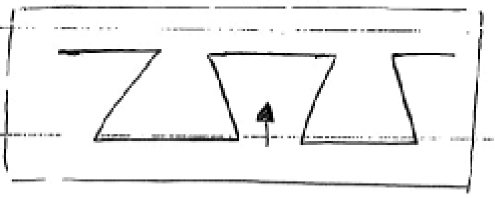
$$\boxed{R_P = \frac{l_M}{\mu_0 \mu_{rec} A_M}}$$

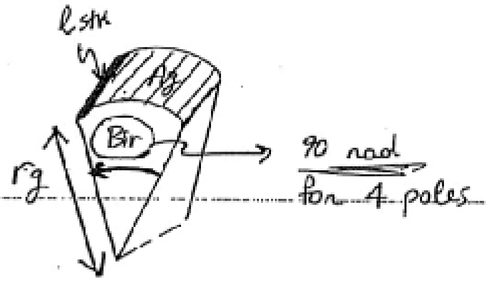
*l_M : length of the magnetic flux in the direction of magnetization

*μ_{rec}: relative permeability of the magnet

*A_M : area of the magnet perpendicular on the direction of magnetization

$$R_g = \frac{g'}{\mu_0 A_g} = \frac{K_c g}{\mu_0 B_{ir} r_g l_{stk}}$$

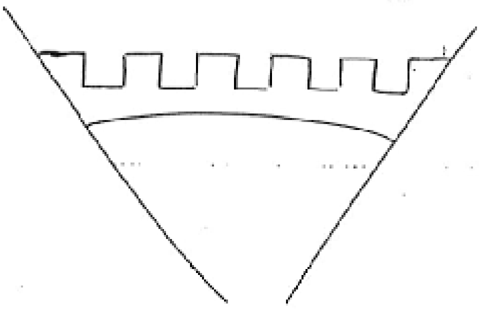




*K_c : Karten coefficient

≡ To account for the effect of slost

$K_c = 1.2$



*g : physical air gap

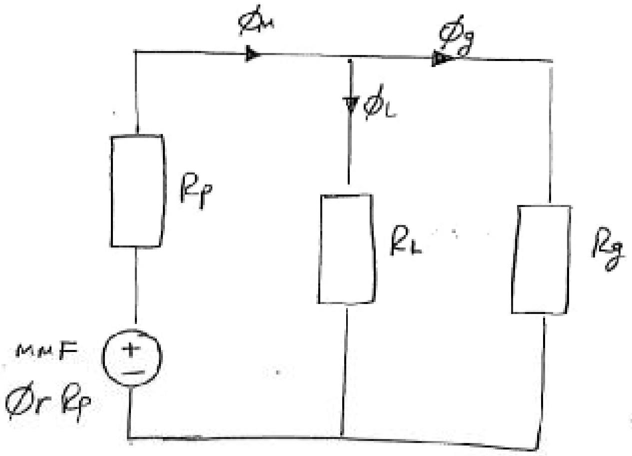
*g': effective air gap

*r_g : midway of the physical air gap

$\Rightarrow$ Normally $R_r = R_s = 0$ ($\mu_r \rightarrow \infty$)

$2000 \rightarrow 6000$

* at no electrical load ($F_a = 0$)



approximate magnetic equivalent circuit for one pole pitch

$B_r \Rightarrow$ given for any PM material

$\phi_r = B_r A_M$

$$\phi_g = \phi_M \frac{R_L}{R_L + R_g}$$

$$\phi_M = \frac{MMF}{R_p + (R_L // R_g)}$$

$$\phi_M = \frac{\phi_r R_p}{R_p + \frac{R_L R_g}{R_L + R_g}}$$

but $\phi_M = \phi_g \dfrac{R_L + R_g}{R_L}$

$$f_{LKG} = \frac{\phi_g}{\phi_M} = \frac{R_L}{R_L + R_g}$$

$$\phi_g = \frac{f_{LKG}}{1 + f_{LKG}(R_g // R_p)} \phi_r$$

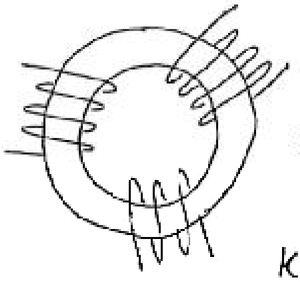
$$B_g = \frac{\phi_g}{A_g}$$

$$\Rightarrow \phi_g = \phi_r \frac{R_p}{R_p + \frac{R_L R_g}{R_L + R_g}} * \frac{R_L}{R_L + R_g}$$

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

$E = 4.44\, \Phi_g \boxed{f} N \boxed{K_w} \rightarrow K_g K_d$

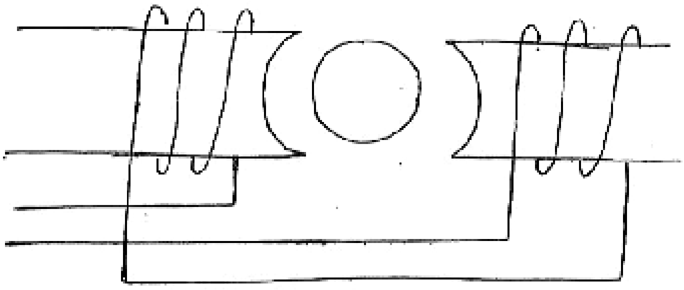
flux per pole

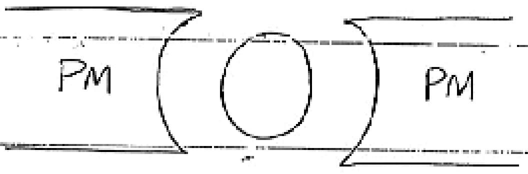


slotless machine

$K_c = 1$

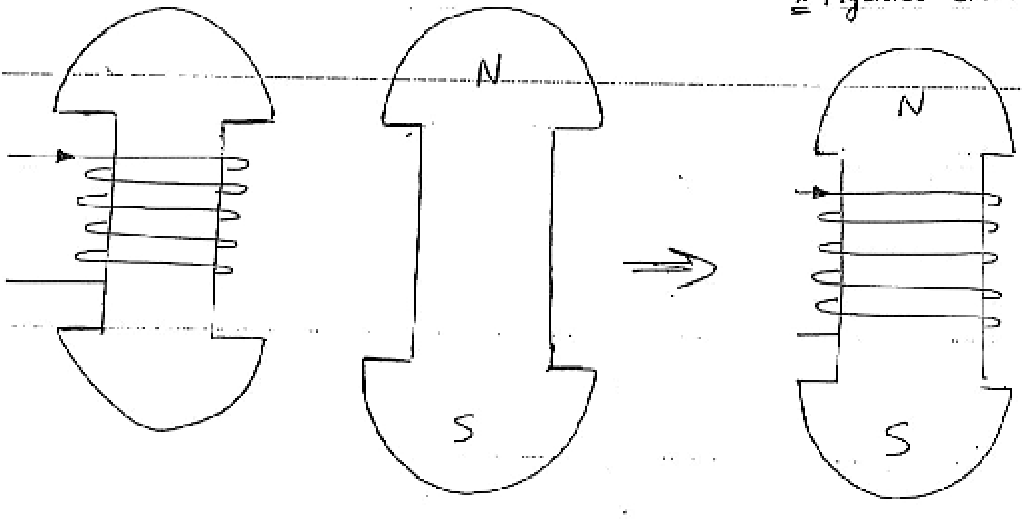
* * *

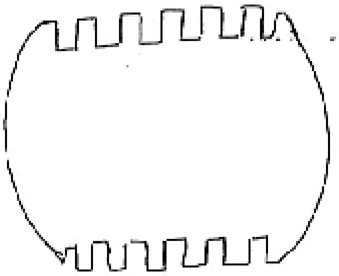


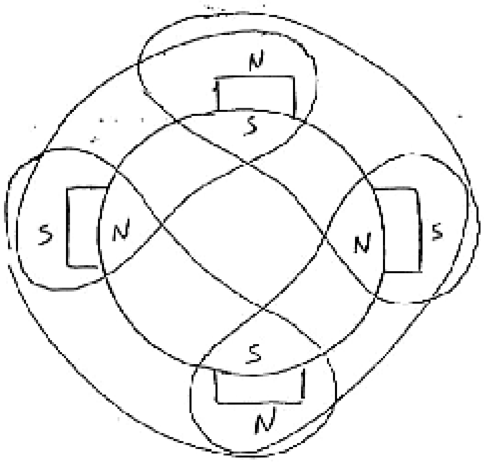


* * *

* Hybrid excited *







※ Advantages of permanent magnetic machines over conventional electrical machines.

① higher ξ ⇒ no copper losses in the field winding (no field winding)

② Lower size & lower weight ⇒ higher power to weight ratio (power / weight)
↳ for the same weigh the same power

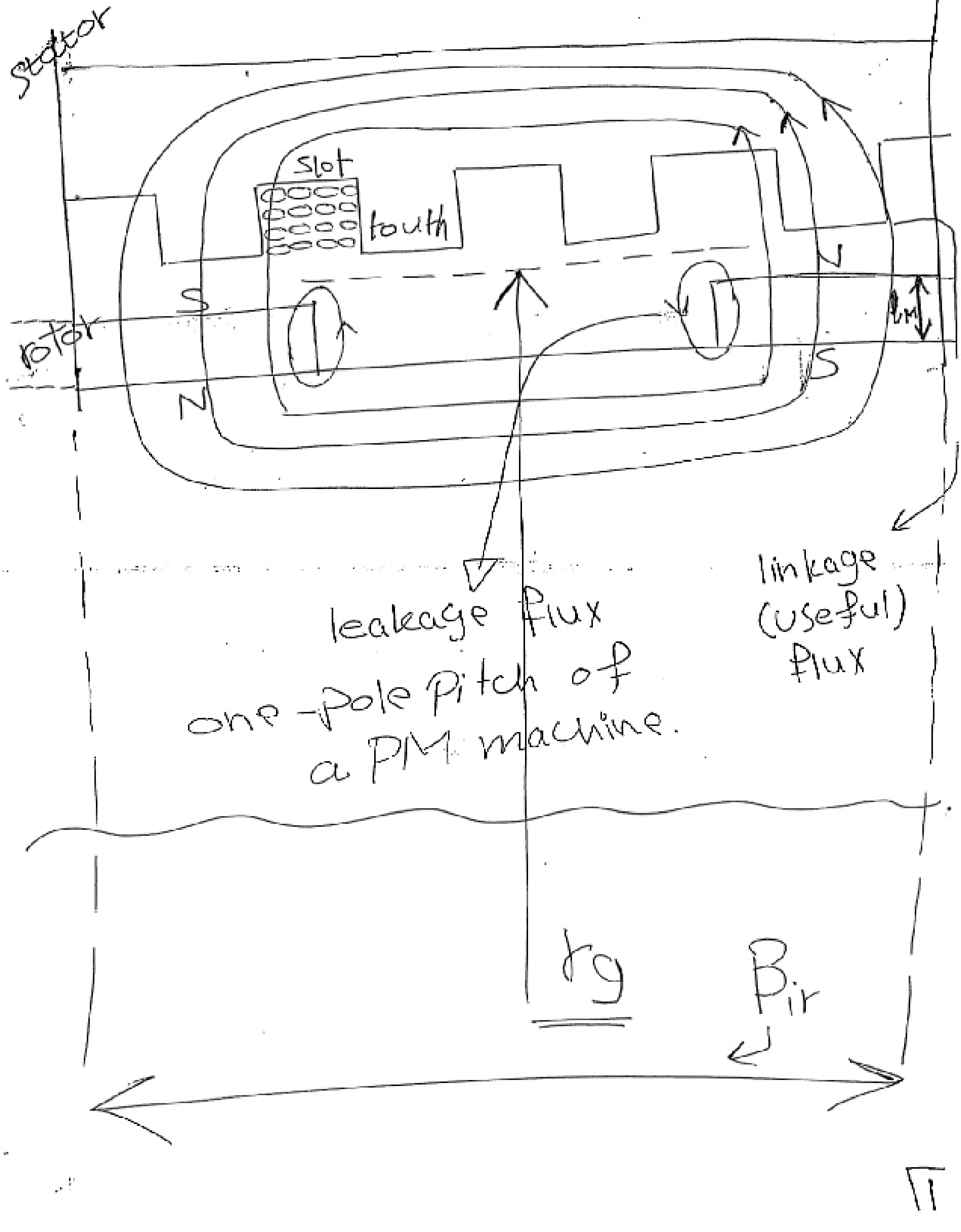
③ Simplicity of design and manufacturing.

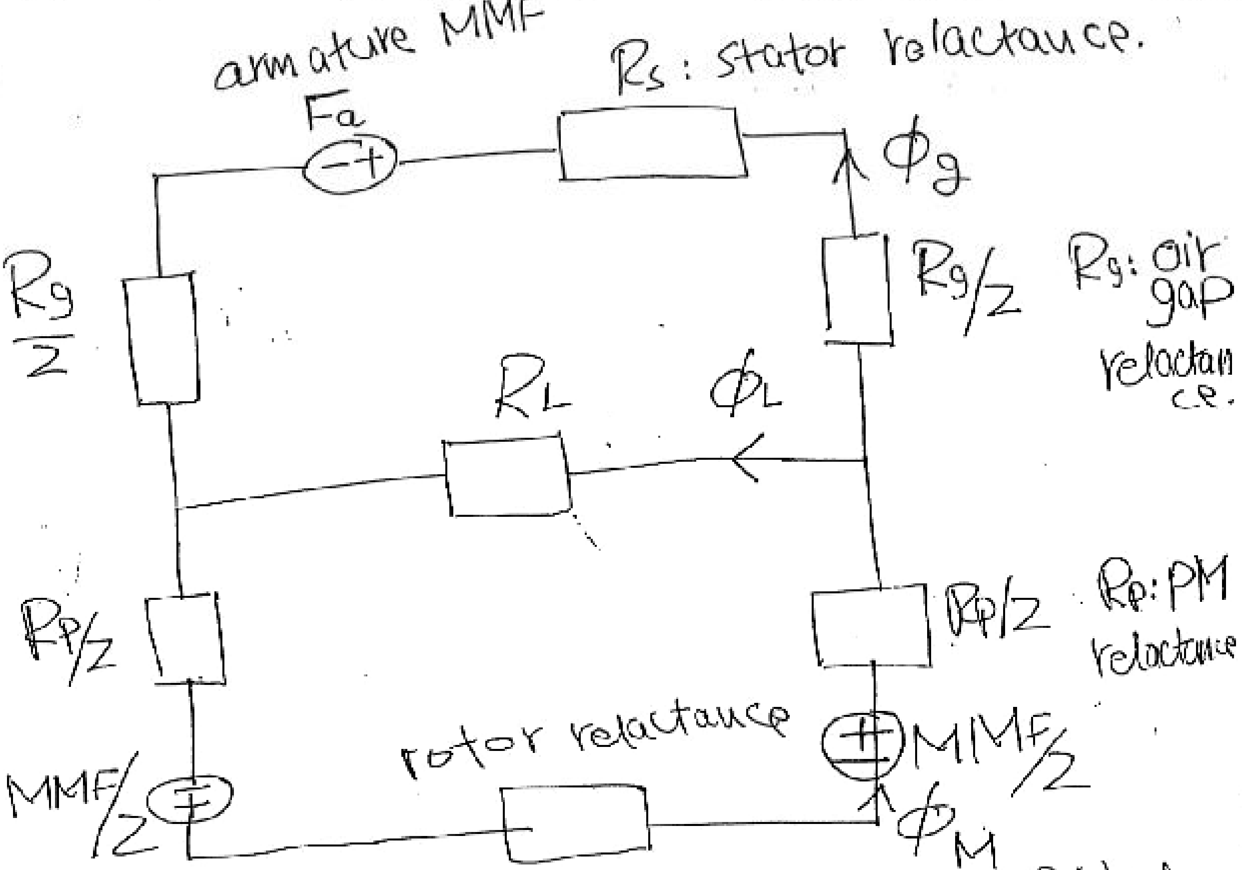
④ Possibility of variance topologies (configurations)

※ Disadvantage : high cost

Nd Fe B
↑
(500 JD/Kg)

Approximate Calculations of flux:





eq. mag. cct R_r of one pole pitch.

R_L : reluctance of the leakage flux path.

*

@ No electricalload → $F_a = 0$.

$$\phi_M = \phi_L + \phi_g$$

$$f_{LKG} = \frac{\phi_g}{\phi_M} = \frac{\phi_g}{\phi_g + \phi_L}$$

↓

Leakage flux coefficient.

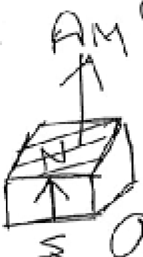
✓ $F_{LKG} < 1$

✓ typical value $F_{LKG} = 0.9$

✓ Practical $F_{LKG} = 0.7 \rightarrow 0.8$

$$* \; R_P = \frac{l_M}{\mu_0 \mu_{rec} A_M}$$

l_M → length of the magnet in the direction of magnetization.



μ_{rec} → relative permeability of the magnet.

A_M → area of the magnet perpindicular on the direction of magnetization effictive air gap.

karter cofficient.

physical air gap

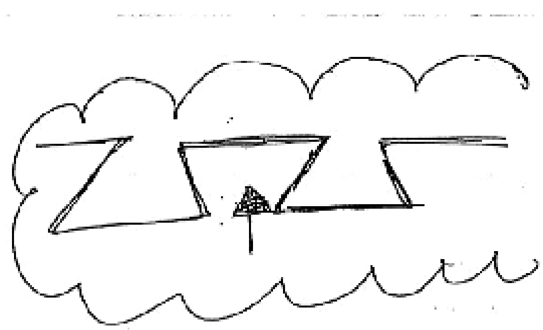
$$R_g = \frac{g'}{\mu_0 A_g} = \frac{k_c \, g}{\mu_0 \pi r_g l_{stk}}$$

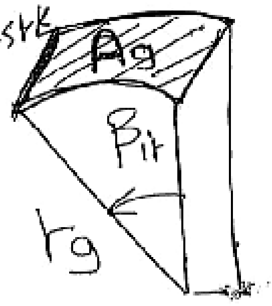
air gap reluctance

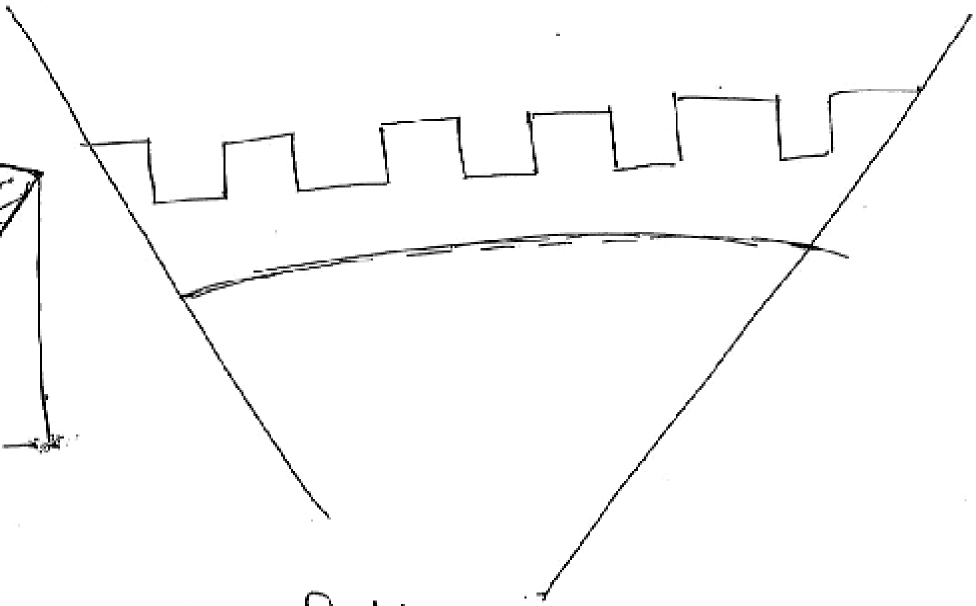
= To account for the effect of slots.

$k_c = \textcircled{1.2}$ #

تأخذ بعين اعتبار
تأثيرال slots.
بسبب ال Slots.
copper
Al
Non mag.
mat.





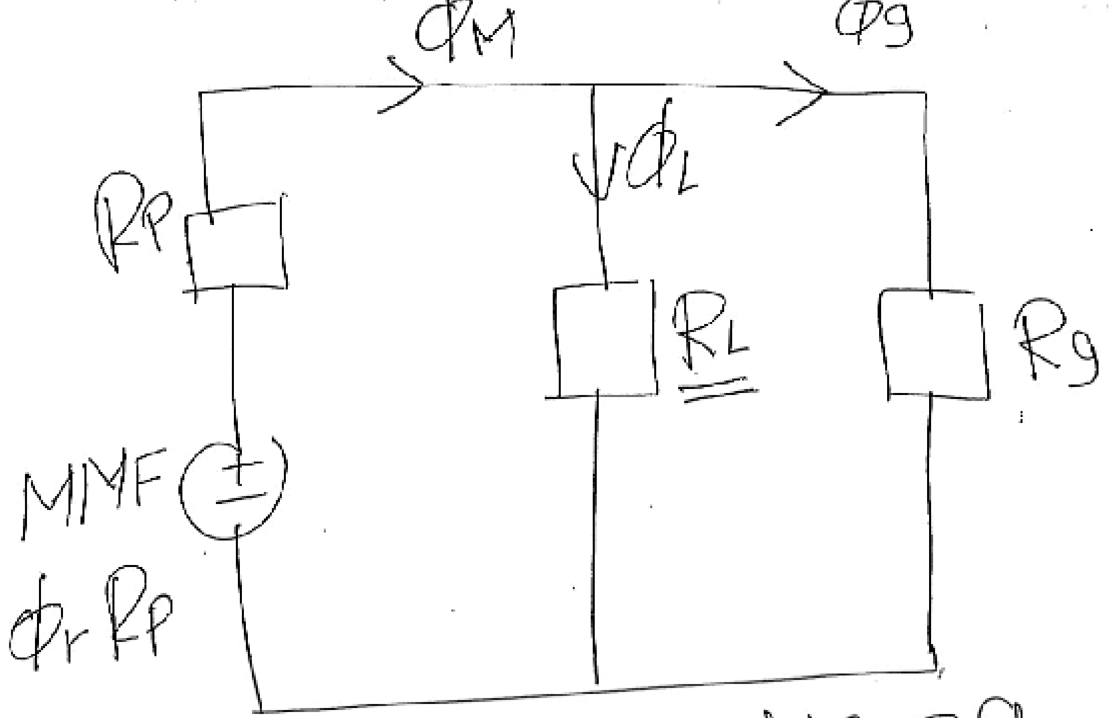


r_g: midway of the physical air gap. #

* Normally $R_r = R_s = 0$

$(\mu_r = \infty)$
2000-6000

at no electrical load $(F_a = 0)$.



approximate magnetic eq. cct for one pole pitch.

$B_r \Rightarrow$ given for any PM material. $\phi_r = B_r A_M$

$$\phi_g = \phi_M \frac{R_L}{R_L + R_g}$$

$$\phi_M = \frac{MMF}{R_P + (R_L // R_g)}$$

$$= \frac{\phi_r R_P}{R_P + \frac{R_L R_g}{R_L + R_g}}$$

but:

$$\phi_M = \frac{\phi_g (R_L + R_g)}{R_L}$$

$$\phi_g = \phi_r \frac{R_P}{R_P + \frac{R_L R_g}{R_L + R_g}} \frac{R_L}{R_L + R_g}$$

$$F_{LKG} = \frac{\phi_g}{\phi_M} = \frac{R_L}{R_L + R_g}$$

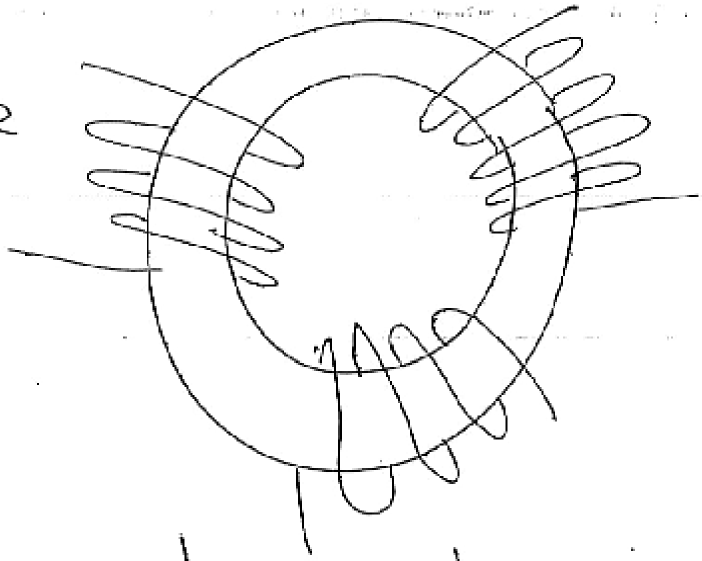
$$\phi_g = \frac{F_{LKG}}{1 + F_{LKG} (R_g // R_P)} \phi_r$$

F

$$B_g = \frac{\phi_g}{A_g} .$$

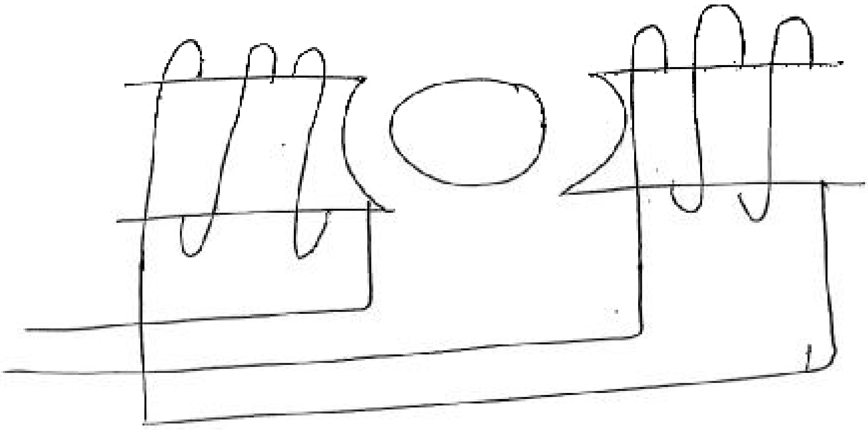
$$E = 4.44 \underset{\substack{\uparrow \\ \text{flux per pole}}}{\phi_g} f \underline{\underline{N}} \underline{\underline{K_\omega}} \Rightarrow k_p k_d$$

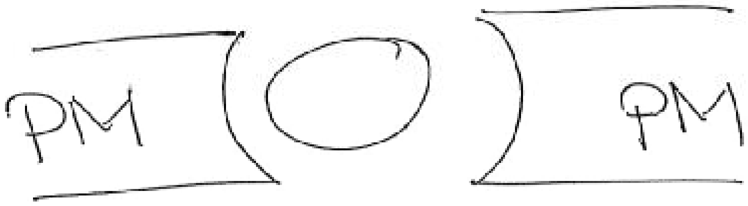
$$f = \frac{nP}{120} .$$

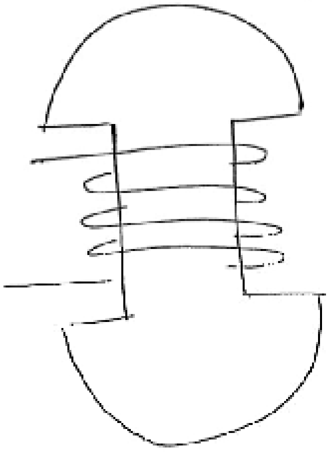


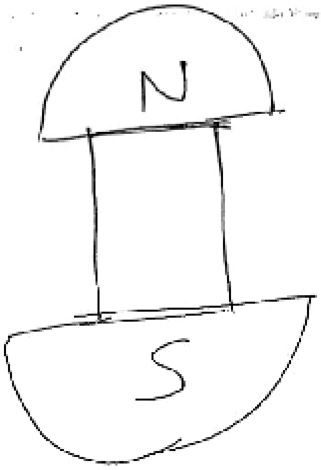
Slotless machine

$$\underline{\underline{K_c = 1 .}} \quad \#$$

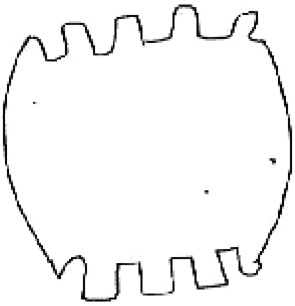


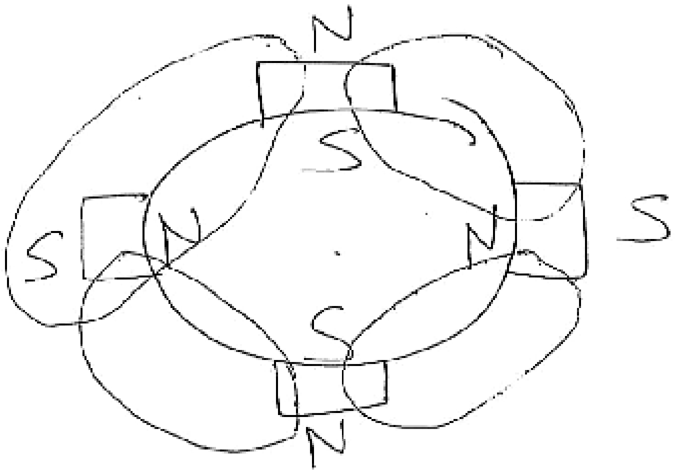






Hibrid excited





10

advantages of Per. M.
machines over convintional
electrical machines :-

① higher η → No copper losses in the field winding.
(No field winding).

② lower size
lower weight
→ higher power to weight ratio.
$\underbrace{\text{(Power / weigh)}}_{}$

for the same weigh → same power

③ simplesty of design and manufacturing.

④ possibilty of variance Topologies (configurations).

dis adv. :- → cost ↑.

#

Nd Fe B

↑

(500 JD/kg)

germany

china

USA

Japan (rare earth)