تقدم لجنة ElCoM الاكاديمية

دفتر لمادة:

الات كهربائية (2)

من شرح:

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ELECTRIC MACHINERY FUNDAMENTALS

CHAPTER
2

TRANSFORMERS

Sub.   Date: /   /

* Chapter 2 :- Transformers :-

2.10 : Three-phase Transformers :-

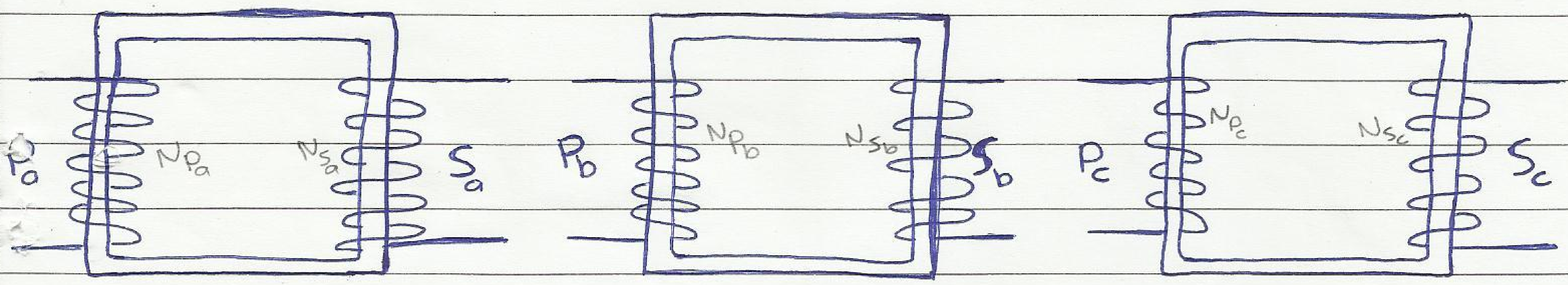
- almost most power system generation, transmission and distribution are three-phase ac system.

- Why we use 3-ø system ??

↳(691+681) الجواب موجود في كتاب بالستين (Appendix A) في صفحة

* Transformers for three-phase circuits can be constructed in one of two ways :-

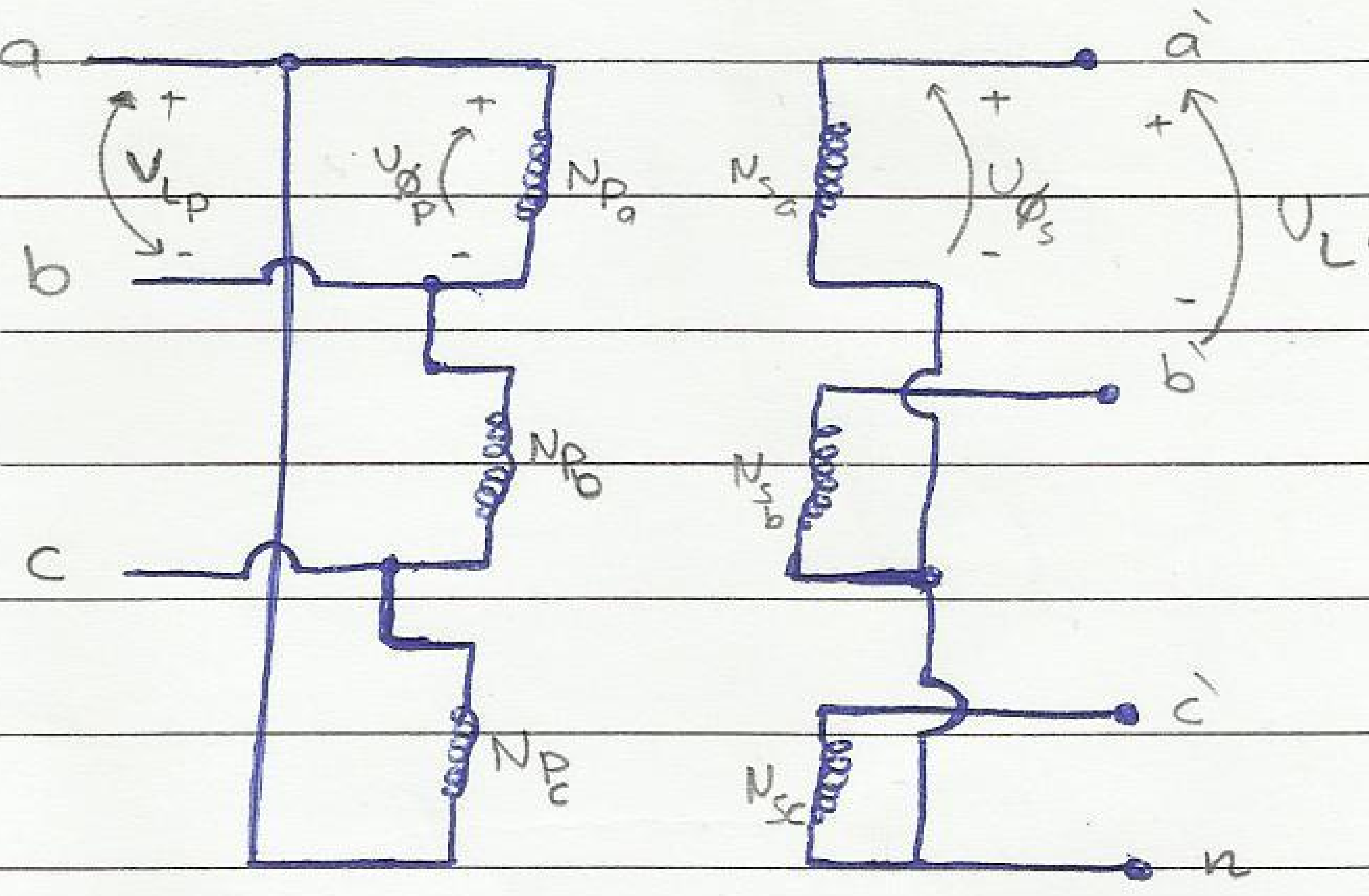
Types 1 :- Three single-phase units :-



a   b   c

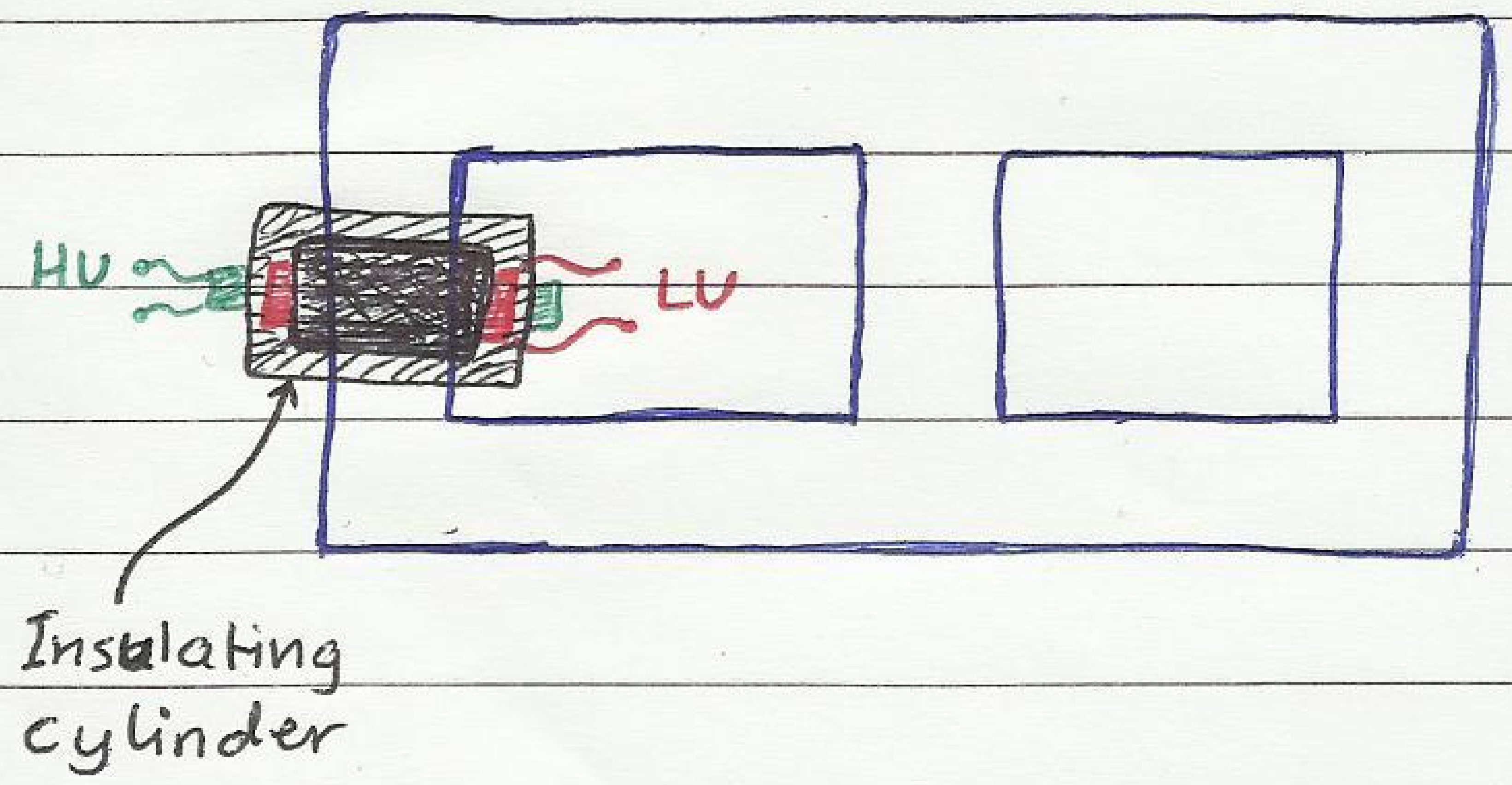
* Advantage :- More reliable construction
↳ each unit can be replaced in case of trouble.

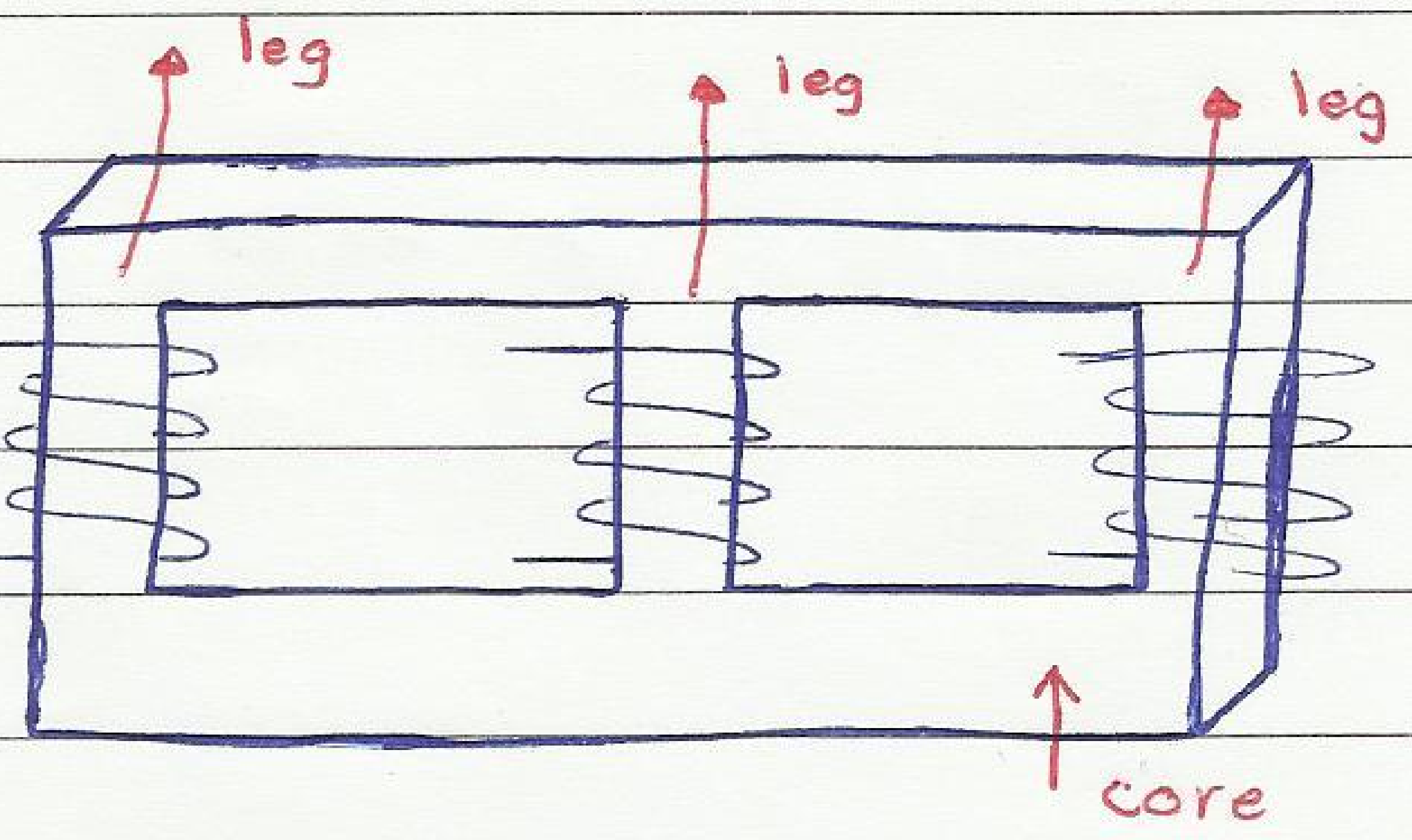
إذا عطلت إحدى الـ phase فإنها لا تؤثر على الأخرى



Δ-Y connection
"Just example"

Type 2 :- Single Three-phase unit :-



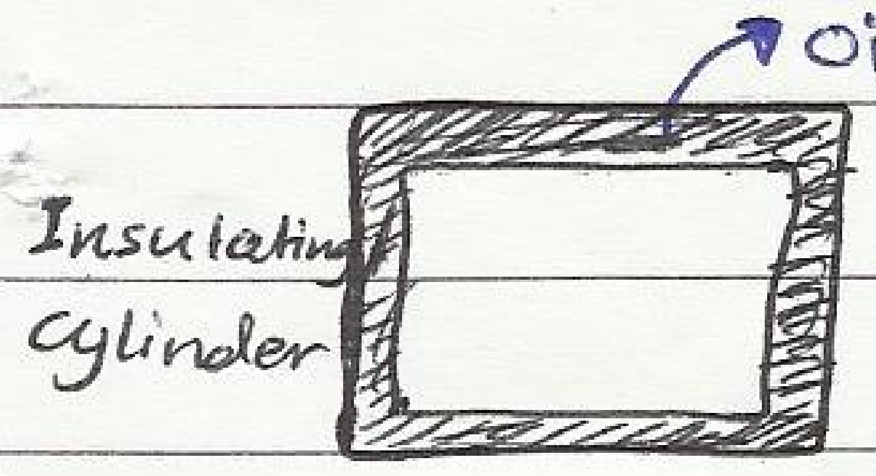


* Advantages :- 1- lower weight .

2- lower size .

3- cheaper .

4- more efficient → power losses ↓ → volume ↓

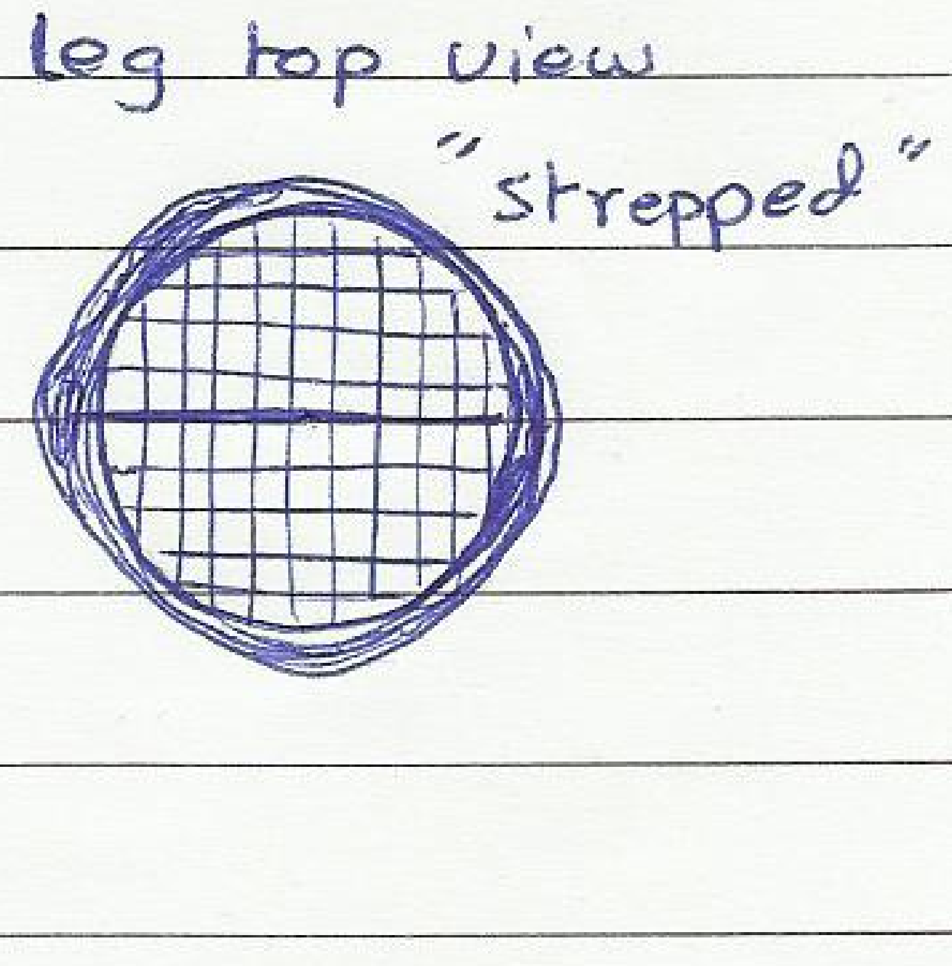


→ advanteges :-

- Insulating
- cooling

* If we look to the leg from the top, we can show this :-

⇓



why ?

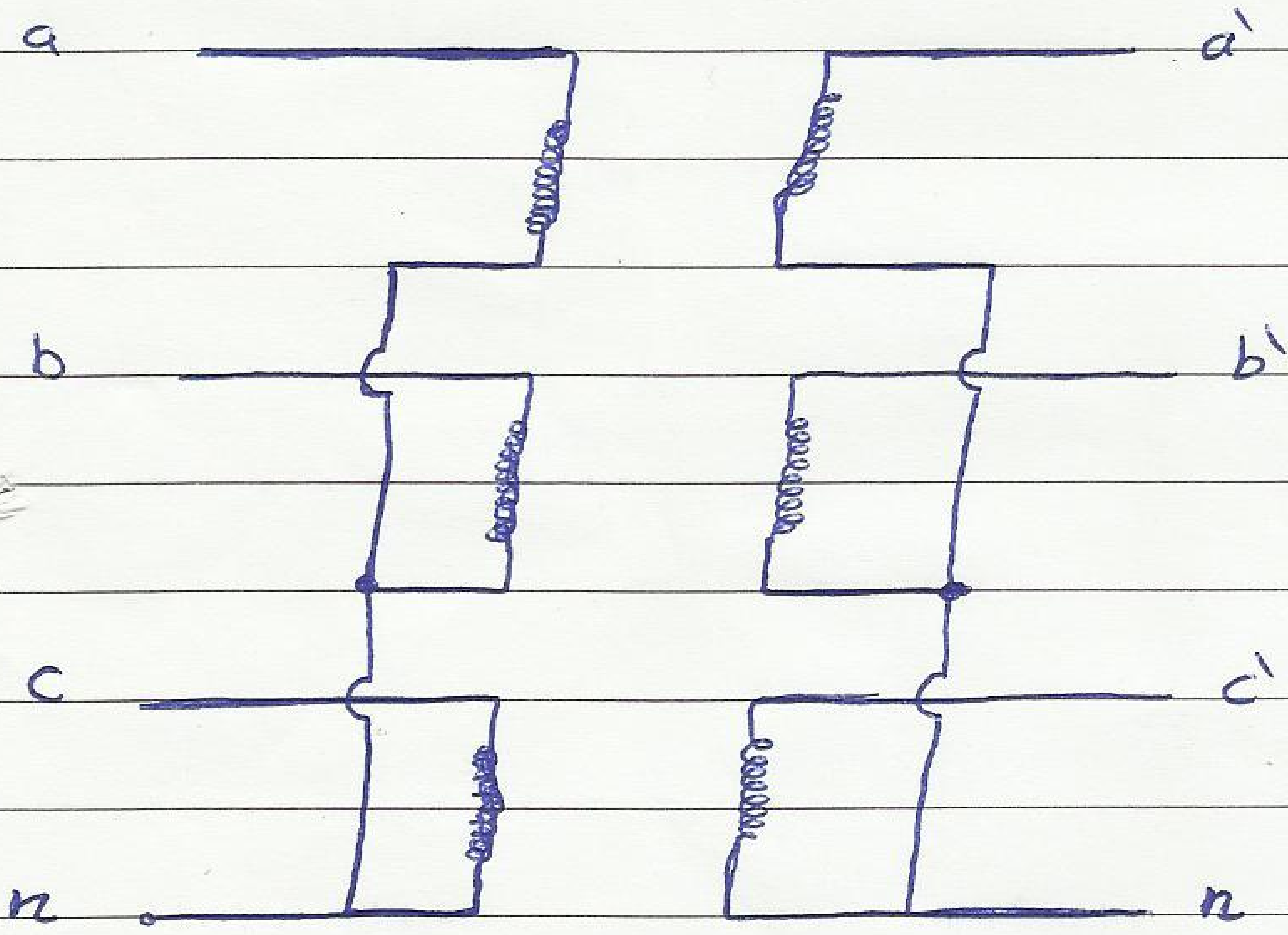
-for the same cross sectional area, the circle has the lowest circumference, thus lowest turn length
→ lower winding resistance.
→ lower losses efficienses .
→ lower cooling power .
→ better Voltage regulation .
→ lower copper losses .

* Three-phase Transformer connections :-

- There are Four possible connections for a three-phase transformer.

1. Wye - Wye (Y-Y)
2. Wye - delta (Y-Δ)
3. delta - Wye (Δ-Y)
4. delta - delta (Δ-Δ)

Π Y-Y connection :-



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

* The Y-Y connection has two problems :-

Π If the loads across the transformer are Unbalanced then the voltages across the phases of transformer become severely Unbalanced.

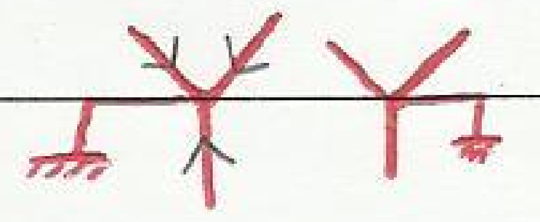
2] There is a serious problem with the third harmonics voltages, due to the nonlinearety of the B/H curve of the core of the transformer, these third harmonics components are inphase.

$$V_{3ha} = \bar{V}_{3h} \sin(3\omega t)$$
$$V_{3hb} = \bar{V}_{3h} \sin(3(\omega t - 120^\circ)) = \bar{V}_{3h} \sin(3\omega t - 360^\circ)$$
$$V_{3hc} = \bar{V}_{3h} \sin(3(\omega t + 120^\circ)) = \bar{V}_{3h} \sin(3\omega t + 360^\circ)$$

$$V_{3h_a} + V_{3h_b} + V_{3h_c} = 3\bar{V}_{3h}$$

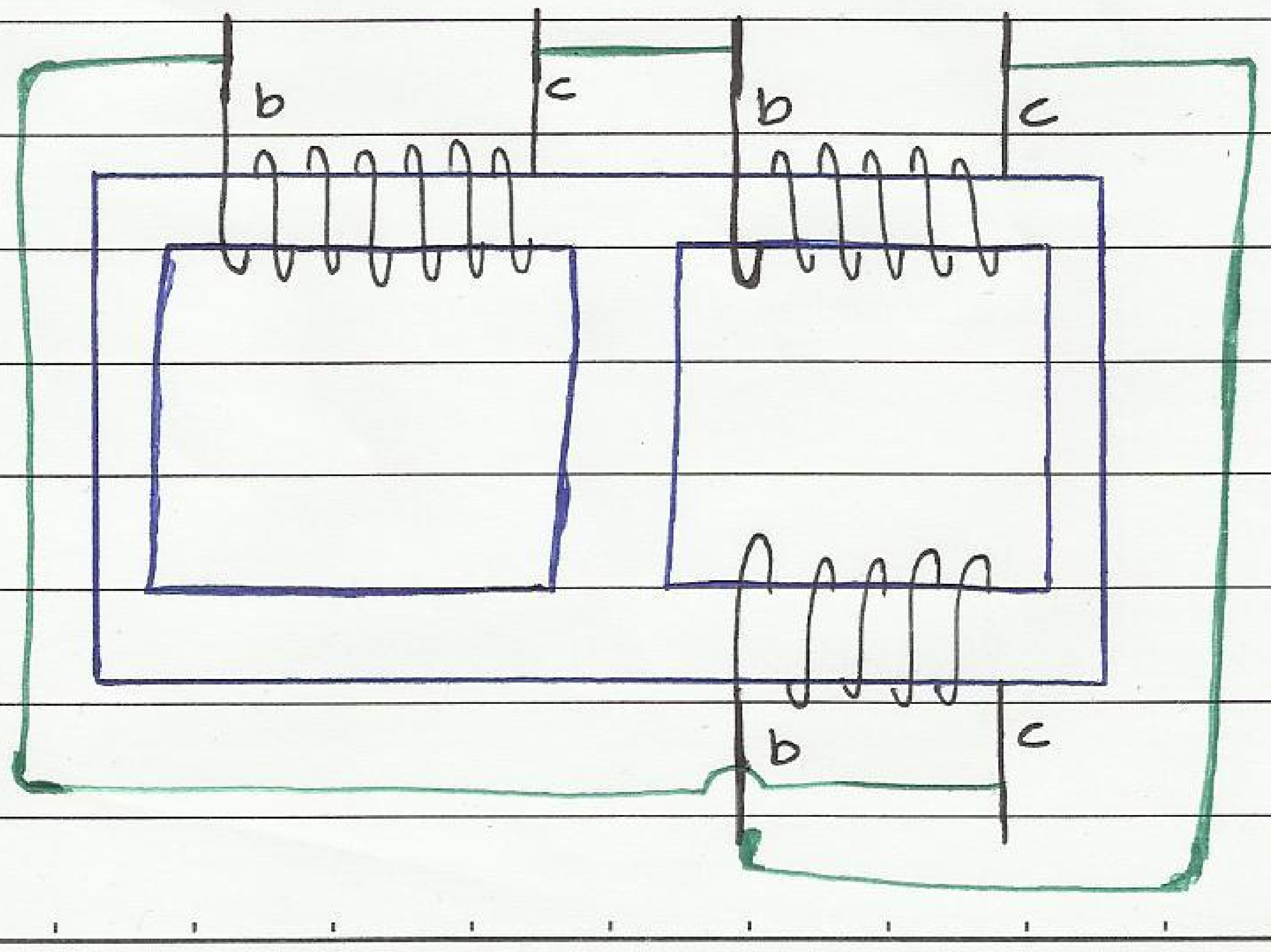
* both the Unbalanced problem and the 3rd harmonics problem can be solved by :-

1) Solidly ground the neutrals of the transformer, especially the primary winding's neutral. (earthing with zero impedance), this permits the additive term harmonic component to cause a current flow in the neutral instead of building up large voltage.



2) Add third winding (tertiary winding) connected in delta to the transformer, In tertiary winding the voltages will add up causing a circulating current to flow within the winding, and the tertiary windings must be large enough to handle the circulating current, so they are usually made about one-third the power rating of the two main windings.

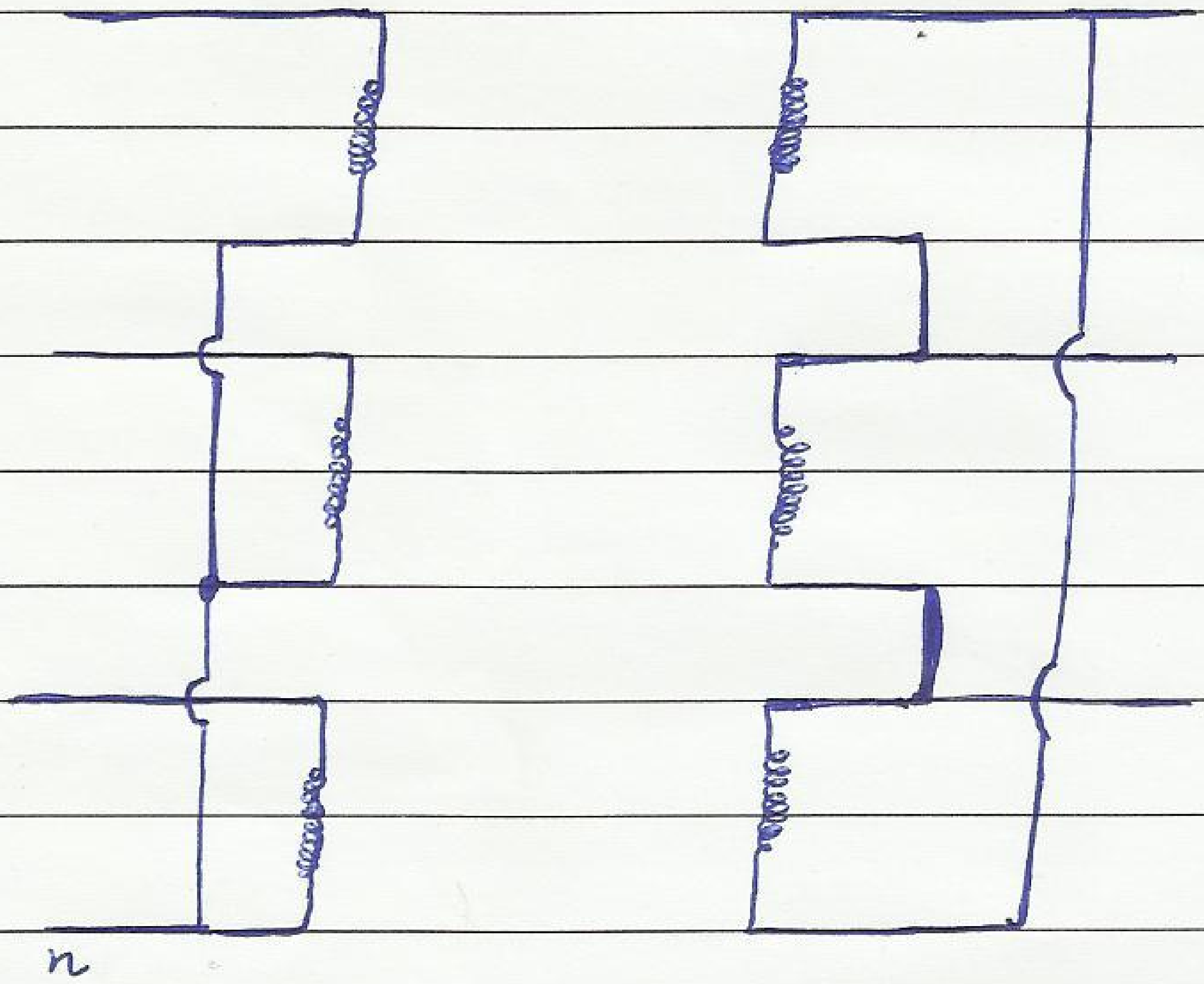
↓ to eliminate 3rd harmonics on transformer



* Note :- tertiary winding is used to supply lights and auxiliary power to the substation were it is located.

⇒ due to these problem there are early uses the Y-Y connection.

2] Y-Δ connection :-



$$\boxed{\frac{V_{LP}}{V_{LS}} = \frac{\sqrt{3}\,V_{\phi P}}{V_{\phi S}} = \sqrt{3}\,a}$$

* In Y-Δ connections the problem of the 3rd harmonics does not exist due to the circulating current of the Δ-Sides, Same thing for the problem of unbalanced loads, which also redistributes any unbalanced that occurs.

* In the Y-Δ connection the secondary voltage is either lagging or leading the primary voltage by 30°.

↳ according to (+ve) or (-ve) sequences.

* Group connection :- indicates the phase shift between primary and secondary voltage.

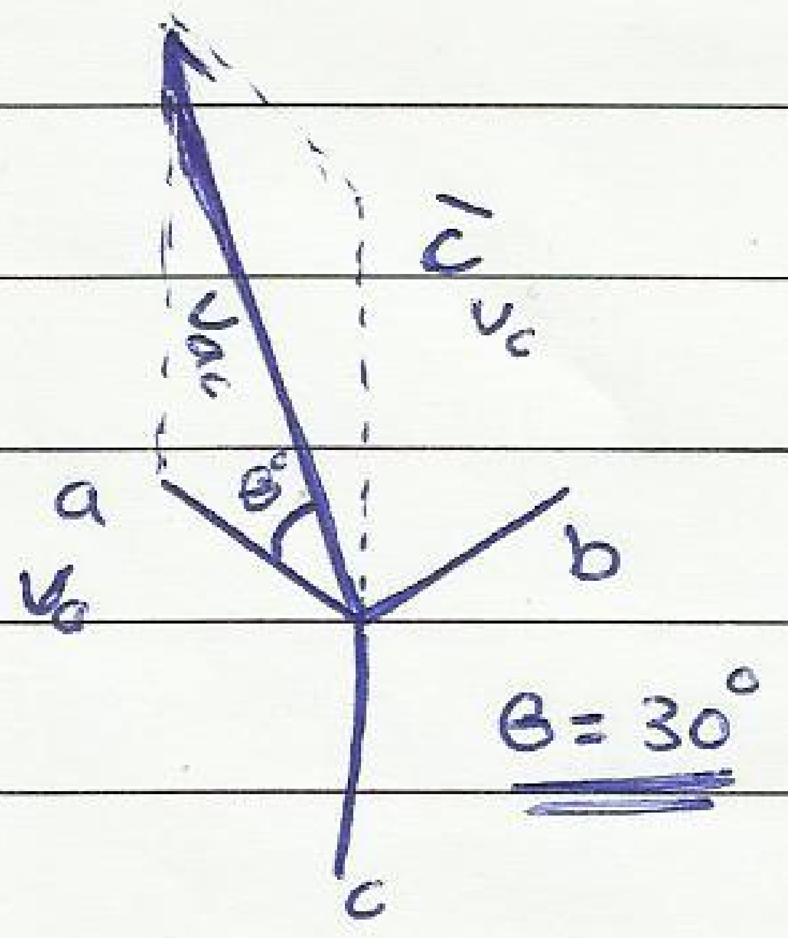
(the reference is counter clockwise)

YD_n *

Y conn.

Δ-conn.

$n * 30° = \theta$

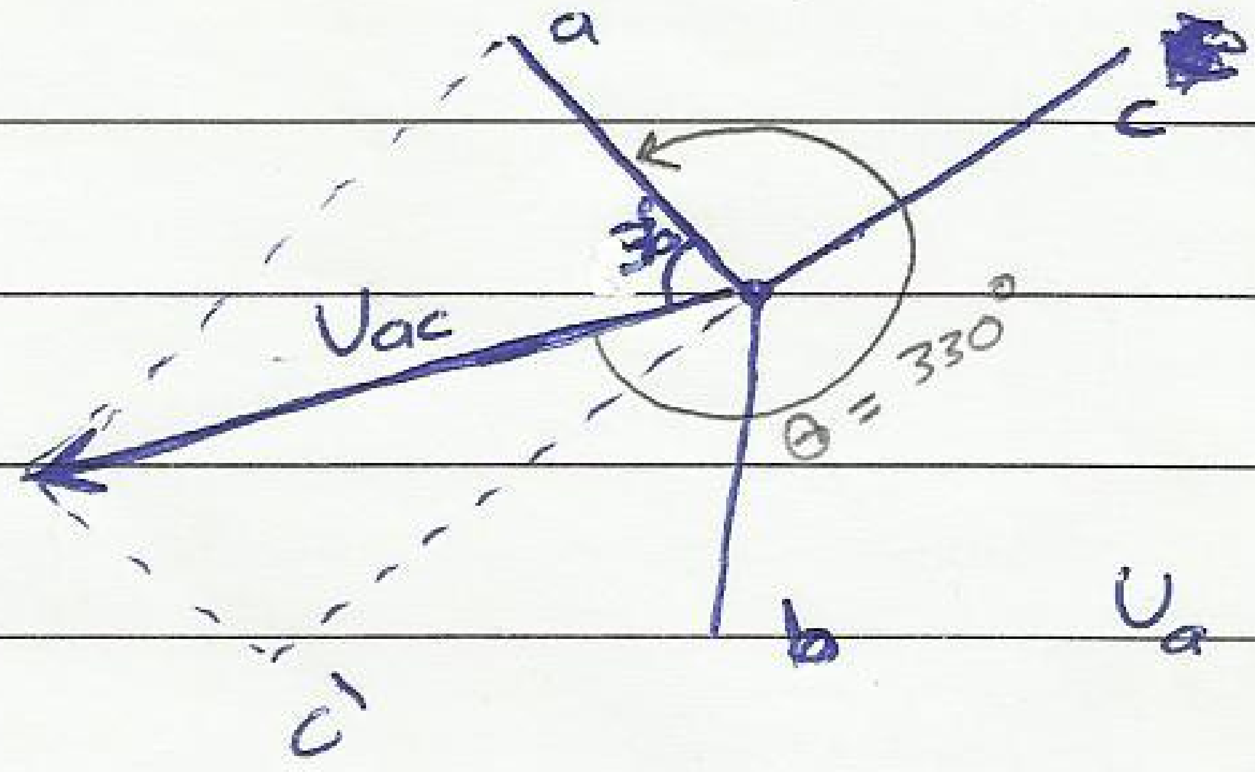


$\theta = 30°$

YD_1

$1 * 30° = 30°$

U_{ac} lags U_a by 30°



U_a lags U_{ac} by 30°

YD_{11}

$11 * 30° = 330°$

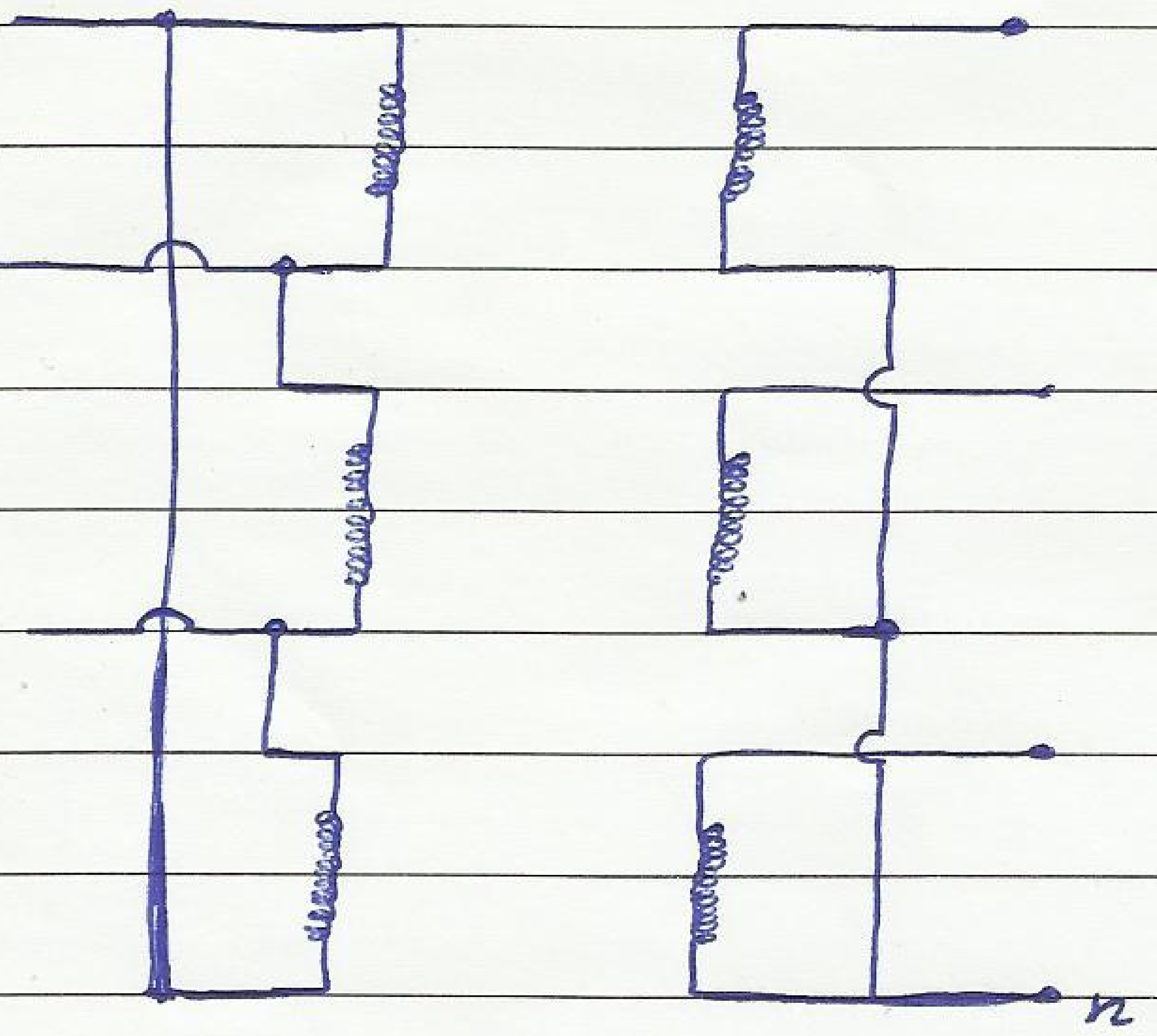
* notes :-

- to determine the Group connection we must move from line to phase and counter clockwise.

- The Group connections is very important if transformers are to be parallel, beccause the phase angle of the transformer's secondary must be equal, Otherwise cause big circulating current will flow within.

- in Y-Y and Δ-Δ the angle always zero.

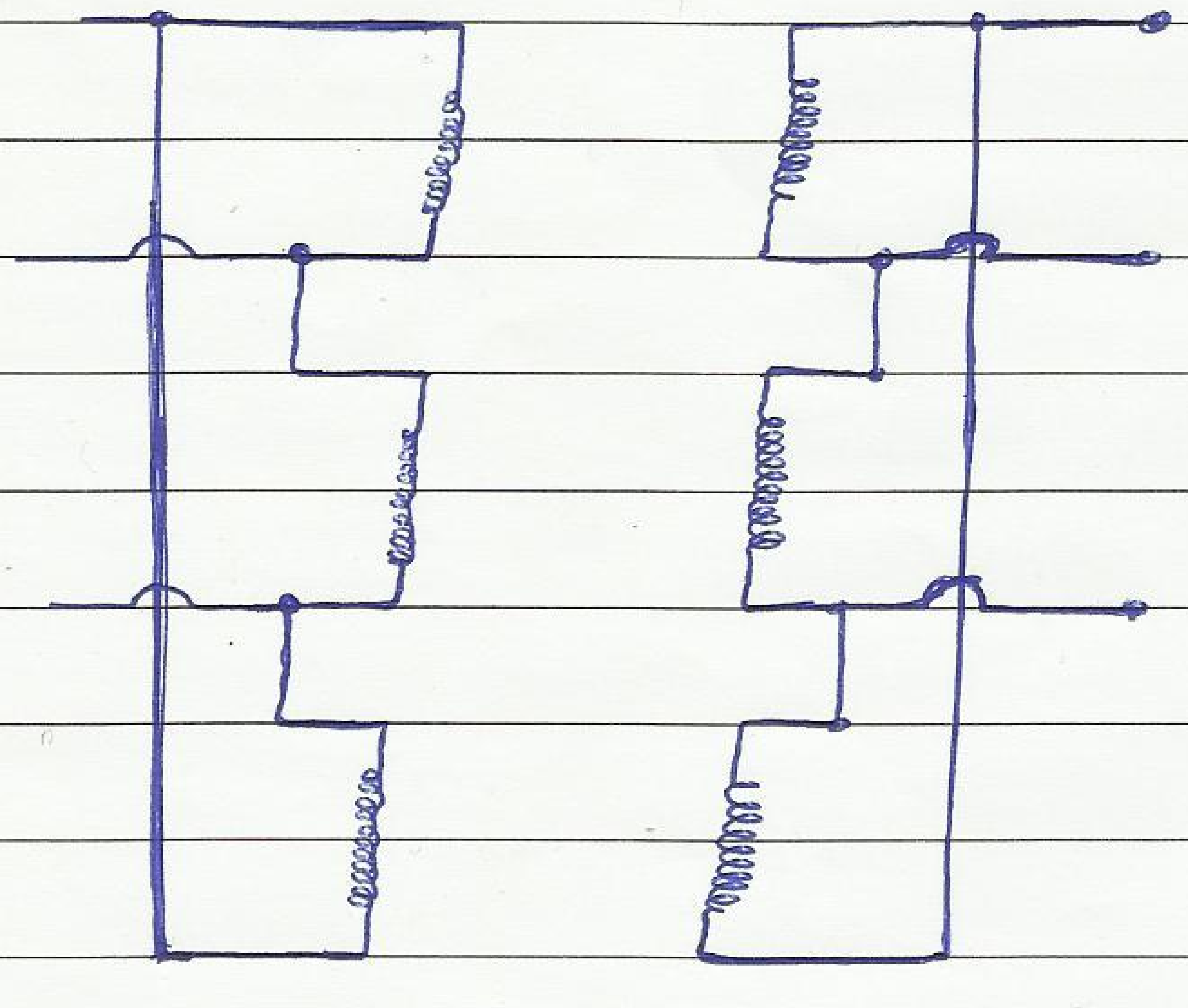
3] Δ-Y connection :-



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

- the same advanteges of the Y-Δ connections.
- As for the group connections there are similar to the previous one.

4] Δ-Δ connections :-



$$\frac{V_{LP}}{V_{LS}} = \frac{V_{\phi P}}{V_{\phi S}} = a$$

* Similar to Y-Y connection, the Δ-Δ has no phase shift associated with its voltages (no Group connection), Unlike the Y-Y connection, the Δ-Δ connection has no problem with the unbalanced loads and 3rd harmonic

* The Per-Unit system for three-phase Transformers :-

- S_{base} :- total base voltampere values of the transformers bank (3-ø transformer).

  * what are the benefits of using per-unit system?
  - There is no meaning for the turns ratio "a" in per unit system " no need reflection".
  - Simple and easiest calculation.

- $$S_{1-\phi,\,base} = \frac{S_{base}}{3}$$

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

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

- $V_{L,\,base} = V_{\phi,\,base}$ if the windings are Δ-connected.

- $V_{L,\,base} = \sqrt{3}\,V_{\phi,\,base}$ if the windings are Y-connected.

Ex 1 : 50 KVA , 13800/208 V , Δ-Y distribution transformer has a resistance of one percent pu , and a reactance of 7% pu.

a) what is the transformer phase impedance reffered to the high voltage side ??

$V_{\phi_{base}} = 13800 \text{ V}$, $S_{base} = 50 * 10^3 \text{ VA}$

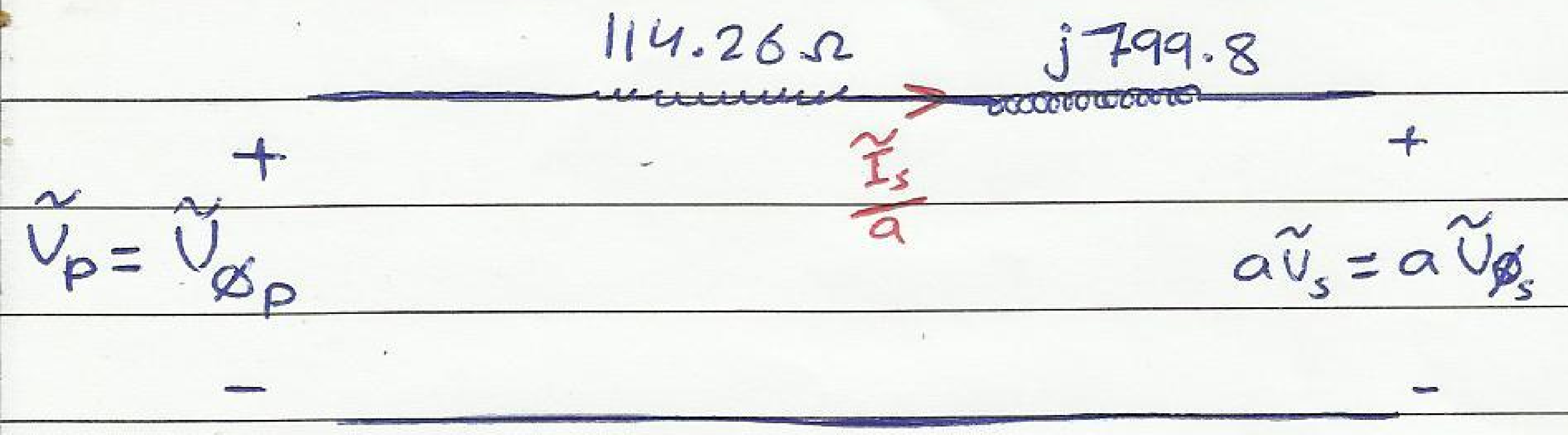
$$Z_{base} = \frac{3(V_{\phi, base})^2}{S_{base}} = \frac{3 * (13800)^2}{50 * 10^3} = 11426 \ \Omega$$

$$Z_{pu} = \frac{Z_{eq}}{Z_{base}} \Rightarrow Z_{eq} = Z_{base} * Z_{pu}$$

$$Z_{pu} = (0.01 + j0.07)$$

$$Z_{eq} = Z_{base}(0.01 + j0.07) = 11426(0.01 + j0.07) = 114.26 + j799.8$$

b) calculate VR at Full load and 0.8 lagging p.f using the calculated high voltage impedance of the previous part ??



ملاحظة :-

نحن دائماً في حل المسائل كل
نظام per phase وليس كل نظام
line - line .

$$\tilde{V}_{\phi_p} = a\tilde{V}_{\phi_s} + \left(\frac{\tilde{I}_s}{a}\right)(114.26 + j799.8)$$

$$\tilde{V}_{\phi_s} = \frac{V_L}{\sqrt{3}} = \frac{208 \angle 0°}{\sqrt{3}} = 120.23 \angle 0°$$ Y- connection

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

$50*10^3 = \sqrt{3}\,(208)\, I_L \Rightarrow I_L = 138.95\text{ A} = I_\phi = I_s$ Y-connected.

$a = \dfrac{V_{\phi p}}{V_{\phi s}} = \dfrac{13800}{208/\sqrt{3}} = 114.78$

$\dfrac{\tilde{I}_s}{a} = \dfrac{138.95}{114.78} \angle -\cos^{-1}(0.8) = 1.21 \angle -36.8°$

$\tilde{V}_p = a\tilde{V}_s + \left(\dfrac{\tilde{I}_s}{a}\right)(114.26 + j\,799.82)$

$\tilde{V}_p = (114.78)(120.23 \angle 0°) + (1.21 \angle -36.8)(114.26 + j\,799.8)$

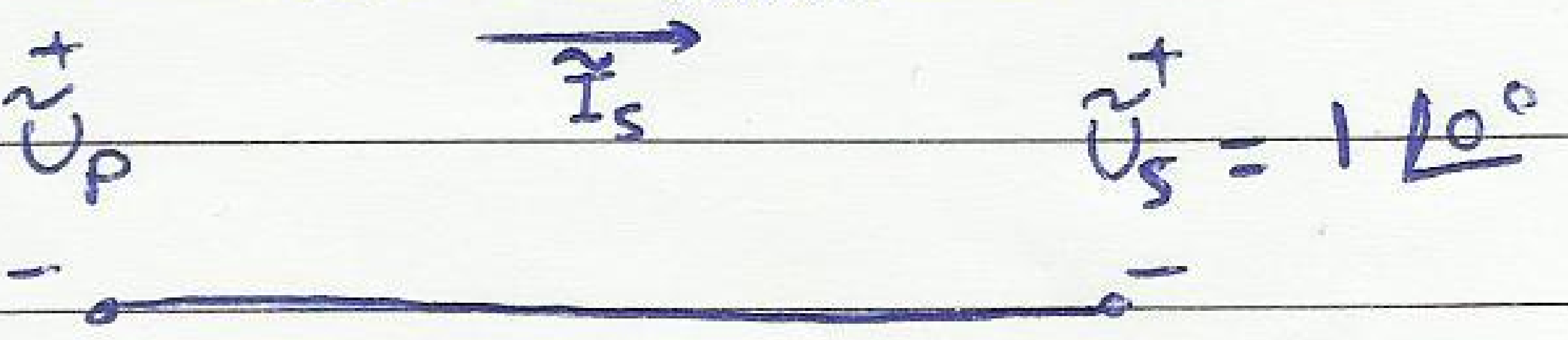
$\tilde{V}_p = 14506 \angle 2.73°$

$VR\% = \dfrac{|\tilde{V}_p| - |a\tilde{V}_s|}{|a\tilde{V}_s|}\,\% = \dfrac{14506 - 13800}{13800} * 100\% = 5.1\%$

c) Repeat the previous part, using per-unit system ??

$\tilde{V}_p = \tilde{V}_s + \tilde{I}_s(R_{eq} + jX_{eq})$

$\tilde{V}_p = 1\angle 0° + (1 \angle -\cos^{-1} 0.8)(0.01 + j0.07)$



عَ
Full-load

$\tilde{V}_p = 1.051 \angle 2.73°$

$VR\% = \dfrac{1.051 - 1}{1} * 100\%$

$= 5.1\%$

d) Repeat part c , but at half load ??

$\tilde{V}_p = \tilde{V}_s + \tilde{I}_s\,(0.01 + j0.07)$

$\tilde{V}_p = 1\angle 0° + (0.5)\angle{-\cos^{-1}0.8}\;(0.01 + j0.07)$

$= 1.025\ \angle 1.398°$

e) Repeat part c, but at 10% over load ??

$\tilde{V}_p = \tilde{V}_s + \tilde{I}_s\,(0.01 + j0.07)$

$= 1\angle 0° + 1.1\angle{-\cos^{-1}0.8}\;(0.01 + j0.07)$

$= 1.056\ \angle 2.98°$

Ex2 :- 100 MVA , 230/115 kV , Δ-Δ connection , 3-Ø power transformer , $R_{eq} = 0.02$ pu , $X_{eq} = 0.055$ pu , $R_c = 120$ pu

$X_M = 18$ pu .

a) If the transformer supplies a load of 80 MVA at 0.85 p.f lagging Draw the phase diagram ?

$p = \frac{80}{100} = 0.8$ pu

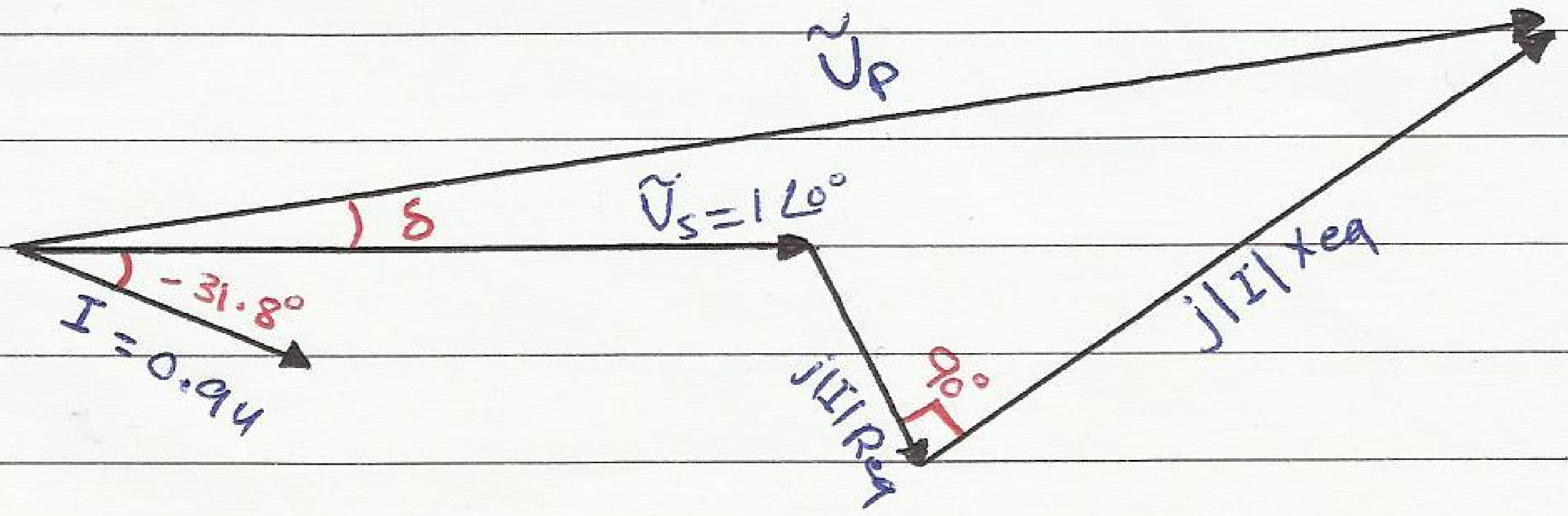
$p = VI\cos\theta$ ⇒ 3-Ø power in per-unit system.

$0.8 = (1) \cdot I \cdot (0.85)$

$I = 0.94$ pu $= 0.94\ \angle{-31.8°}$

لاحظ أن ال power في

ال per unit لا يوجد بها 3, $\sqrt{3}$



b) calculate UR under the operating conditions ??

$$\tilde{U}_p = \tilde{U}_s + \tilde{I}\,(0.02 + j0.055)$$

$$= 1\angle 0^\circ + (0.94\angle -31.8^\circ)(0.02 + j0.055)$$

$$= 1.0476\ \angle 1.788\ \text{pu}$$

$$UR\% = \frac{|\tilde{U}_{P_F}| - |\tilde{U}_{P_n}|}{|\tilde{U}_{P_n}|} = \frac{1.0476 - 1}{1} = 4.76\,\%$$

c) calculate η % ??

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

$$= \frac{P_{out}}{P_{out} + P_{loss}} = \frac{V_s I_s \cos\phi}{V_s I_s \cos\phi + I^2 R_{eq} + \frac{(\tilde{U}_p)^2}{R_c}}$$

$$= \frac{(1)(0.94)(0.85)}{(1)(0.94)(0.85) + (0.94)^2(0.02) + \frac{(1.0476)^2}{120}} = 97\,\%$$

d) calculate the actual value of Z_{eq} ?

$$S_{base} = 100 * 10^6 \Rightarrow S_{1-\phi,\,base} = \frac{S_{base}}{3} = 33.33 * 10^6$$

$U_{\phi,\,base} = 230 * 10^3$ refered to primary

$= 115 * 10^3$ reffered to secondary.

$$Z_{base} = \frac{3\,(U_{\phi.\,base})^2}{S_{base}} = \frac{3\,(230 * 10^3)}{100 * 10^6} =$$

$$Z_{pu} = (0.02 + j0.055)$$

$$Z_{eq} = Z_{base} * Z_{pu}$$

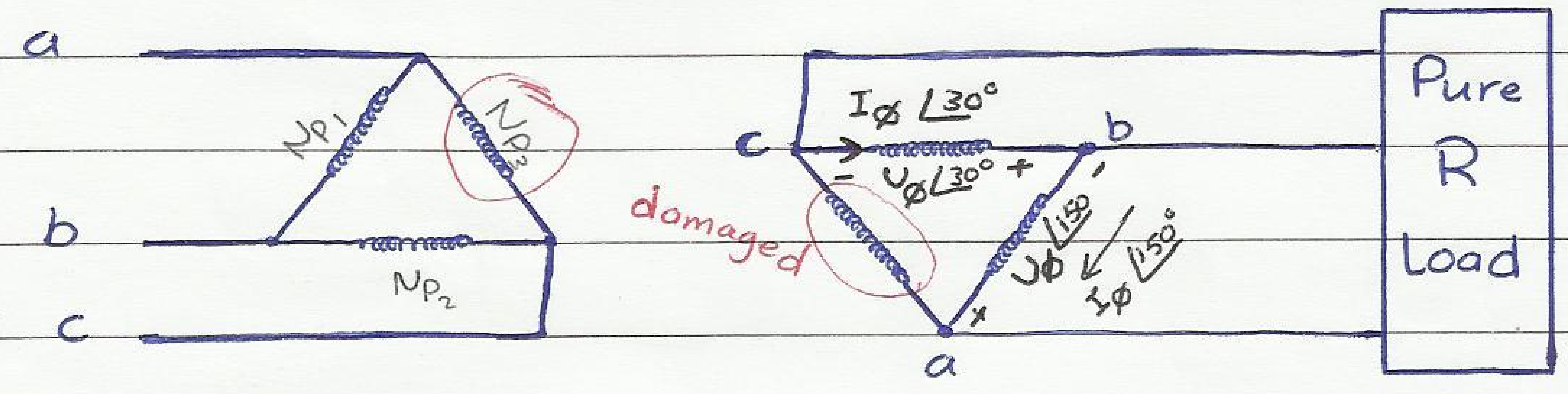
2.11 : Three-phase transformation using two transformers :-

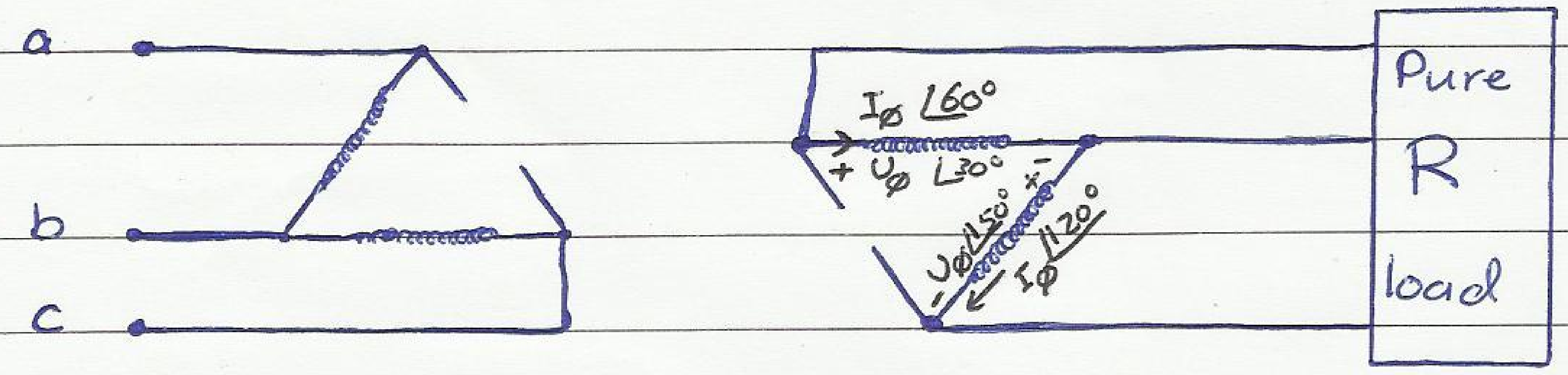
- There are ways to perform (3-ϕ) transformation with only two transformers, all techniques that does so involve a reduction in the power handling capability of the transformer.

① The open-Δ (V-V) connection.
② The open-Y open-Δ connection.
③ The scott T connection.
④ The three-phase T connection.

1] Open-Δ (V-V) connection :-

This happens in case of Δ-Δ 3-ϕ transformer when one of the phases is damaged and removed for repair.





$V_A + V_B + V_C = 0$ (The voltage are still balanced, because it is open circuit).

- Solving the circuit using "mesh analysis".

$P_1 = V_\phi I_\phi \cos(150° - 120°) = V_\phi I_\phi \cos 30° = \frac{\sqrt{3}}{2} V_\phi I_\phi$ (power delivered by phase number 1).

$P_2 = V_\phi I_\phi \cos(60° - 30°) = \frac{\sqrt{3}}{2} V_\phi I_\phi$

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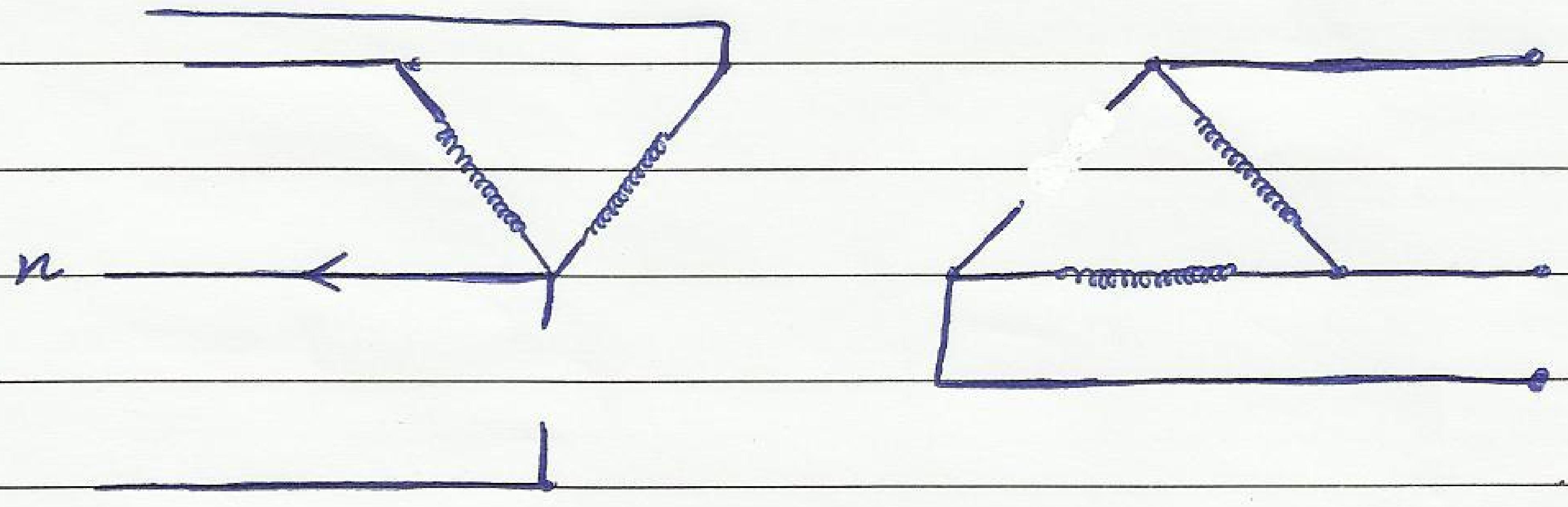
$$P_{T,2\emptyset} = P_{Total} = P_1 + P_2$$

$P_1 + P_2 = \sqrt{3}\, U_\emptyset I_\emptyset \Rightarrow$ Total power delivered by the two phases.

$$\frac{P_{T,2\emptyset}}{P_{T3\emptyset}} = \frac{\sqrt{3}\, U_\emptyset I_\emptyset}{3\, U_\emptyset I_\emptyset} = \frac{1}{\sqrt{3}} = 0.577$$

* The total power delivered incase in open-Δ connections is 57.7% of the power in case of healthy system (The power of the 2-0 is 0.577 from the total 3-0 power).

2] open-Y open-Δ :-



* The power developed in this case is the same as previous one, The voltages are still balanced and the power still 57.7% of that correct system.

* A major disadvantages in this connection is that a very large return current in the neutral primary circuit

- the protection system might dedicate a single phase to ground fault.

بنقدر نفحص من خلالها
كنه ال single phase الخرابات
بنوصل اوميتر على ال neutral ونشوف
قيمة التيار، لازم تكون تقريباً صفر، إذا كانت
القيمة كبيرة يعني انه في phase خراب

2.12 :- Transformer ratings and related problems :-

* Transformers have four major ratings S, V, I and F.

$p = \sqrt{3}\, V_L I_L \cos\phi$, if $p = 0 \Rightarrow$ ($\phi = 90^\circ$ pure inductance or capacitance).

$Q = \sqrt{3}\, V_L I_L \sin\phi$, if $Q = 0 \Rightarrow$ ($\phi = 0^\circ$ pure resistance load).

↳ it's possible to have a transformer running at rated conditions (rated current) with zero output active power if the load is pure indactive or capacitive.

* The voltage and frequency ratings of a transformer :-

$$E_{rms} = 4.44\,\phi F N$$

- Suppose that the transformer will run at a freq. lower than the rated (nominal).

$$E_{rms_1} = 4.44\,\phi_1 f_1 N_1$$

$$E_{rms_2} = 4.44\,\phi_2 f_2 N_2$$

$$\frac{E_{rms_1}}{E_{rms_2}} = \frac{4.44\,\phi_1 f_1 N_1}{4.44\,\phi_2 f_2 N_2} \qquad f_2 < f_1$$

Normally $N_1 = N_2$ (same transformer)

if the same voltage is applied, then $E_{rms_1} = E_{rms_2}$

$$1 = \frac{\phi_1 f_1}{\phi_2 f_2} \Rightarrow \phi_2 = \frac{f_1}{f_2}\phi_1$$

if $f_1 = 60$ Hz (USA) system.

and $f_2 = 50$ Hz (EU) system.

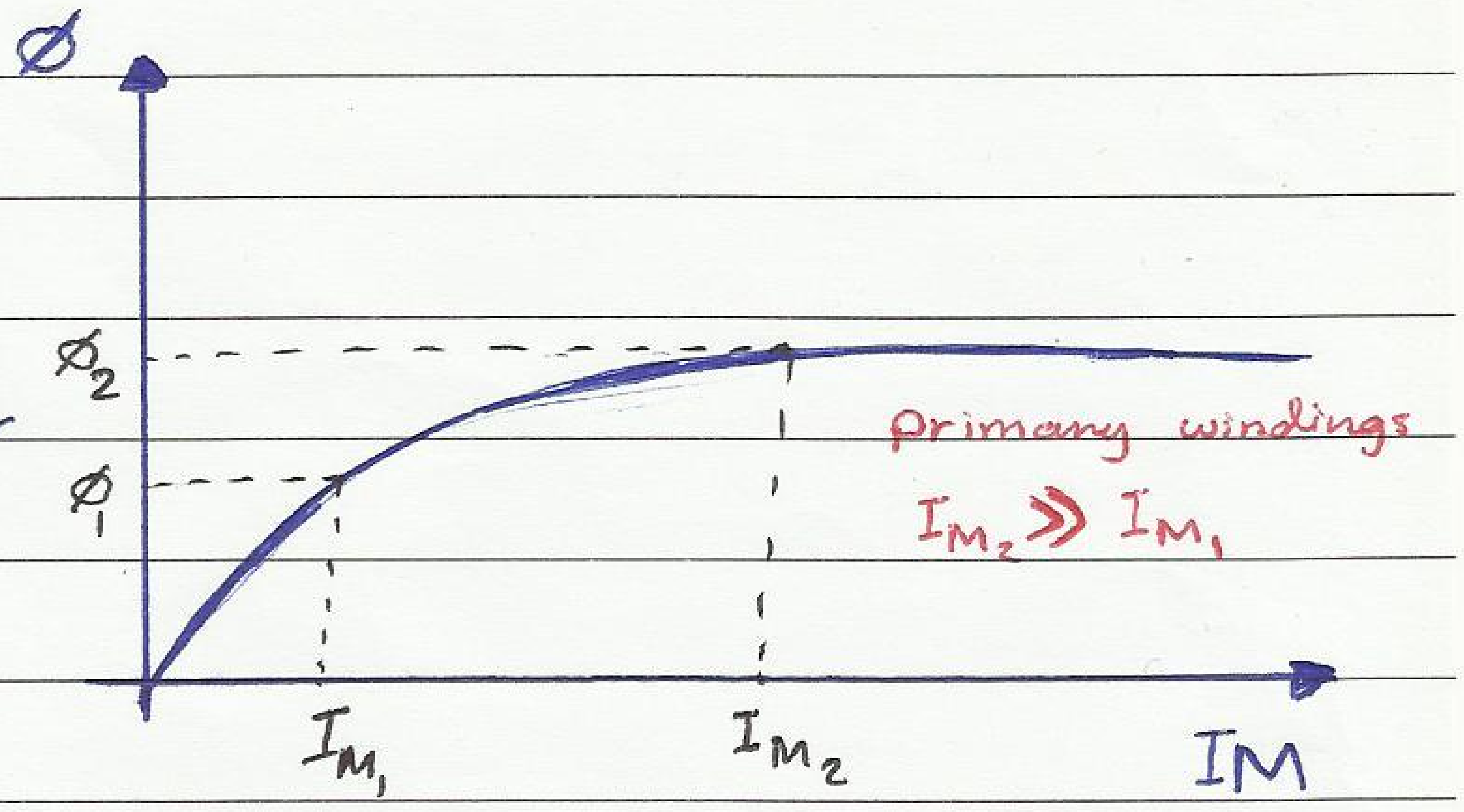
$$\phi_2 = \frac{60}{50}\phi_1$$

$$\boxed{\phi_2 = 1.2\,\phi_1}$$

⇒ reducing the frequency, increasing the magnitizing current due to the saturation of B(H) curve of the ferromagnetic material of the transformer for the same applied voltage.

لم تغير الـ f ⇐ بتغير ∅ ⇐ over heat ومنه o/p

مغطي الـ "Primary".



primary windings

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

- this applies also for induction motors.

  Induction Motor = Transformer (same concept)

  I_M in I.M > I_M in Transformer

  ↳ Because air gap ⇒ air gap has high reluctance.

لازم نغير الـ voltage
لأنه التيار عالي جداً
وهاي مشكلة كبيرة

- due to saturation, the magnitization current in case of (f_2) is much higher than the case of nominal freq. providing that $(F_2 < f_1)$.

- to solve this problem change the voltage at the same rate of the change of the frequency (reduce the voltage at the same ratio of the two frequencies)

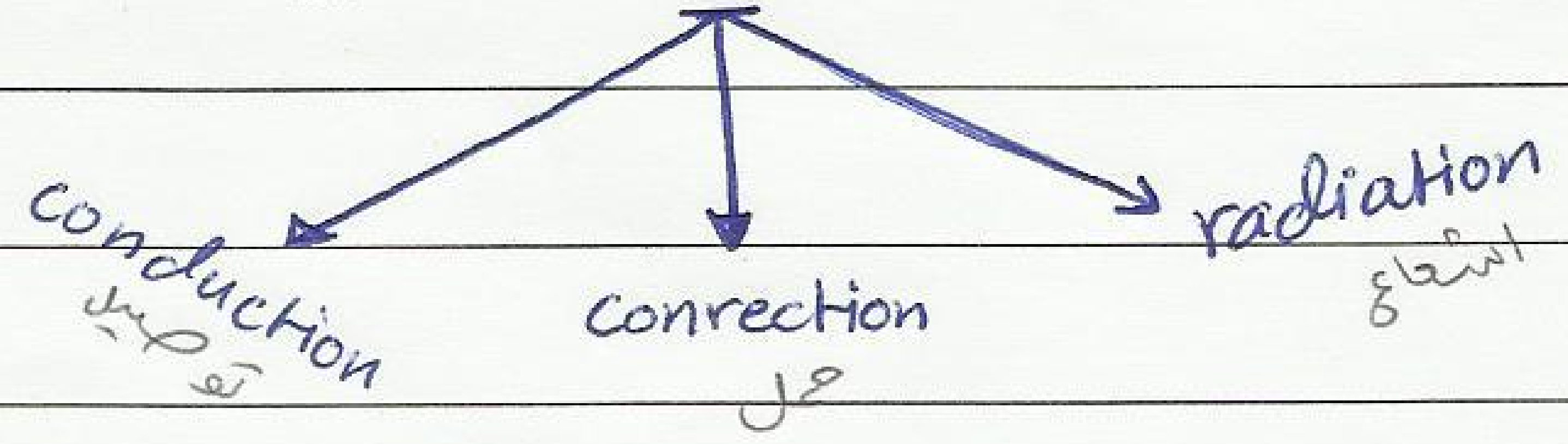
  for this case :-

$$E_{new} = \frac{50}{60} E_{old} \Rightarrow \text{Derating}$$

* The rated conditions of the transformer is governed by the current output of the secondary.

* The apparent power ratings of a Transformer :-

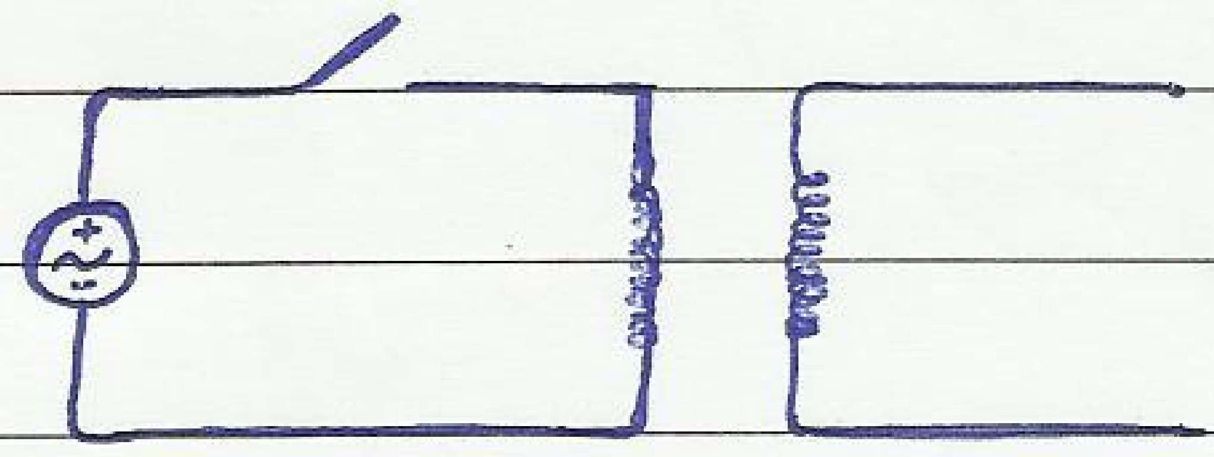
- overloading the transformer is possible up to (1.5) of its ratings, provided that the heat dissipation is guaranteed.



- you can run the transformer overloaded up to 1.5 ⇒ 150% if good cooling condition are provided.

- There is no meaning for the P.F of the transformer except at no-load and short circuit conditions. ⇐ تيار ال primary & secondary تجاهات
  ↳ applied to transmission line too.

* The problem of current Inrush :-

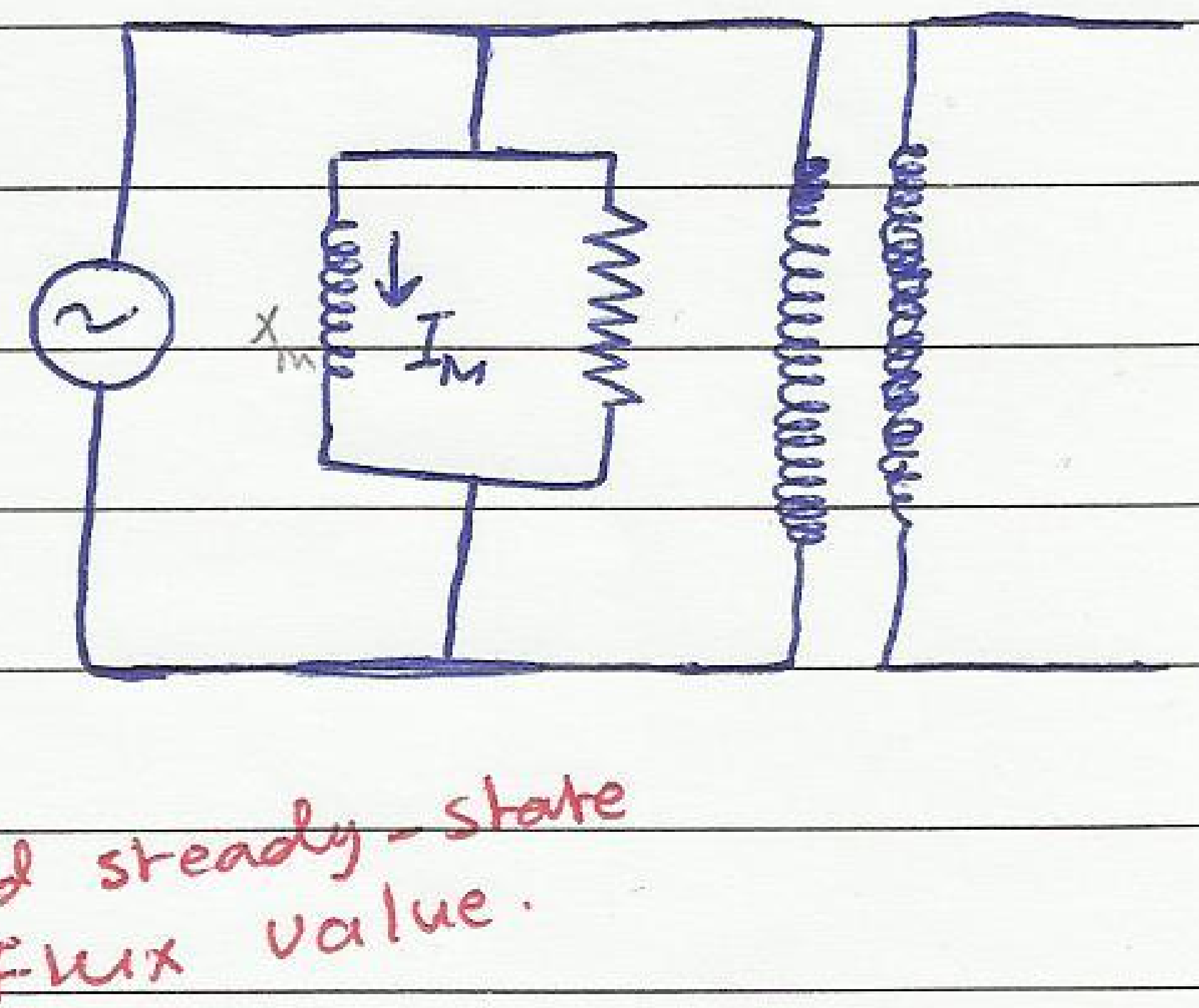


if $v(t) = V_m \sin(\omega t + \theta)$

$\theta = \frac{\pi}{2} = 90^\circ$

$v(t) = V_m \cos \omega t$

$$\phi_{max} = \frac{1}{N_p} \int_0^{\pi/\omega} V_m \cos \omega t \, dt = 0$$



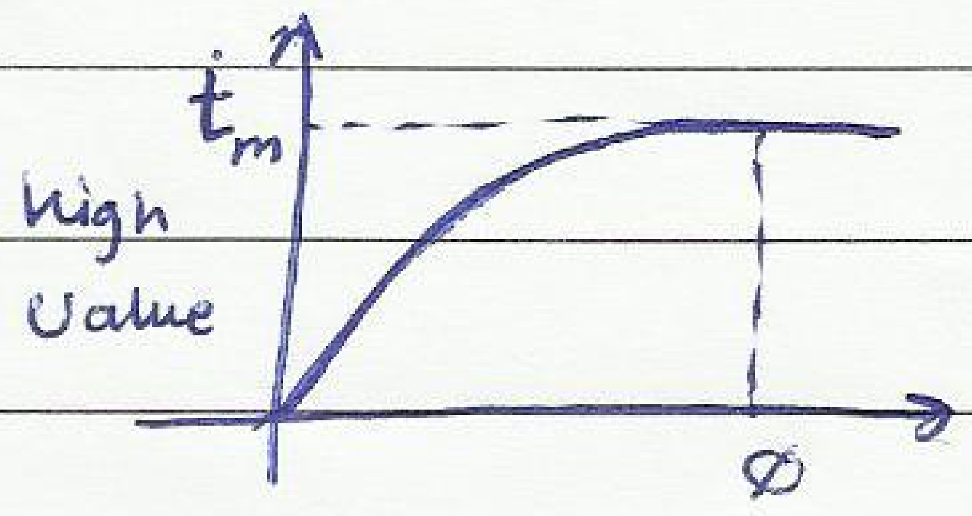
$\theta = 0^\circ \Rightarrow v(t) = V_m \sin \omega t$

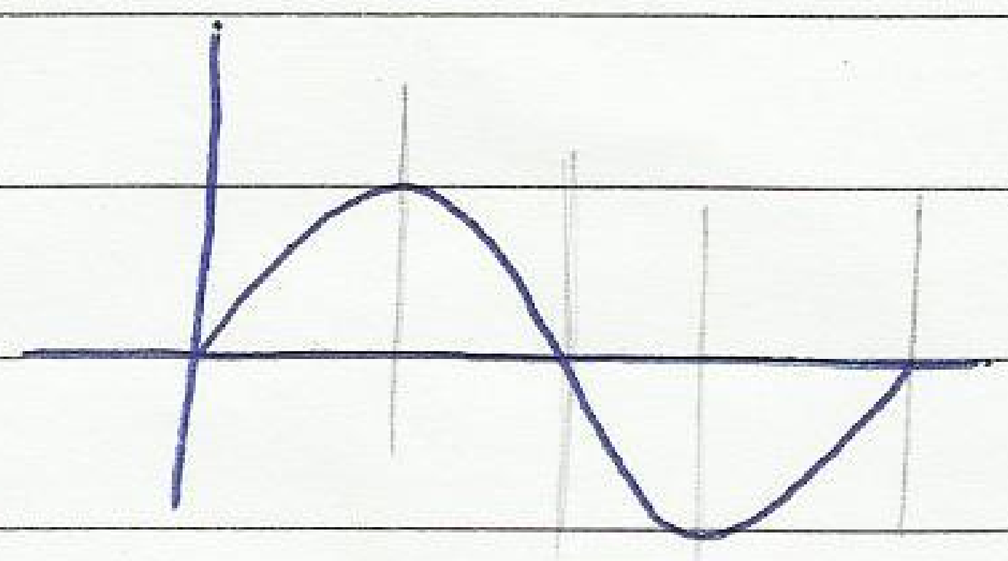
$$\phi_{max} = \frac{1}{N_p} \int_0^{\pi/\omega} V_m \sin \omega t \, dt = \boxed{\frac{2 V_m}{\omega N_p}}$$

rated steady-state Flux value.

ضعف ال rated يعني زاد ال Flux وبالتالي زاد ال I_M ، I_M بيمر في X_M ، وبالتالي X_M بتكون قيمة صغيرة جداً (short circuit)

* Inrush current :- starting current in the transformer, its value depends on the instant of switching (the current with drown by transformer at starting).





θ :- The instant of switching the supply.

- switching current high ? why ?

- إما دخلنا في ال saturation في ال B(H) curve
- او ان قيمة X_M صغيرة جداً (short cct.)

* Inrush current ≈ (5-7) for the rating current

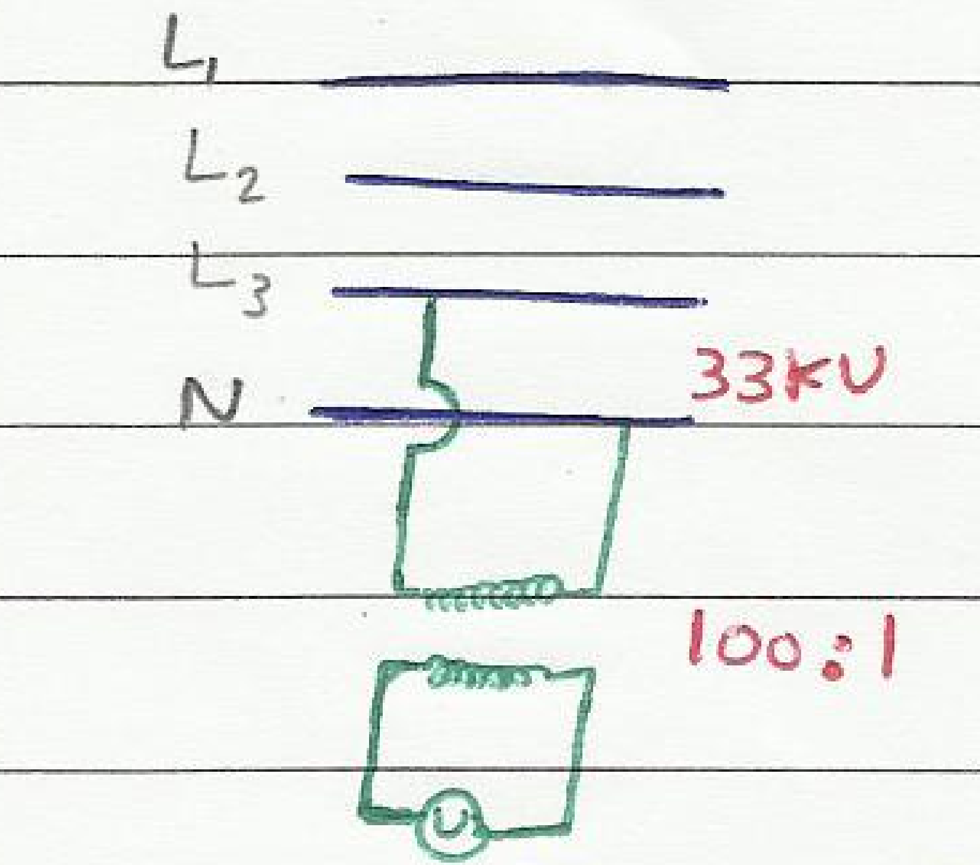
$$\text{copper losses} = I^2 \cdot R$$
$$= (5-7)^2\, I^2 . R$$

2.13 :- Instrument transformer :-

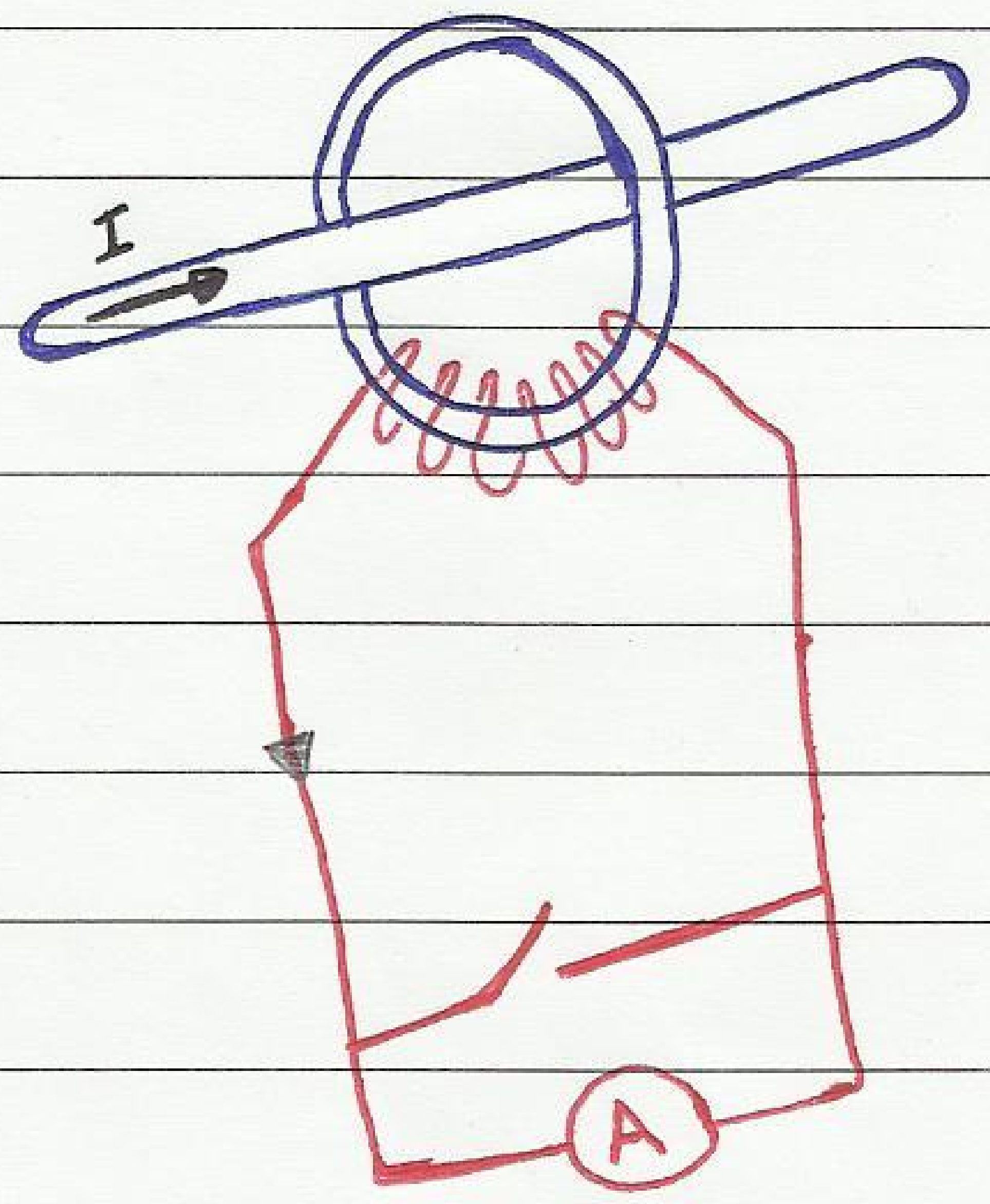
For measuring application

VT
(Voltage Transformer)

CT
(current transformer)



$$\frac{33000}{100} = 330\ V$$



step down .

يعني إزا عنا تيار تقريباً = 100A
صعب أجيب Amoter بيقيس مثل هيك
تيارات فبستخدم CT .

* It's important to keep the secondery of CT short cct. at all runing condition and VT keep it open cct.

* problems :-

2.10 , 2.13 , 2.18 , 2.19 , 2.20 , 2.21 , 2.23

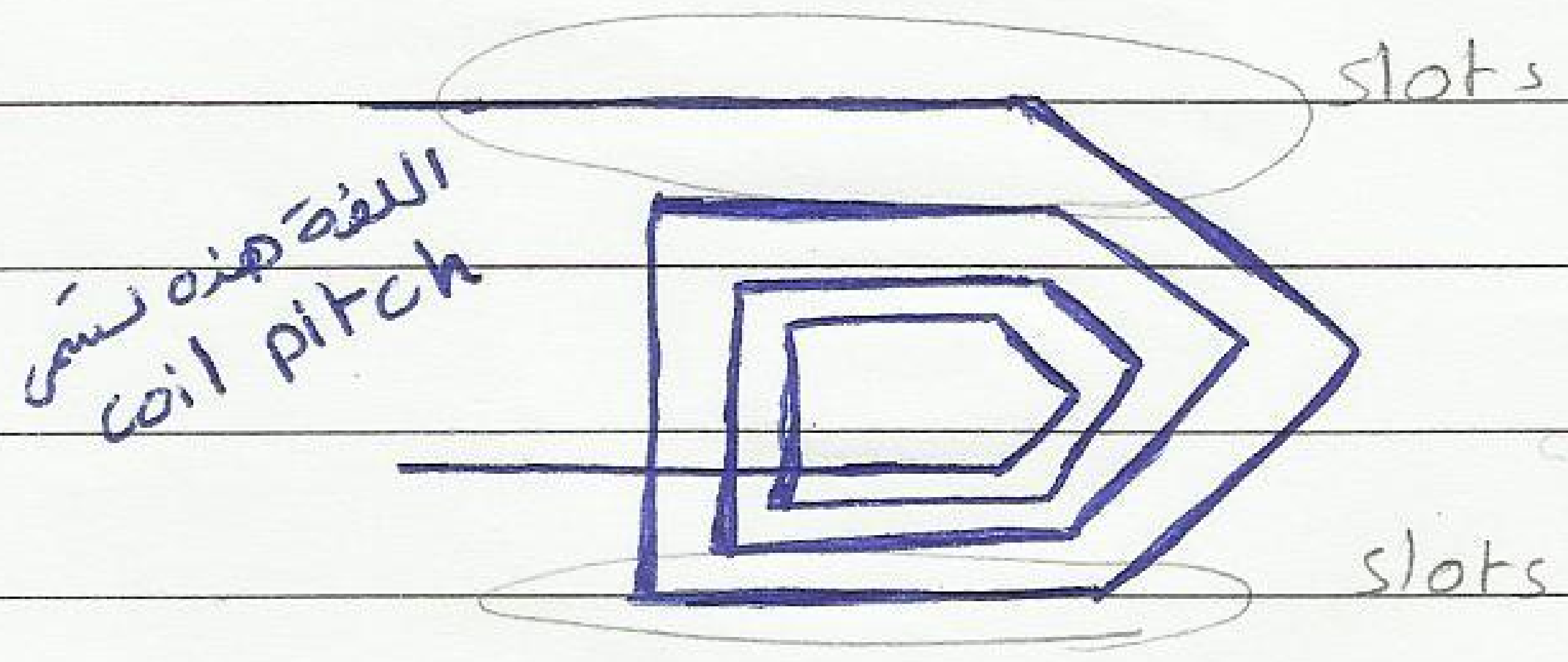
APPENDIX B

COIL PITCH AND DISTRIBUTED WINDINGS

* Notes on A.C Machine :-

Appendix B :- coil pitch and distributed windings :-

↳ the sinusoidal air gap flux density distribution produces sinusoidal Induced voltage. نفس الشكل



B.1 :- The effect of coil pitch on AC Machines :-

\- In general, air gap flux density distribution is not pure sinusoidal and therefore harmonics exists in the induced voltage of Ac generators.

Out of phase

$U = -N \frac{d\phi}{dt}$

مشتقة

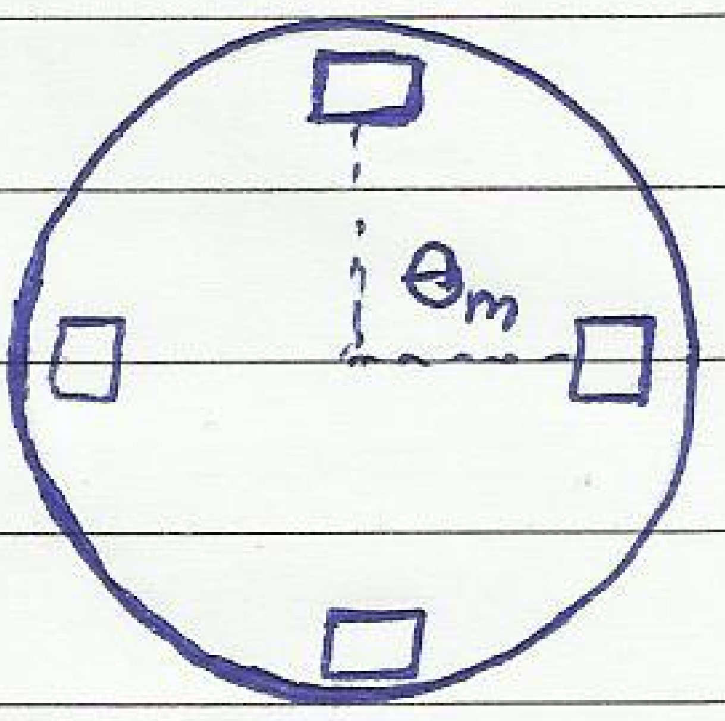
\- to reduce these unwanted harmonics several techniques are used. one of these techniques is called "Fractional-pitch winding".

* The pitch of a coil :-

The pole pitch P_p is the angular distance between two adjacent poles on a machine.

$$P_p = \frac{360^\circ}{P} \text{ (mechanical degree)}$$

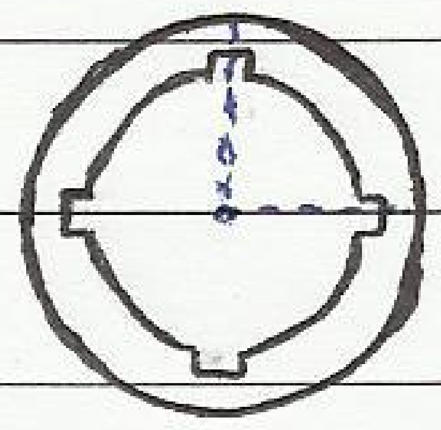
P → no. of poles



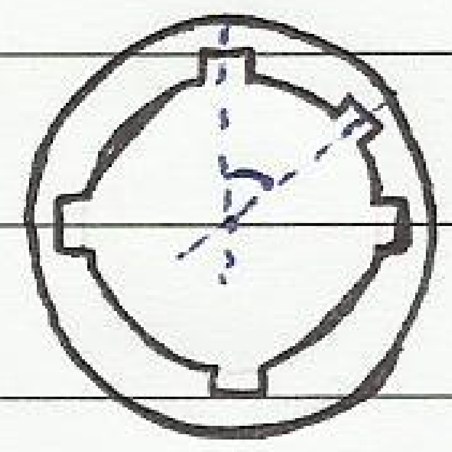
$$\boxed{\theta_e = \frac{P}{2}\,\theta_m}$$

* Regardless the number of poles, the pole pitch P_p is always (180°) electrical degree.

⇒ If the stator coil extends (span/occupy) across the same angle as the pole pitch it's called a " Full-pitch coil ".



⇒ If the stator coil extends across the angle smaller than a pole pitch it's called a " Fractional - pitch coil " and this is one way to eliminate the 5th and 7th harmonics.



* The pitch of the coil "ρ" is often expressed as a fraction, i.e : $\frac{5}{6}$ or $\frac{7}{8}$ of the pole pitch.

$$\boxed{\rho = \frac{\theta_m}{P_p} * 180^\circ} \text{ .... coil pitch}$$

where, ρ : coil pitch

θ_m : mechanical angle covered by the coil in degree.

P_p : machine pole pitch = $\frac{360^\circ}{P}$

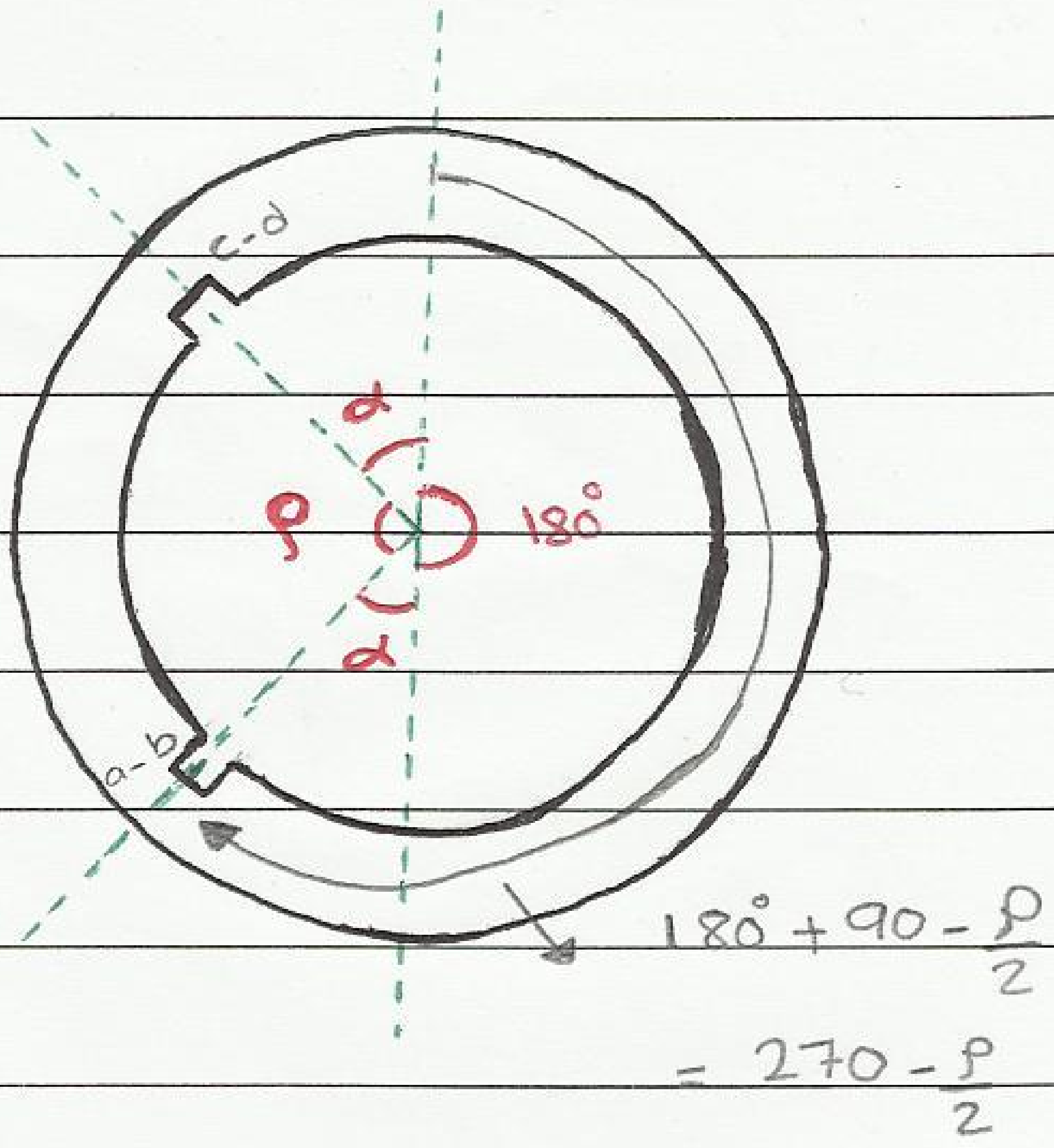
$$\rho = \frac{\theta_m P}{360^\circ} * 180^\circ = \frac{P}{2} \theta_m$$

* Windings employing fractional pitch coil are known as " chorded winding "

* The induced voltage of a fractional - pitch coil :-

$$\rho + \alpha + \alpha = 180^\circ$$

$$\rho + 2\alpha = 180^\circ$$



$$2\alpha = 180 - \rho$$

$$\boxed{\alpha = 90 - \frac{\rho}{2}}$$

$B = B_M \cos\alpha$ magnitude of flux density.

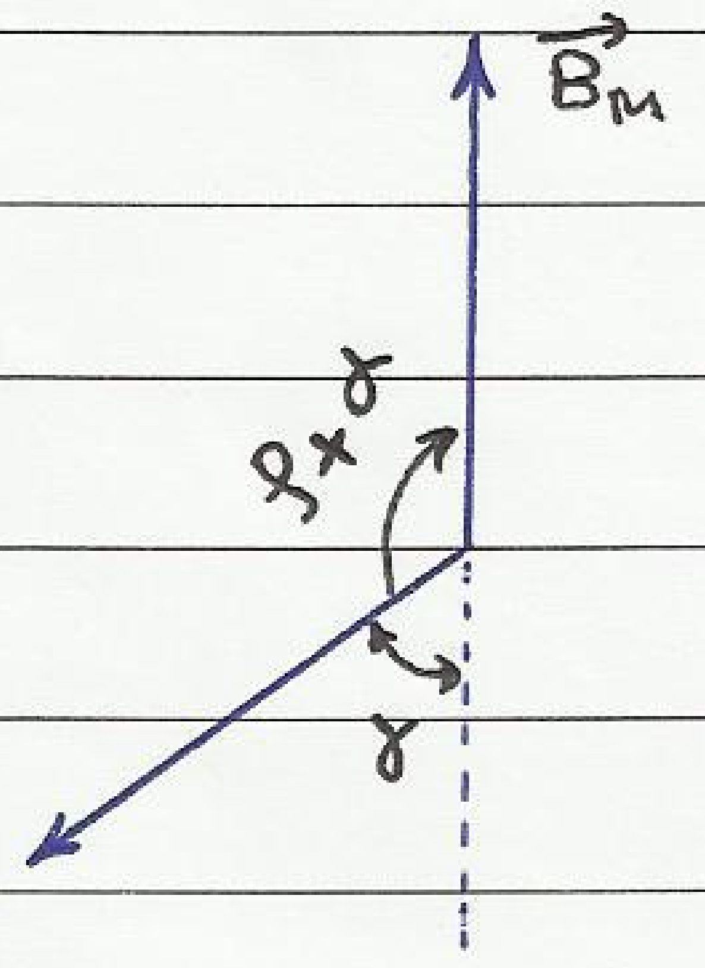
$$B = B_M \cos(\omega_m t - \alpha)$$

① Segment ab :-

$$e_{ind} = (\vec{U} \times \vec{B}) \cdot \vec{I}$$

$$= UBl$$

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



$$= VB_M \cos\left[\omega t - \left(90 - \frac{\rho}{2}\right)\right] l$$

$$e_{ind} = VB_M \cos\left(\omega t - 90 + \frac{\rho}{2}\right) l$$

② Segment bc :-

$e_{ind} = 0$, $(\vec{U} \times \vec{B}) \perp \vec{I}$

③ Segment cd :-

$$e_{ind} = VB_m \cos(\omega t - 90 + \frac{\rho}{2}) L$$

④ segment da :-

$$e_{ind} = 0$$

$$e_{tot.} = 2VB_M L \cos(\omega t - 90 + \frac{\rho}{2})$$

$$e_{tot} = 2VB_M l \cos \omega t \sin \frac{\rho}{2}$$

$\boxed{E_{rms} = e_{rms} = e_{tot} = 4.44 \phi N f K_p}$ .... In general (for p-pole machines).

where $K_p = \sin \frac{\rho}{2}$

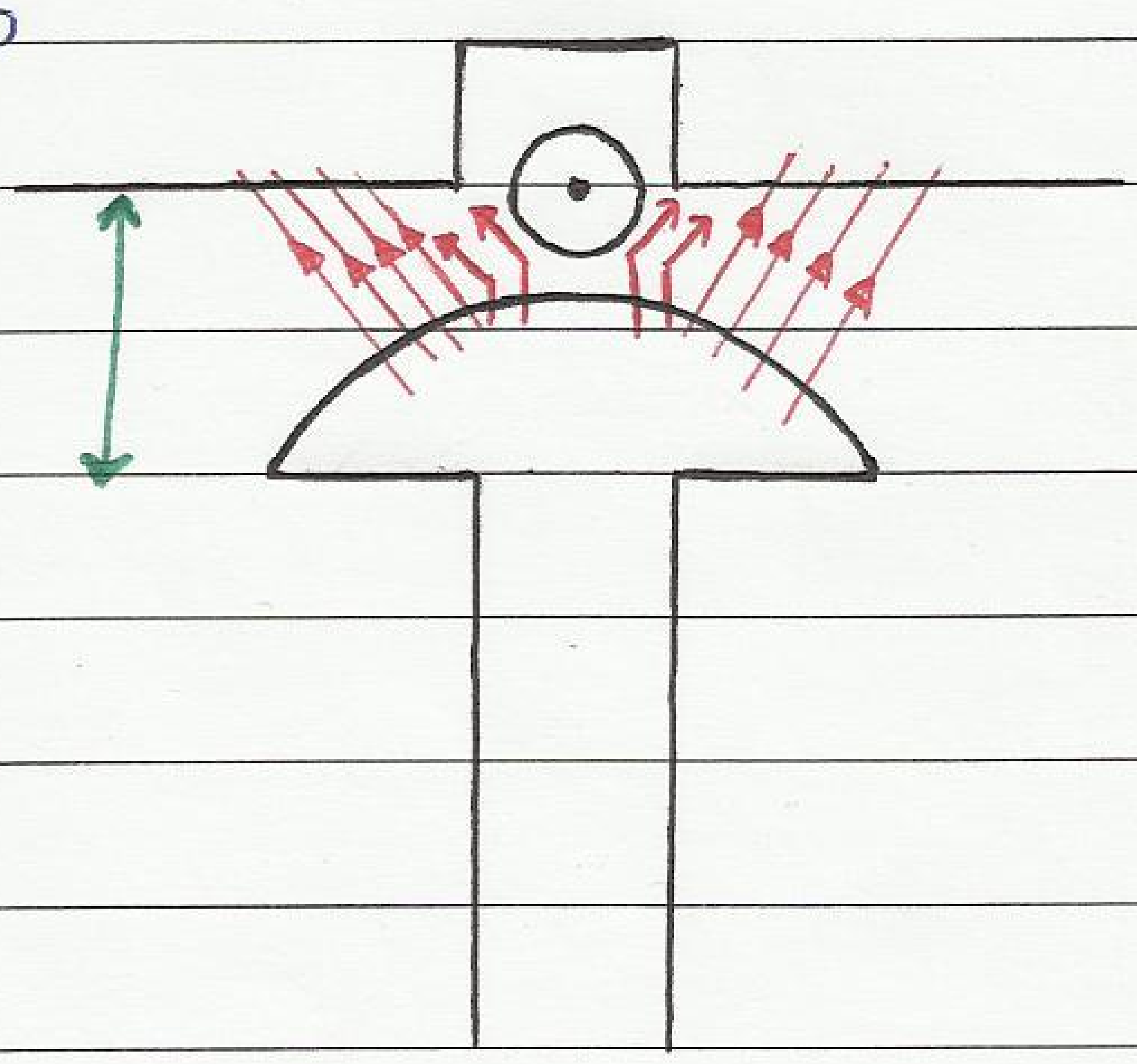
$\downarrow$

pitch factor for any pole number

"winding pitch factor, coil pitch factor"

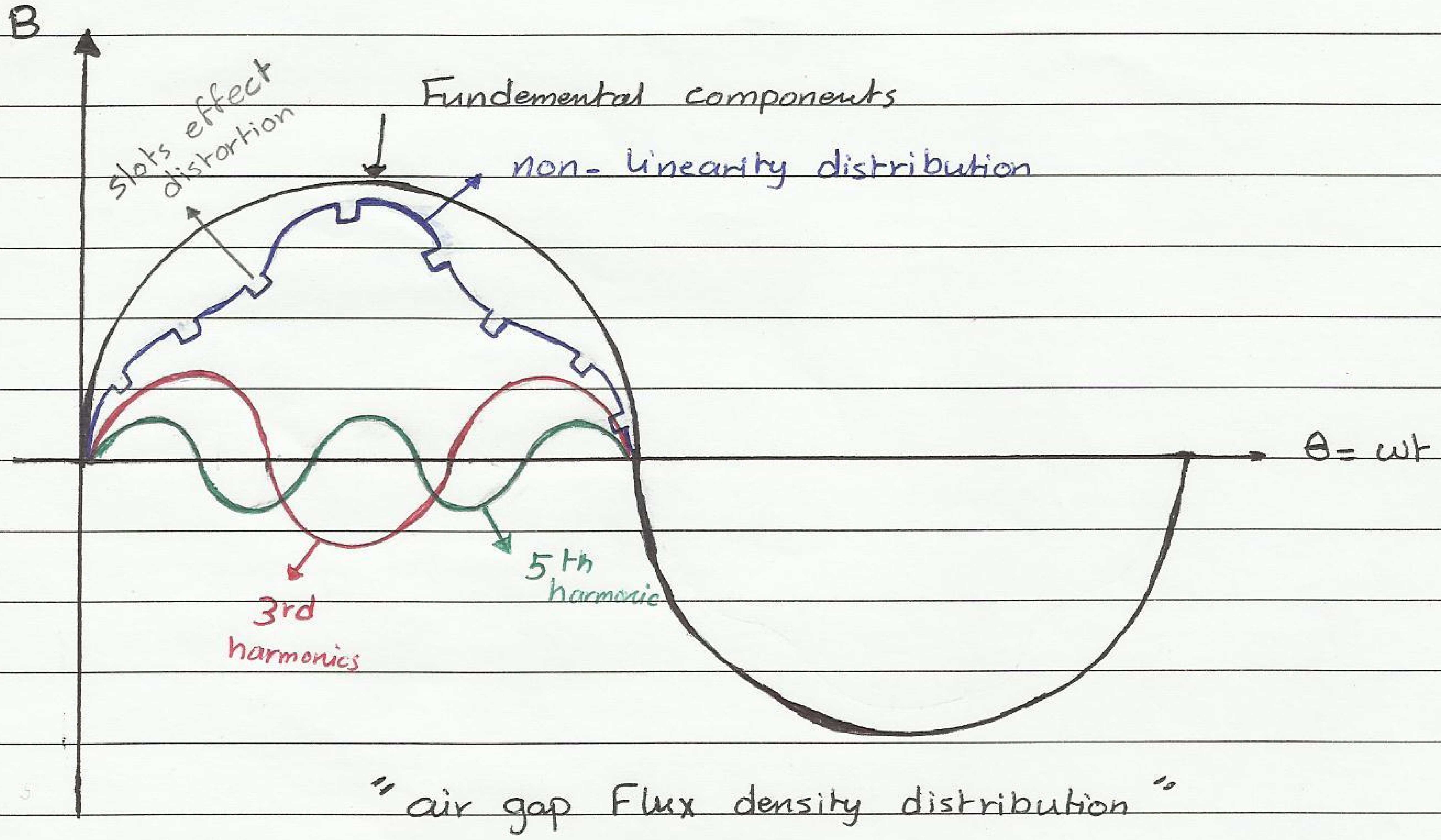
* Harmonics problem and fractional-pitch windings :-

* In salient pole machines the air gap flux density distribution is not pure sinusoidal due to the non-linearity of B/H curve & slots of the stator winding.



Salient pole

⇒ the air gap Flux density distribution in salient pole machine Look like this :-



" air gap Flux density distribution "

* Only odd harmonics exists in the waveform of the induced voltage i.e (3rd, 5th, 7th, ...), the 3rd harmonics and it's even multiples are removed and odd multiple is exist, in both case in Y and Δ connected stator, as the number of harmonic increase, its magnitud decreases, and therefore only the 5th and 7th components are of prime concerve will should be reduced, the 5th and 7th components are exists but have very small magnitude, 3rd and odd multiple disappear in the Δ connection and solidly grounded Y- connection windings.

$$\boxed{K_p = \sin \frac{\overset{\text{nu}}{\gamma}\rho}{2}}$$

where K_p :- pitch Factor of the coil at the harmonic Frequency.

ρ :- electrical angle of the coil pitch.

γ :- index of the harmonic frequency (number of the harmonic being examined).

Ex1 : 3-φ , p=2 , Pole pitch = 5/6 , what are the coil pitch Factors of the harmonics presented in this machine coil? Does this pitch help suppress the harmonic content of the generated voltage ??

Sol. $\rho_p = \frac{360°}{P} = \frac{360°}{2} = 180°$ electrical and mechanical

$\rho = \frac{5}{6} * 180° = 150°$ mechanical

$\rho = \theta_e = \frac{P}{2}\theta_m = \frac{2}{2} * 150° = 150°$ electrical

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

$k_p = \sin\frac{(1)(150)}{2} = 0.966$

$k_p = \sin\frac{(3)(150)}{2} = -0.703$ doesn't appear (doesn't exist).

$k_p = \sin\frac{(5)(150)}{2} = 0.259$

$k_p = \sin\frac{(7)(150)}{2} = 0.259$

$k_p = \sin\frac{(9)(150)}{2} = -0.707$ doesn't appear.

* Conclusion :-

- Fractional pitch windings strongly reduce the harmonic of the machine output voltage while causing only a small decrease in it's Fundamental voltage.

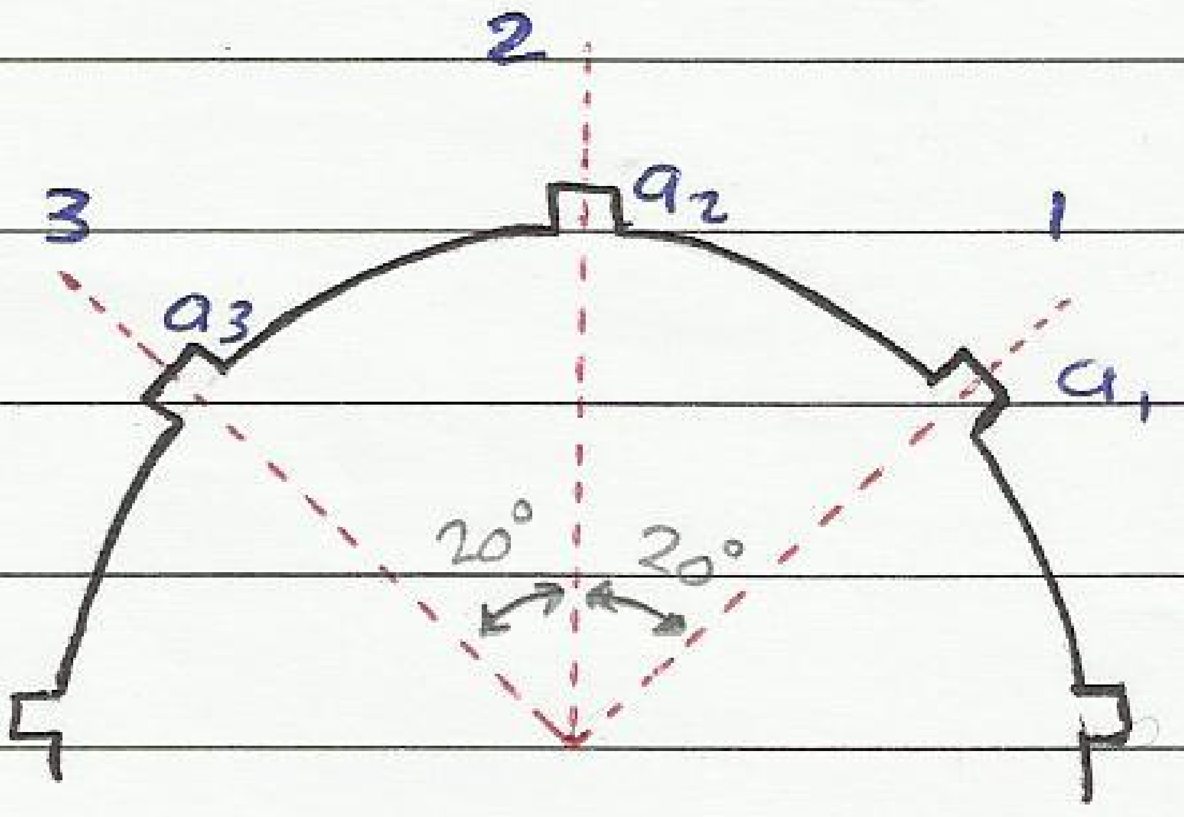
"reduce the harmonic contain in 5th and 7th component reduce the voltage of the Fundamental components"

B.2 :- Distribution windings and distribution Factor :-

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

$\bar{E}_{a_2} = E \angle 0^\circ$

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



$$E_{tot.} = \bar{E}_{a_1} + \bar{E}_{a_2} + \bar{E}_{a_3} = E\angle -20 + E\angle 0 + E\angle 20$$
$$= 2.879\,E$$

⇒ If the windings are not distributed $E_{tot} = 3E$.

$$K_d = \frac{U_\phi \text{ actual}}{U_\phi \text{ expected with no distribution}} = \frac{2.879}{3}$$

winding distribution Factor

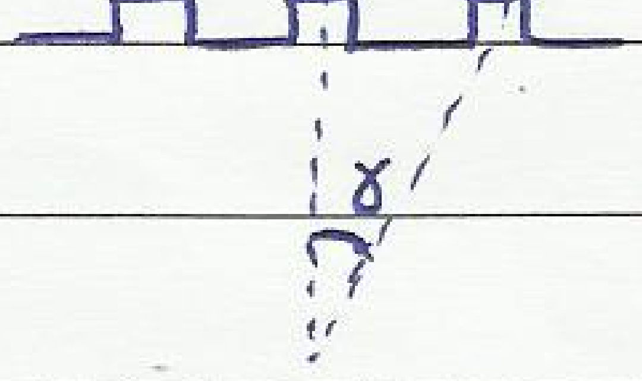
* another method $K_d = \frac{\sin(n\overset{\text{mechanical}}{\gamma}/2)}{n \sin(\gamma/2)}$

where, n :- number of slots / pole / phase.

γ :- "Slot pitch", angle between every two successive slots

داعًا تعتبر mechanical angle ال

Manual sol. بيكو غلط بيعتبرها electrical



$\Rightarrow \frac{360^\circ}{\text{no. of slot}}$

* as the number of slots inc↑, K_d approaches to (1).

* Example to find $\underline{n}$ [illegible] :-

if ~~[illegible]~~ no. of slots = 18 and 3-ϕ, $P = 2$

$n = 18/2/3 = \underline{\underline{3}}$

$$\gamma = \frac{360}{18} = 20^\circ$$

* The pitch Factor (k_p) and distribution Factor (k_d) are combined in two a single winding Factor.

$$\boxed{k_w = k_p * k_d}$$

$$E_A = E_{rms} = 4.44\, N \phi f k_w$$
$$= 4.44\, N \phi f k_p k_d$$

Ex: 3-ø, 2 poles, 18 slots Find k_d ?

$$k_d = \frac{\sin(n\gamma/2)}{n \sin(\gamma/2)}$$

$n = 18/2/3 = 3$

$\gamma = \frac{360}{18} = 20°$

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

Ex2:- a synchronouns machine $p=2$, 3-ø, Y-connected stator double layer 4 coils/phase, 10 turn/coil, The winding has a pitch of 150° electrical, $n = 3000$ rpm, $\phi = 0.019$ wb/pole.

a) Find the slot pitch in elect. and mechanical degrees?

$4 \frac{\text{coil}}{\text{Phase}} \Rightarrow 3 * 4 = 12$ slots

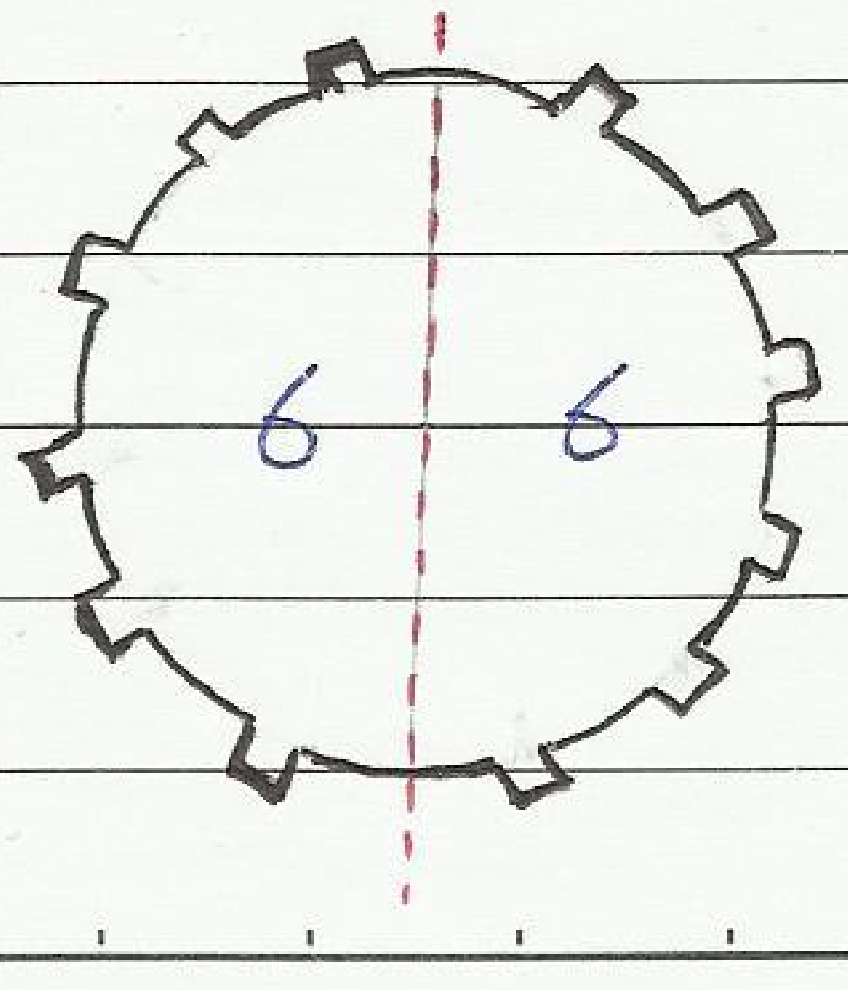
$\gamma = \frac{360}{12} = 30°$ electrical and mechanical ($P=2$)

b) How many slots do the coils span (extend) ??

$180° \rightarrow 6$ slots

$150° \rightarrow X$

$X = \frac{150}{180} * 6 = 5$ slots



Coil pitch $= \frac{5}{6}$

c) what is the magnitude of the phase voltage of one phase of this machine?

$E_A = 4.44\, \phi f N_p k_w$

$= 4.44\, \phi f N k_d k_p$

$f = \frac{nP}{120} = \frac{3000 * 2}{120} = 50\ Hz$

$\phi = 0.019$ wb/pole

$N_p = 4\ \frac{\text{coil}}{\text{phase}} * 10\ \frac{\text{turn}}{\text{Coil}} = 40$ turns/phase

$k_p = \sin\frac{\gamma P}{2} = \sin\frac{(1)(150)}{2} = 0.966$

$k_d = \frac{\sin(n\gamma/2)}{n \sin(\gamma/2)}$ $n = 12/2/3 = 2$

$\gamma = 30°$

$k_d = 0.966$

ملاحظة مهمة :-

إذا ذكر في السؤال أنه التصميم تبع الماشين
على أساس (Double-layer) بيكون عنا التالي :-
no. of slots = no. of coil
وبعدين بنقسم على ٣ عشان اطلع عدد الـ coil في الـ
phase الواحدة ، اما إذا ذكر السؤال أنه
single-layer ، فبنقسم عدد الـ slots على ٢
وإذا ذكر أنه 4-layer بنضرب بـ ٢ وهكذا

$E_A = (4.44)(0.019)(50)(40)(0.966)(0.966) = 157V$

d) V_T?

$V_T = \sqrt{3}\, E_A = \sqrt{3}\,(157) = 272\ V$

e) what is the fifth harmonic and seventh harmonic component suppresion factor done by the fractional pitch winding arrangment?

$k_p = \sin\frac{(5)(150)}{2} = 0.259$

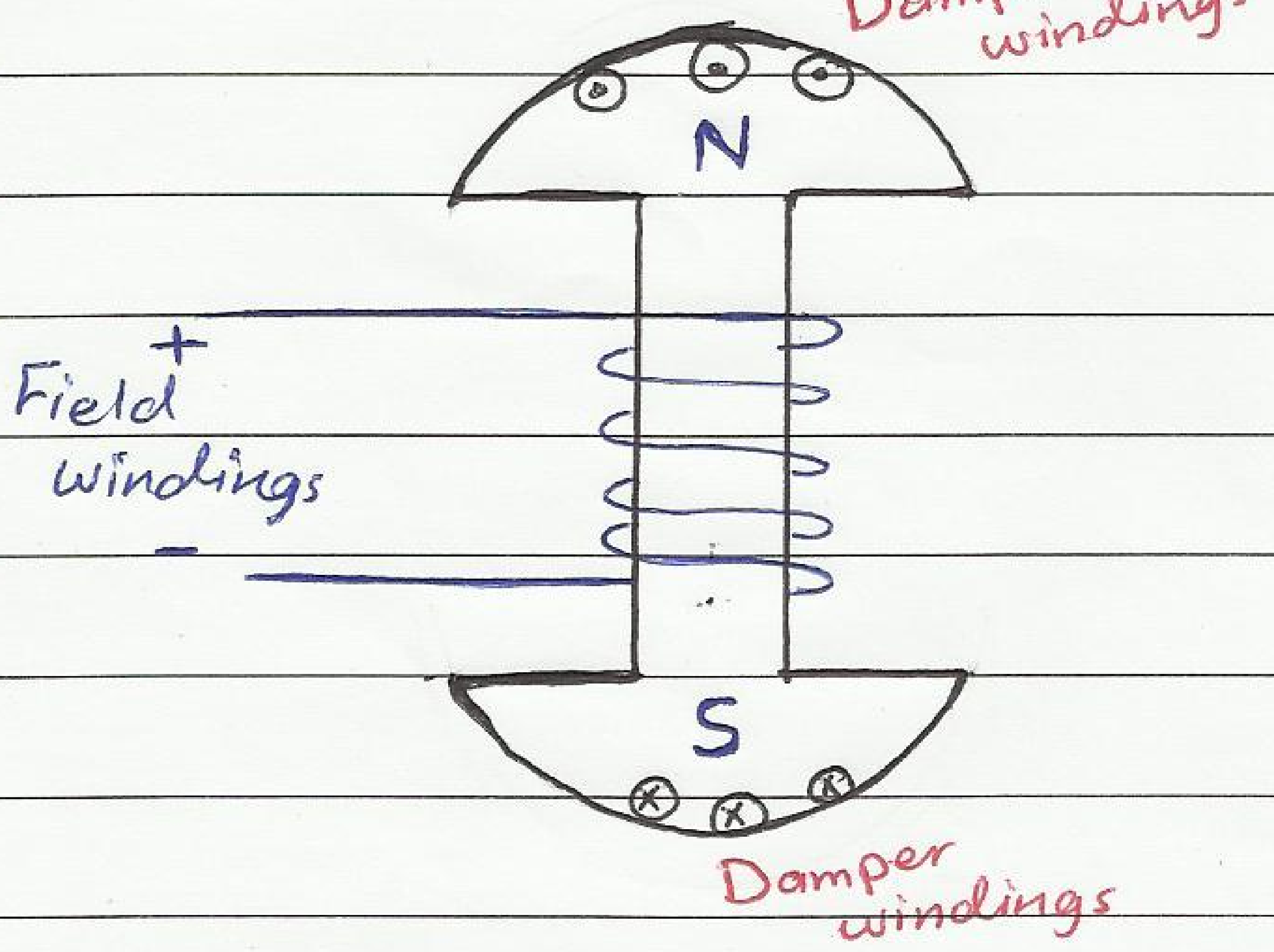
$k_p = \sin\frac{(7)(150)}{2} = 0.259$

all problem are very important (1-8)

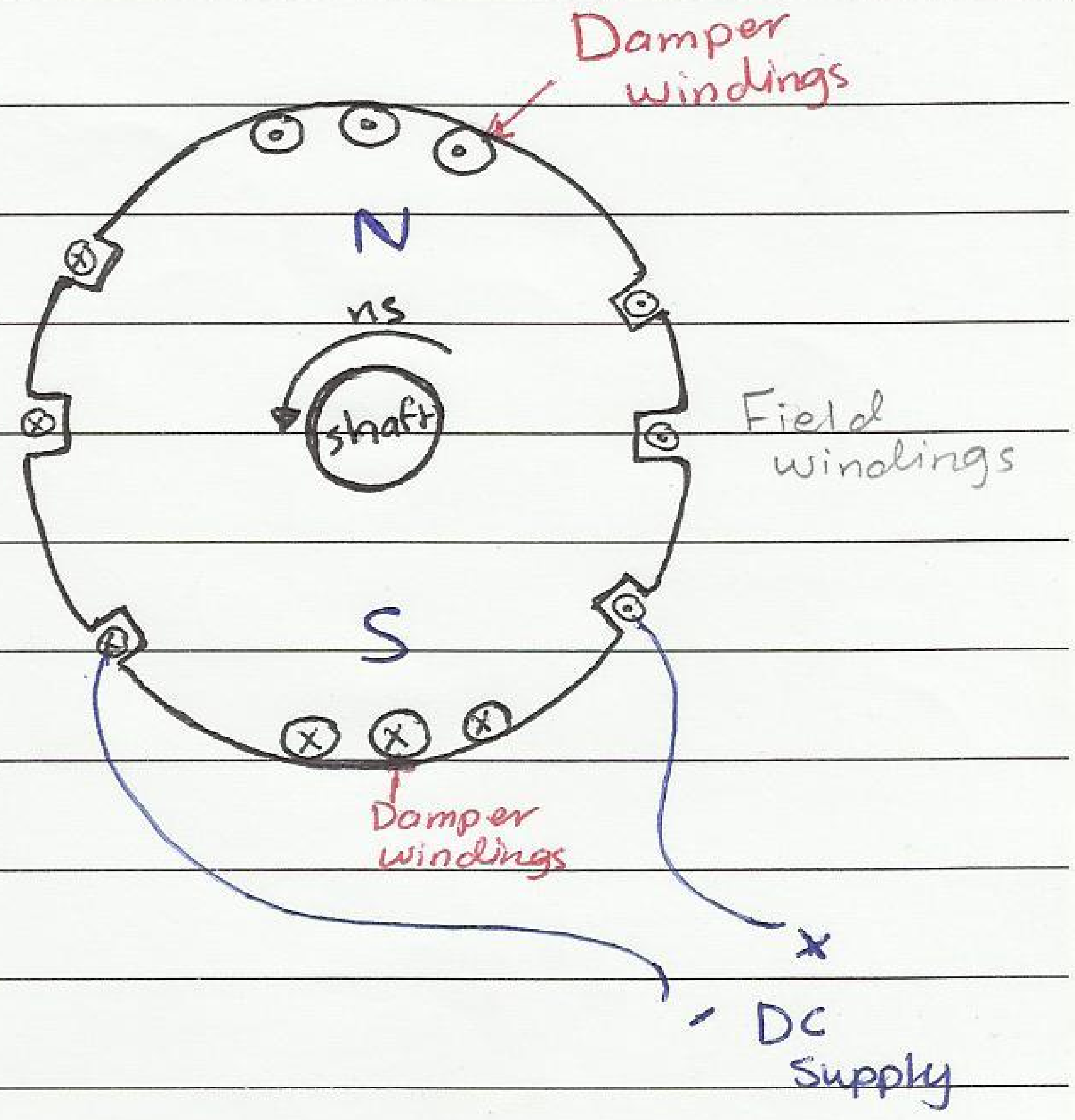
CHAPTER
5

SYNCHRONOUS GENERATORS

* Synchronouns Generator :-



"Salient pole type"

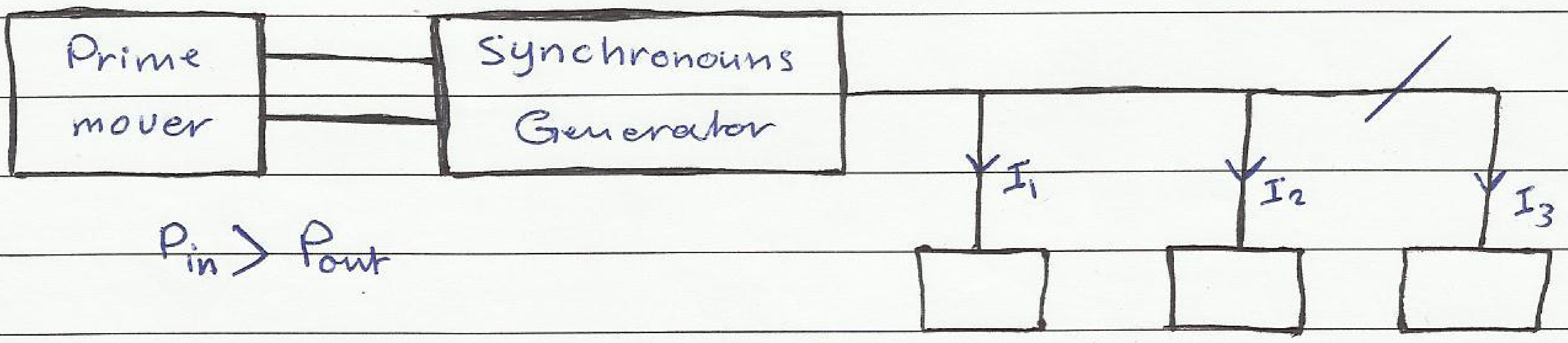


"cylindrical rotor type"

* damper winding :- are windings placed in slots curved ~~at~~ the ~~rotor~~ pole face of the rotor of synchronouns generator, they are short circuited from both ends, they are used to damp oscillation in case of transients, In steady state the induced voltage and current inside them are Zero. So, why we use damper winding?

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

② It's also used to start synchronouns Motor.

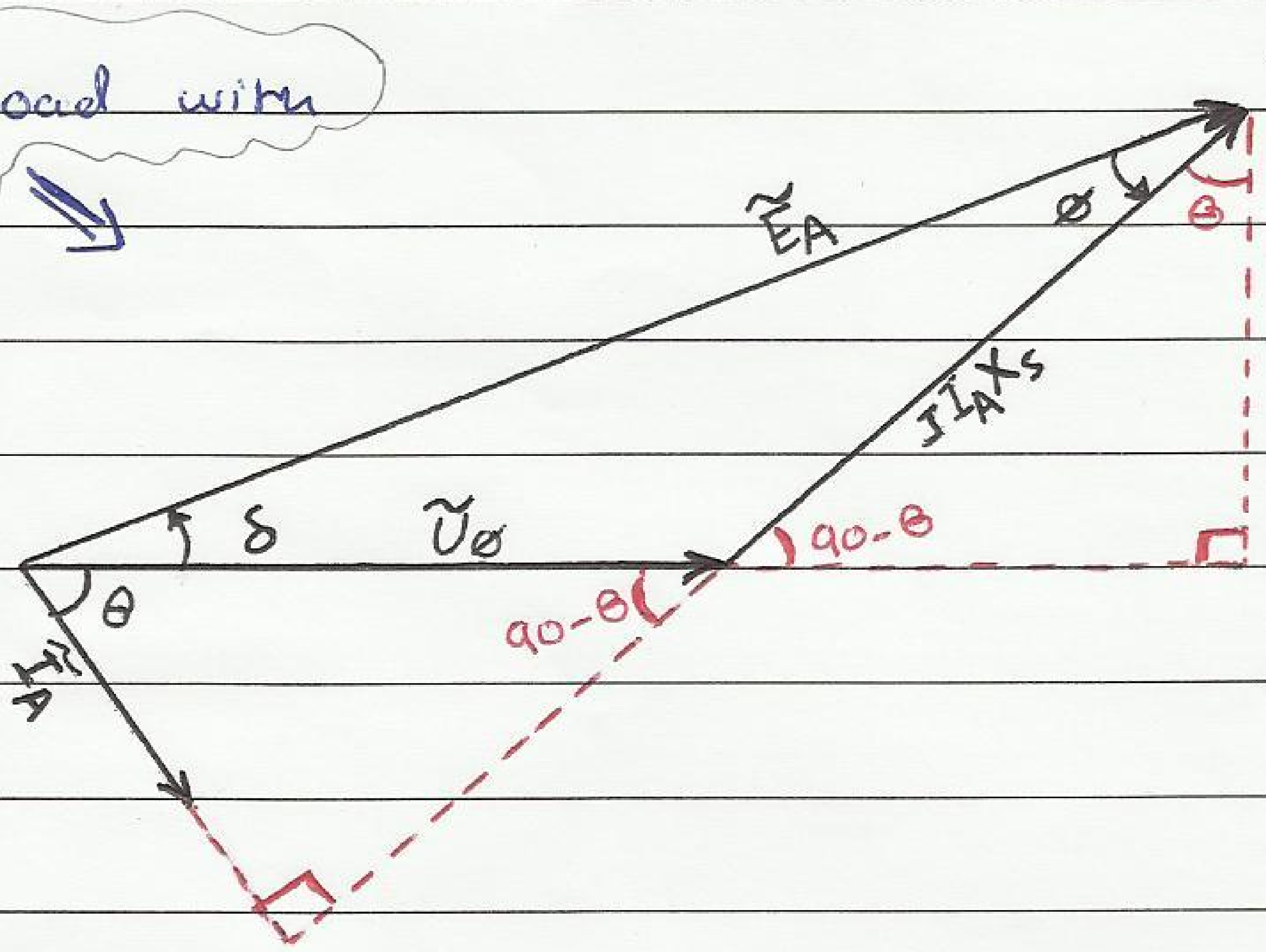


$P_{in} > P_{out}$

"Stability Problem"

* power and Torque in synchronouns Generator :-

inductive load with neglected R_A ⇘



$$E_A \sin\delta = I_A X_s \sin(90-\theta)$$

$$E_A \sin\delta = I_A X_s \cos\theta$$

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

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

$$\boxed{P_{out} = \frac{3 V_\phi E_A \sin\delta}{X_s}}$$ ...... power angle equation

if $\delta = 0 \Rightarrow P_{out} = 0$ ⇒ There is no-load.

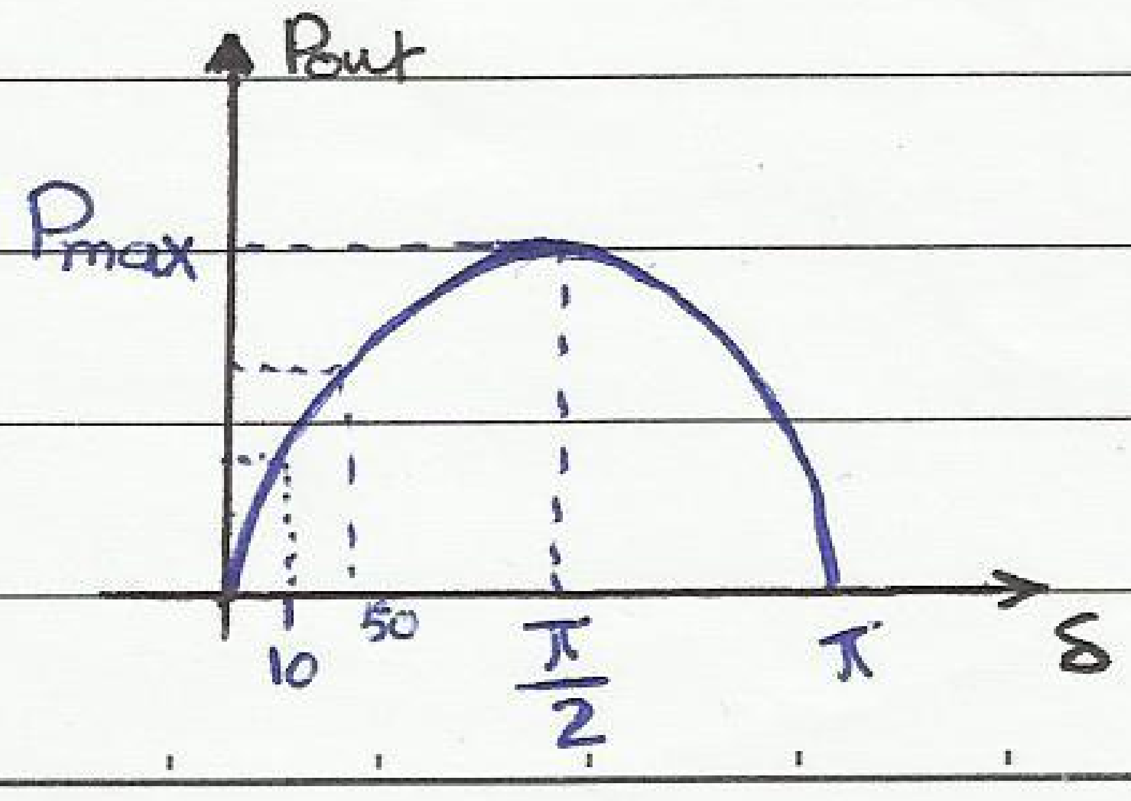
if $\delta = 90° \Rightarrow P_{out} = P_{max} = \frac{3 V_\phi E_A}{X_s}$

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

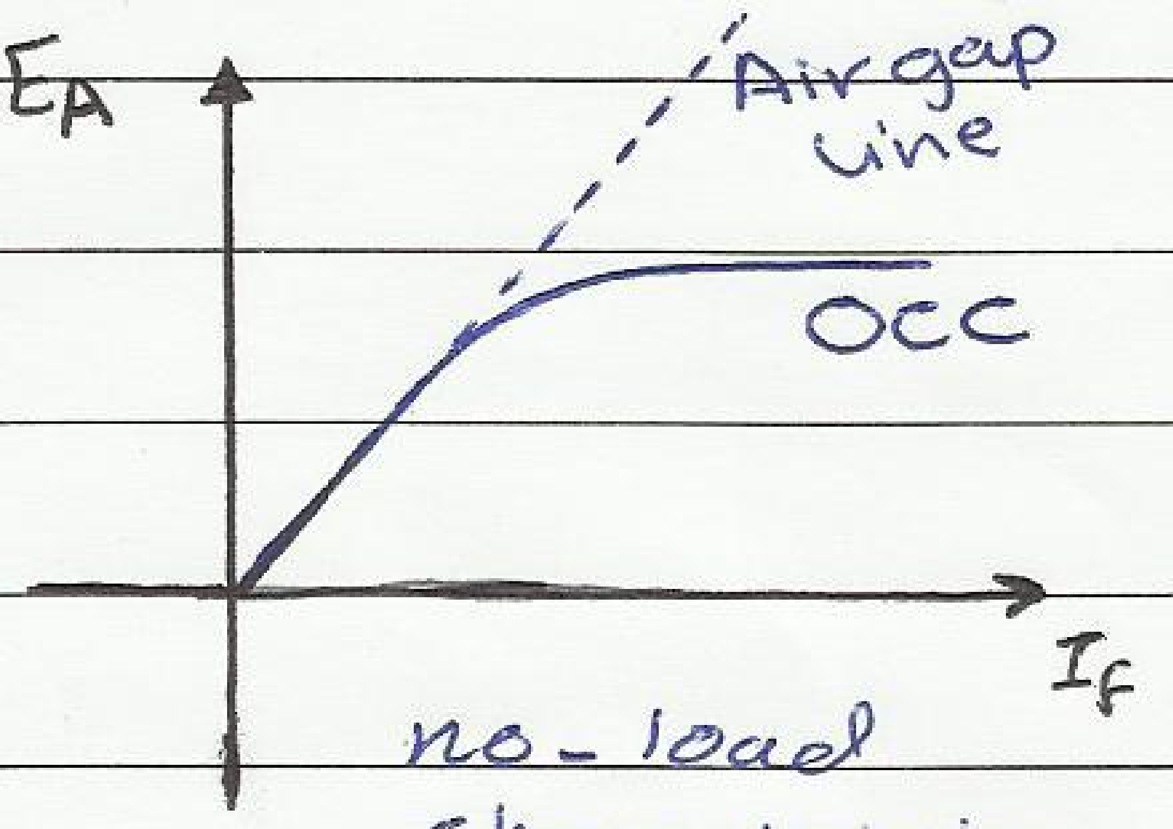
$P_{max} = \frac{3 V_\phi E_A}{X_s}$ ⇒ static stability limit (very important in power system stability analysis)

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

⇒ typical value for $\delta = 10° \rightarrow 30°$ at Full-load (real machines)

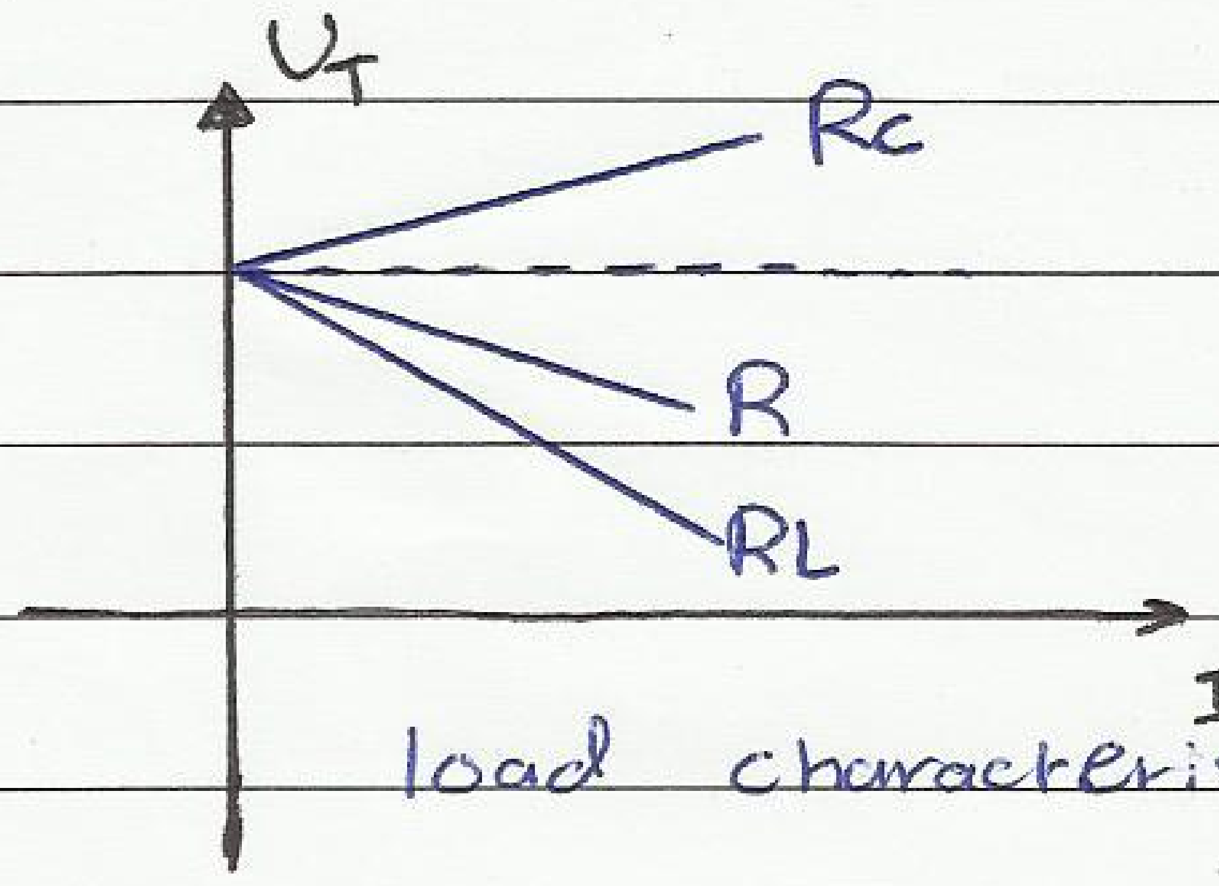


* No-load & load characteristics of Synchronouns Generator :-



no-load characteristics

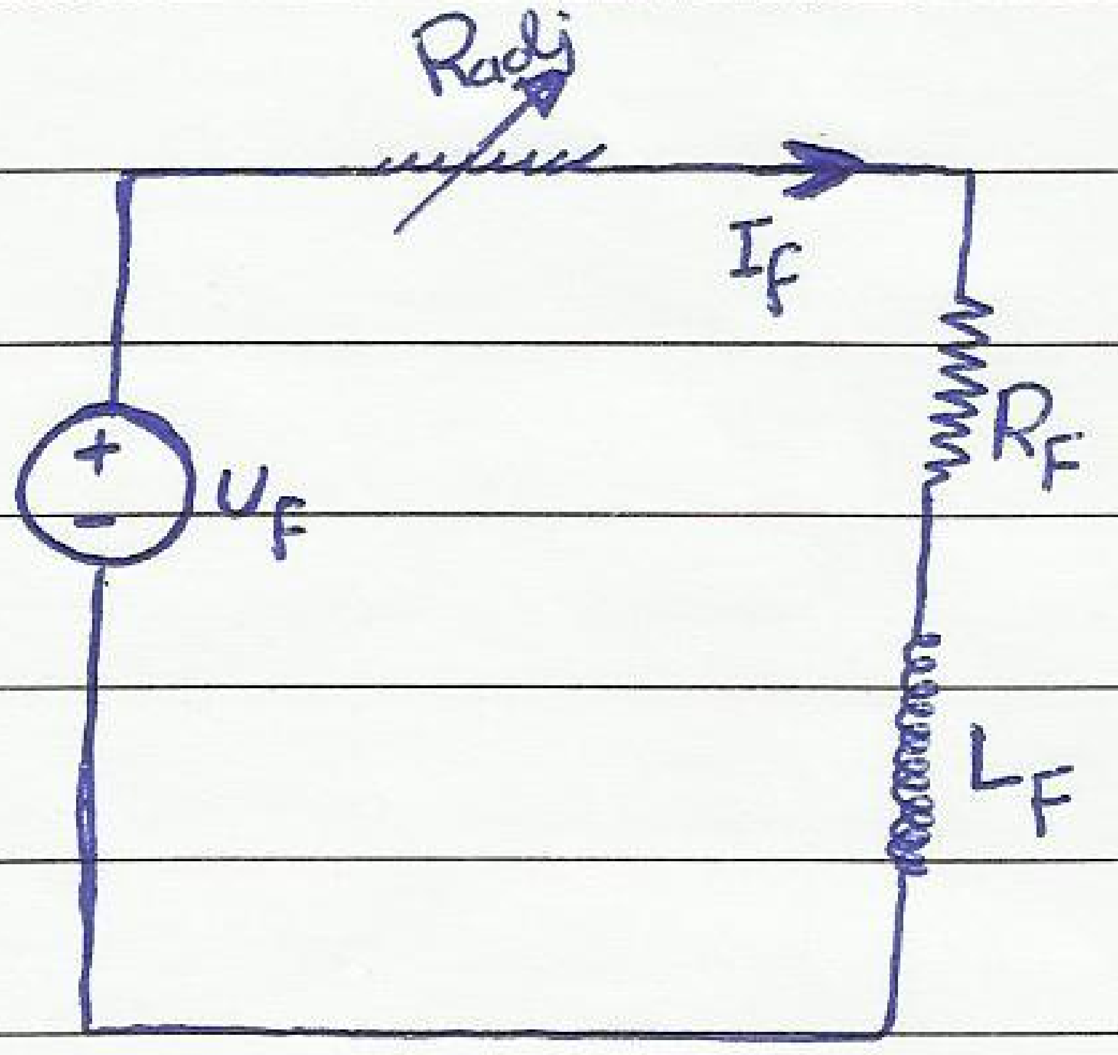
Table
curve
equation

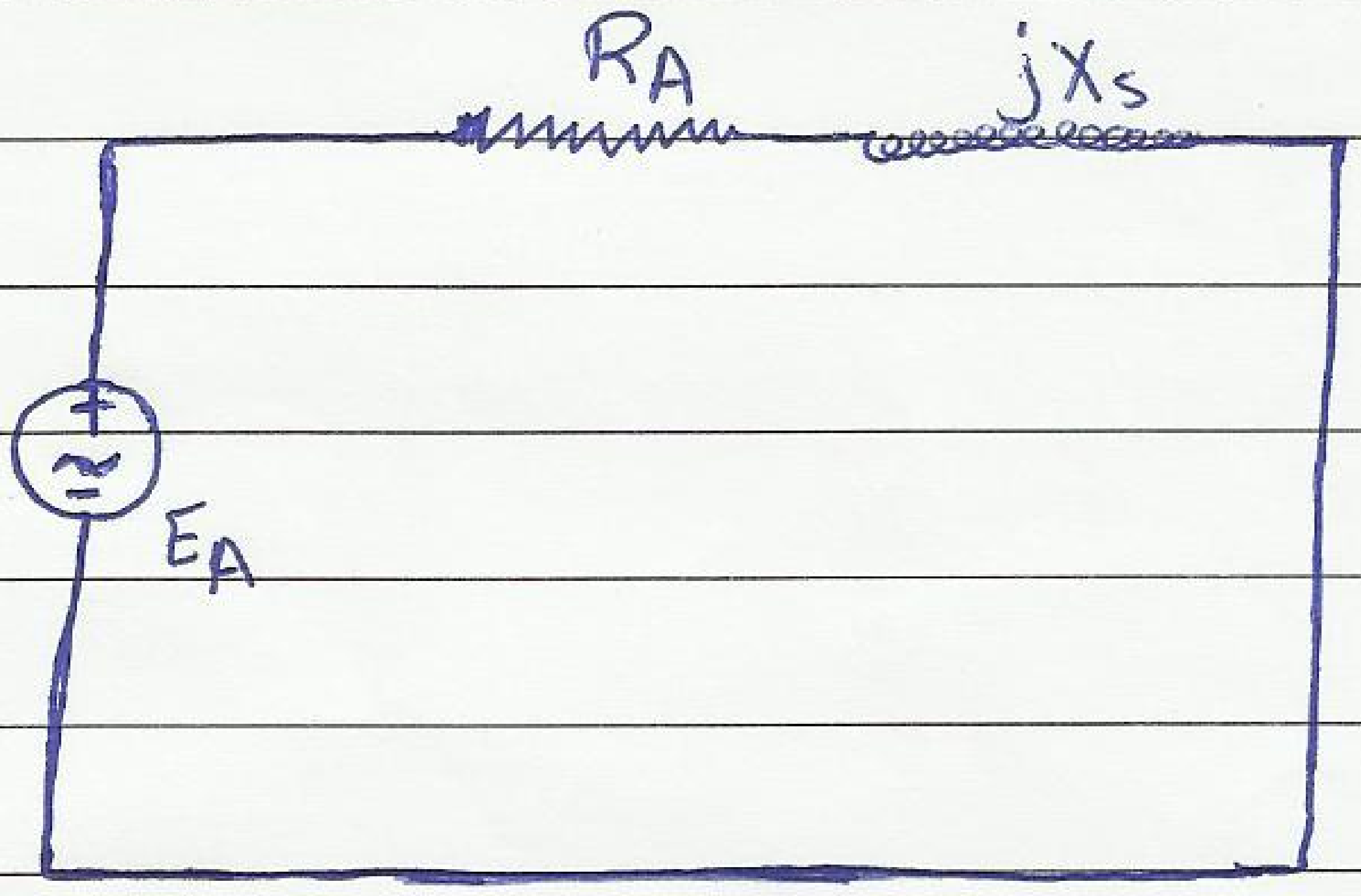


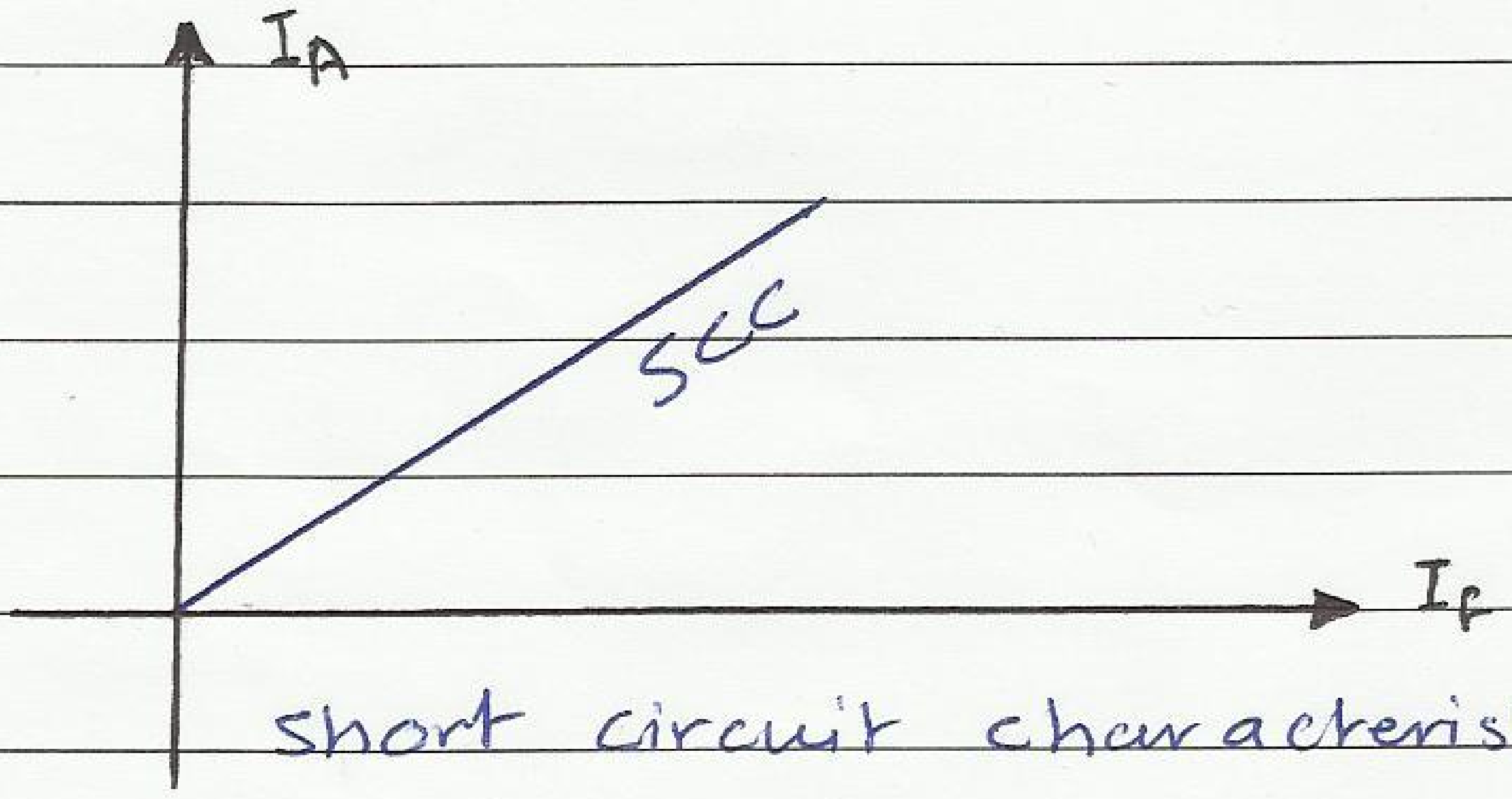
load characteristics

$$UR\% = \frac{E_A - V_T}{V_T} \times 100\%$$

* short circuit Test :-



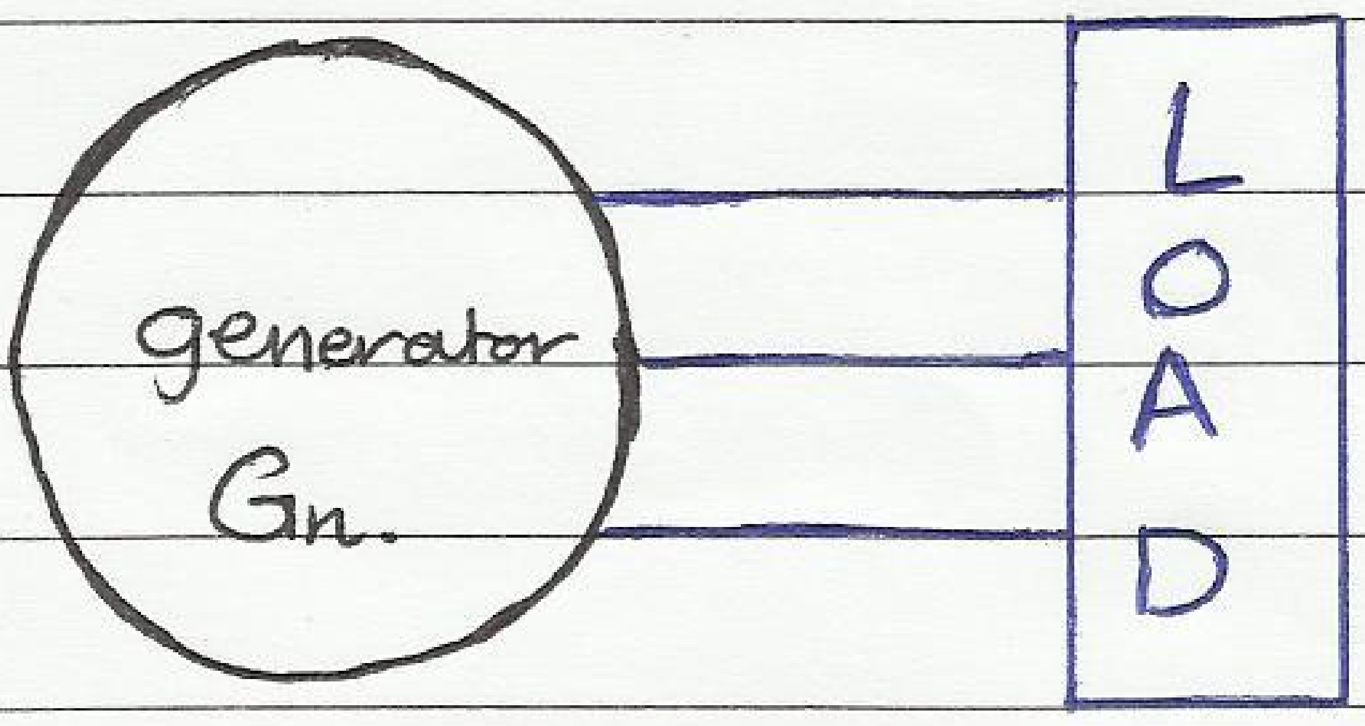




short circuit characteristic

* 5.8 :- The synchronouns Generator operating alone :-

↳ seperated from the network (grid) ~~and~~ (Farm, pumping system, ...)



(1) with lagging power factor load :-

* assumption :-

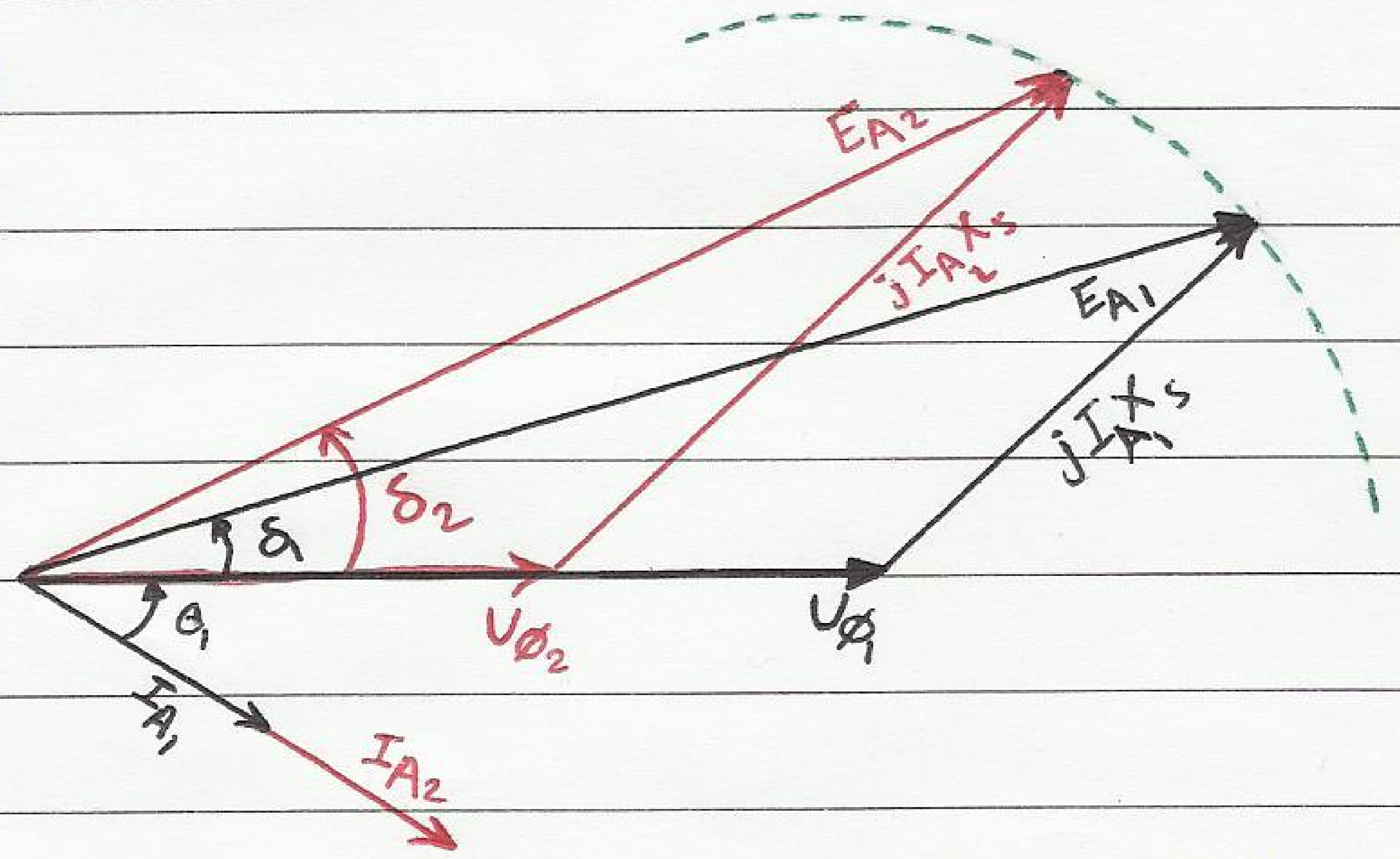
- no changes on $|\bar{E}_A|$ (constant $|\bar{E}_A|$) ⇒ Fixed i_f.
- no changes on p.f of the load ⇒ fixed θ.
- no changes on the rotational speed (constant ω) ⇒ fixed f.

* As the power (active, reactive) demand increases, I_A increases.

$|E_{A_1}| = |\bar{E}_{A_2}|$

$UR > 0$

lagging P.F



* based on assumptions if the power demand (P_{out}) is increases, then, $I_A \uparrow$, $\delta \uparrow$, $V_\phi \downarrow$, $V_{\phi_2} < V_{\phi_1}$, $\delta_2 > \delta_1$

⇒ As the load increases, the demand for P_{out} and/or Q_{out} increases.

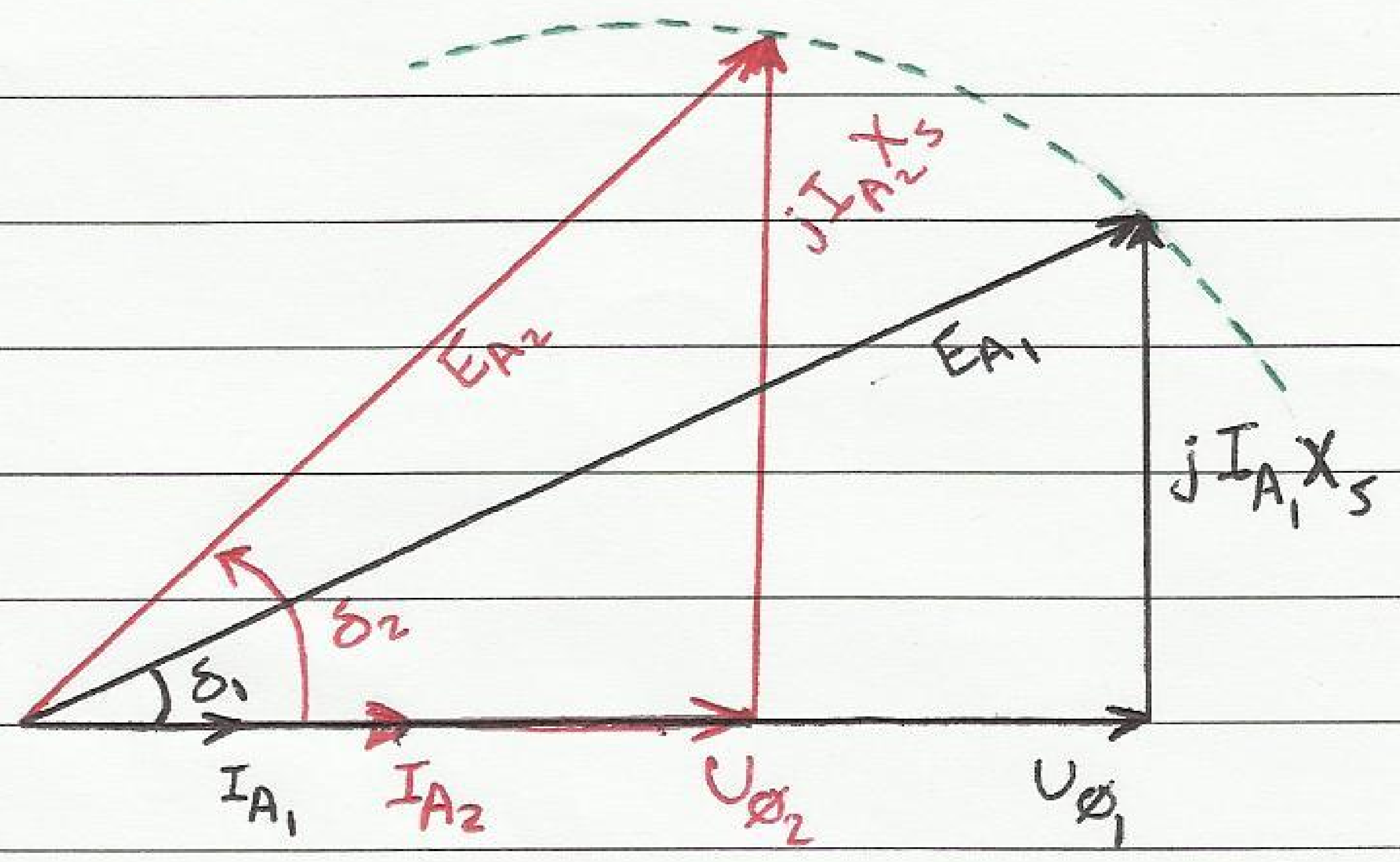
(2) unity power factor :-

$|\tilde{E}_A|$ constant

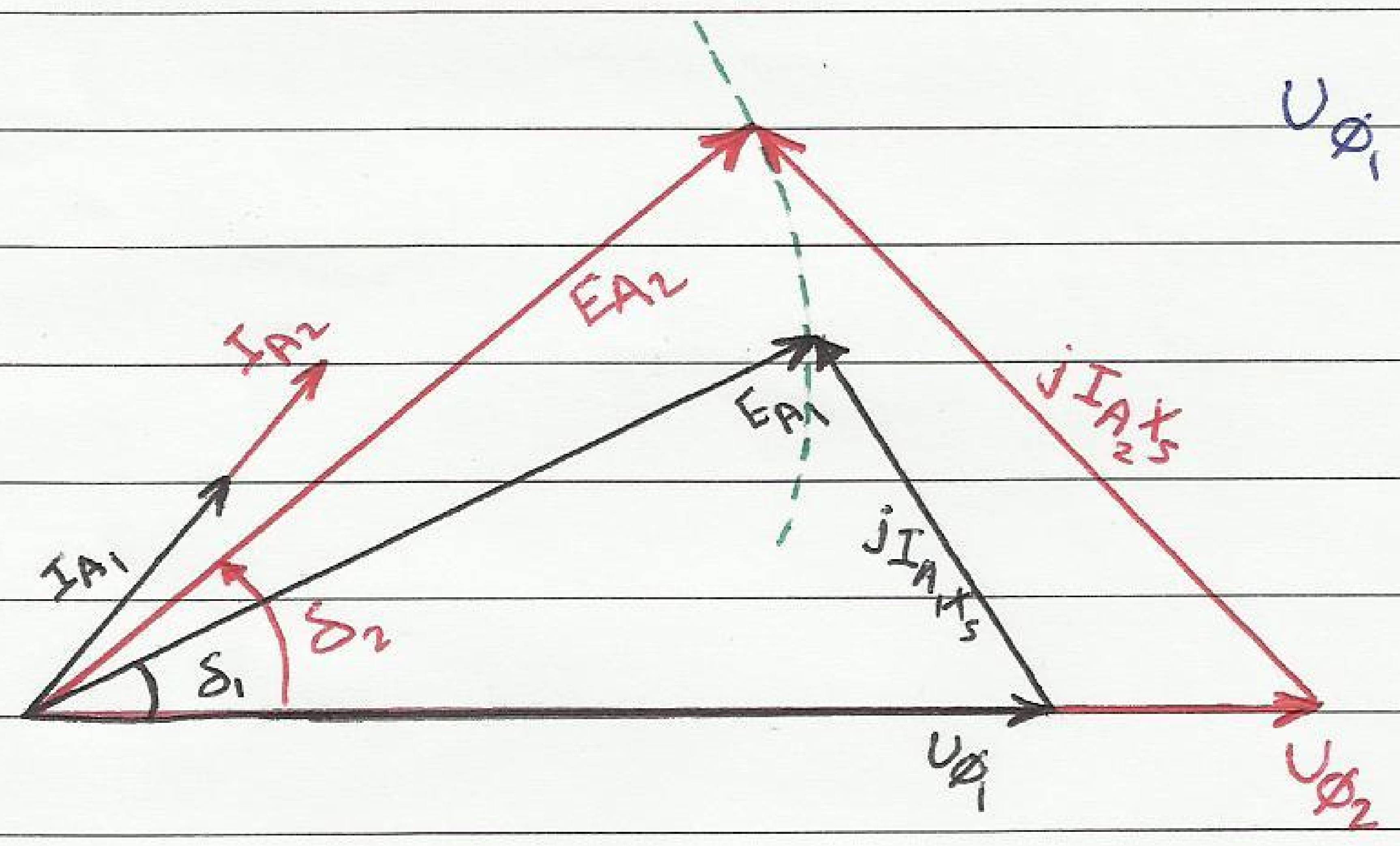
$VR > 0$

$V_{\phi_2} < V_{\phi_1}$

$\delta_2 > \delta_1$



(3) Leading power Factor :-



$V_{\phi_1} < V_{\phi_2}$

$\theta_1 = \theta_2$

$\delta_2 > \delta_1$

$VR < 0$

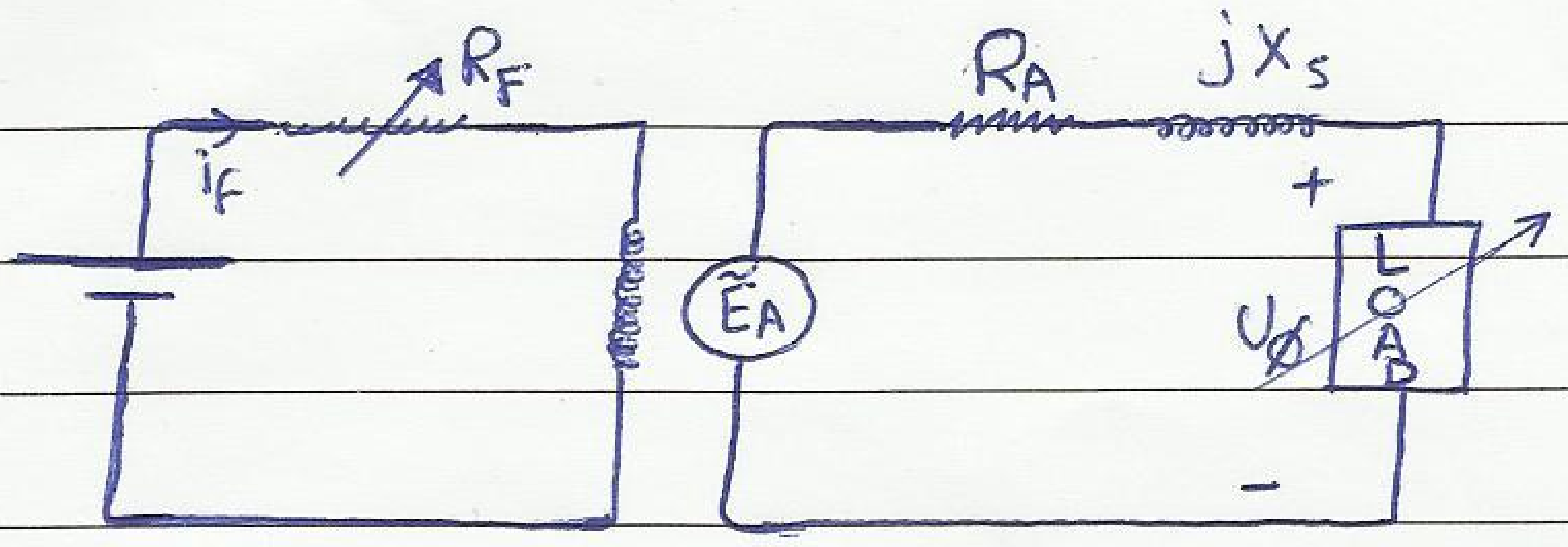
$|\tilde{E}_{A_1}| = |\tilde{E}_{A_2}|$

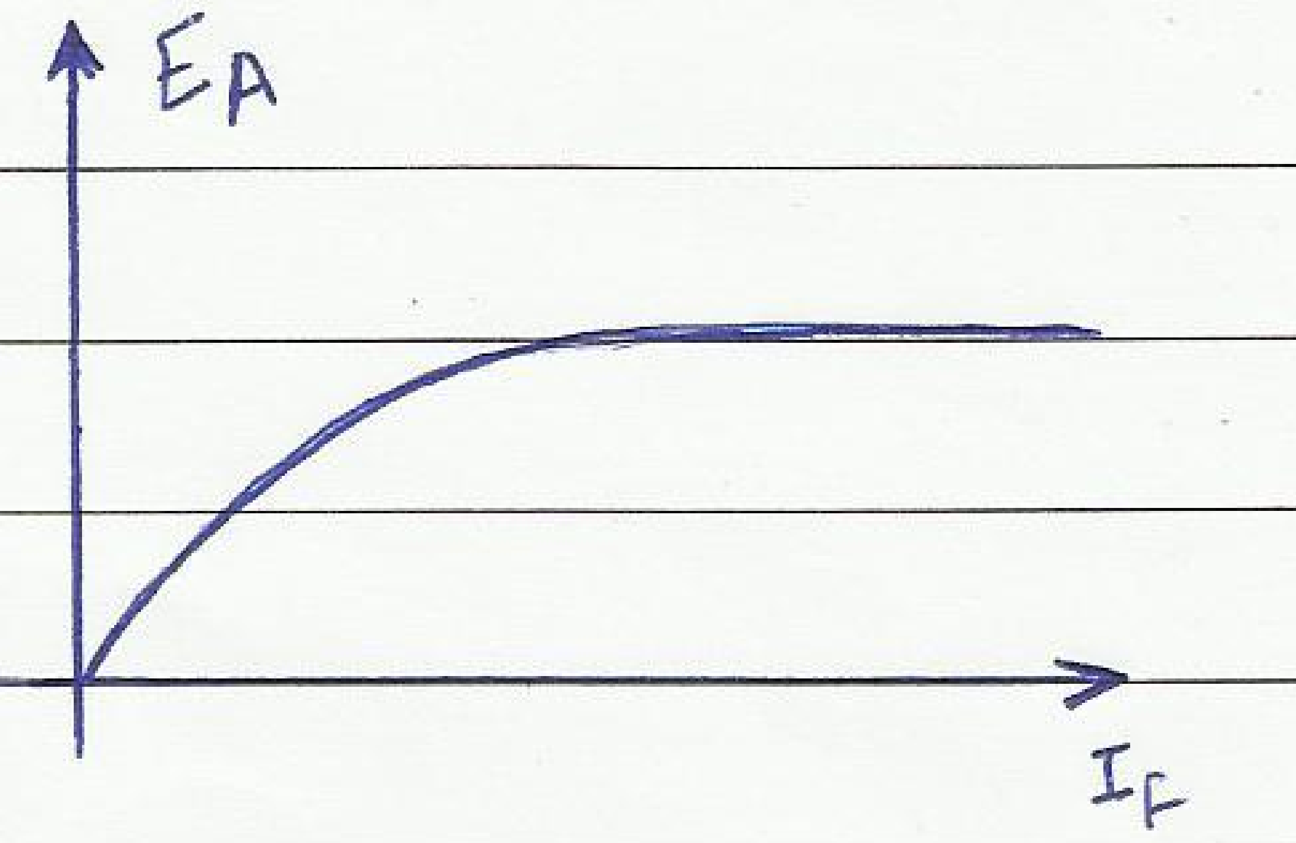
* How to keep constant (3-ϕ) voltage?

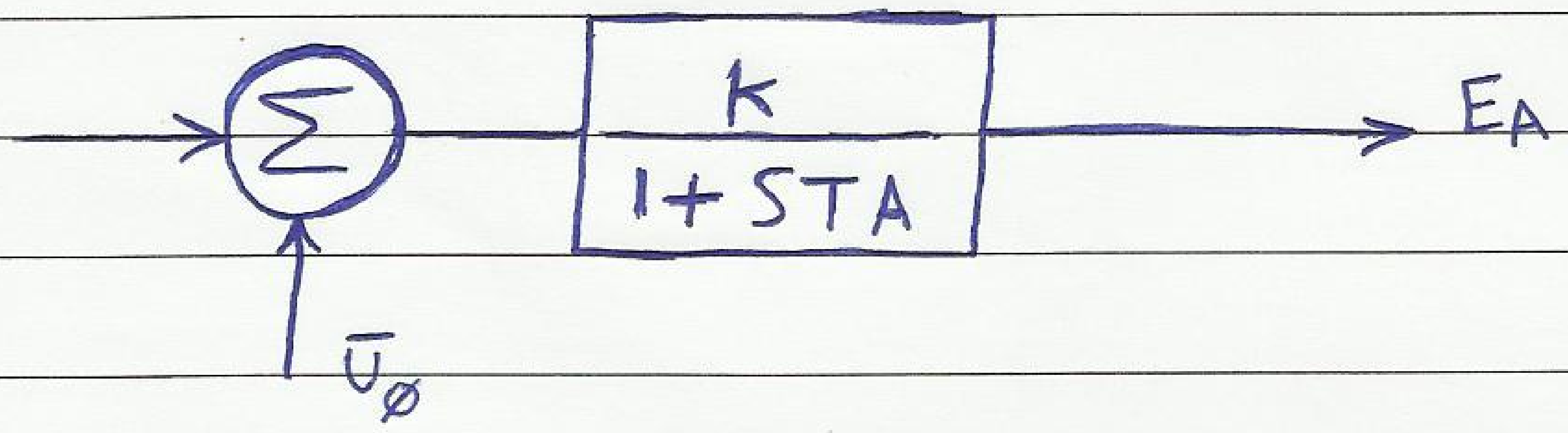
↳ This is done by what is called Automatic voltage Regulation (AUR) which is a negative feed back control system, where the output of the system (V_ϕ) is measured and the Field current (I_f) is modified automatically to adjust (E_A) to keep constant (V_T). i.e :- AUR adjust I_f such that V_ϕ is constant.

بيزيد قيمة ال excitation current وبالتالي

بتصير قيمة E_A ⇐ V↓ , Reactive power↑







" we control V_ϕ by ϕ and fixing ω since $E_A = k\phi\omega$ "

AVR

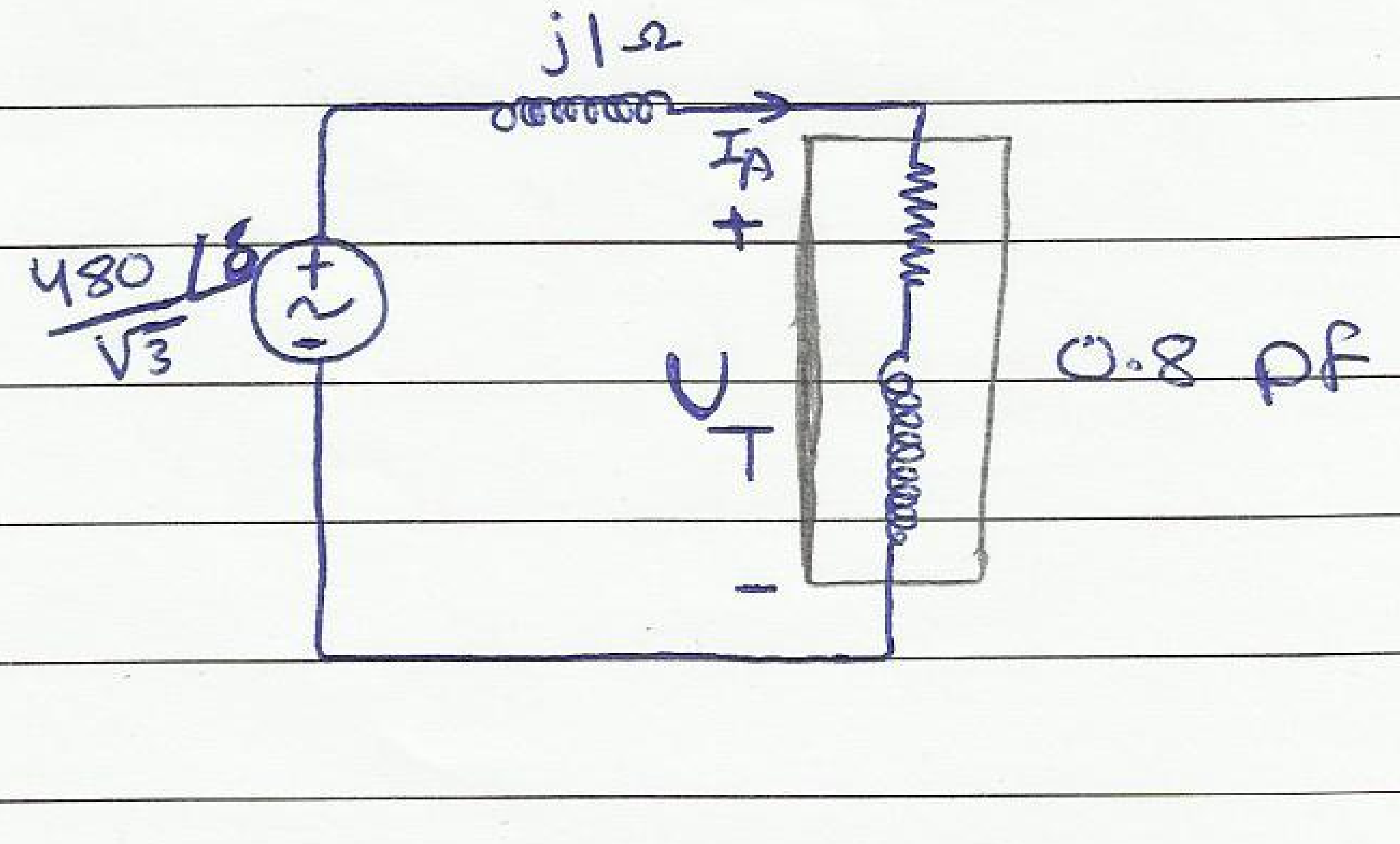
Ex: 480 V, 60 Hz, Y- conn., 6 poles synchronouns generator has a per-phase synchronouns reactance $X_s = 1\,\Omega$ and $R_A = 0$, its Full-load armeture current is 60 A at 0.8 power Factor lagging this generator has Friction and windage losses of 1.5 kw and core losses of 1 kw the Field current is adjusted such that the terminal voltage at no-load is 480 V.

a) n = ??

$$f = \frac{np}{120} \Rightarrow n_s = \frac{120f}{P} = \frac{(120)(60)}{6} = 1200 \text{ rpm}$$

b) ① V_T with rated load and 0.8 p.f lagging ?

$\tilde{I}_A = 60 \angle -\cos^{-1} 0.8$



$\tilde{I}_A = 60 \angle -37.8$ A

$\bar{E}_A = \tilde{V}_T + \tilde{I}_A (jX_s)$

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$$\Rightarrow \frac{480}{\sqrt{3}}\angle\delta = V_T\angle 0 + (60\angle{-37.8} * j1)$$

⋮

$277.5 \cos\delta = V_T + 60\cos 3.13°$ .....(1) real = real

$277.5 \sin\delta = 60 \sin 53.13°$ .....(2) Img = Img

1/2 :-

$V_T = 236.8\,V$

$V_T = 410\angle 0°$ line voltage.

② V_T with rated load and pf = 1 unity pf ?

$V_T = 468.9\,V$ line voltage

③ V_T with rated load and pf = 0.8 leading ?

$V_T = 535\,V$ line voltage

c) calculate the efficiency at Full-load at 0.8 p.f lagging (b-1) ?

$$\eta\% = \frac{P_{out}}{P_{in}} * 100 = \frac{\sqrt{3}\,V_L I_L \cos\theta}{\sqrt{3}\,V_L I_L \cos\theta + P_{core} + \underset{\swarrow\, R_A = 0\;(3I_A^2R_A)}{P_{copper}} + P_{friction}} = 93.2\%$$

d) calculate the induced counter torque which the prime mover must apply to overcome it ?

↳ Anti torque developed (From the load)

$$T = \frac{P_{out}}{\omega_s} = \frac{\sqrt{3}\,V_L I_L \cos\phi}{\frac{2\pi n}{60}} = \frac{(\sqrt{3})(410)(60)(0.8)}{\frac{(2\pi)(1200)}{60}}$$ = 27[illegible].3 N.m

e) calculate the voltage regulation for all loads for part (b) ?

① $VR = \frac{E_A - V_\phi}{V_\phi} * 100\% = \frac{(480/\sqrt{3}) - 236.8}{236.8} * 100\% = 17.2\%$

② 2.6 %

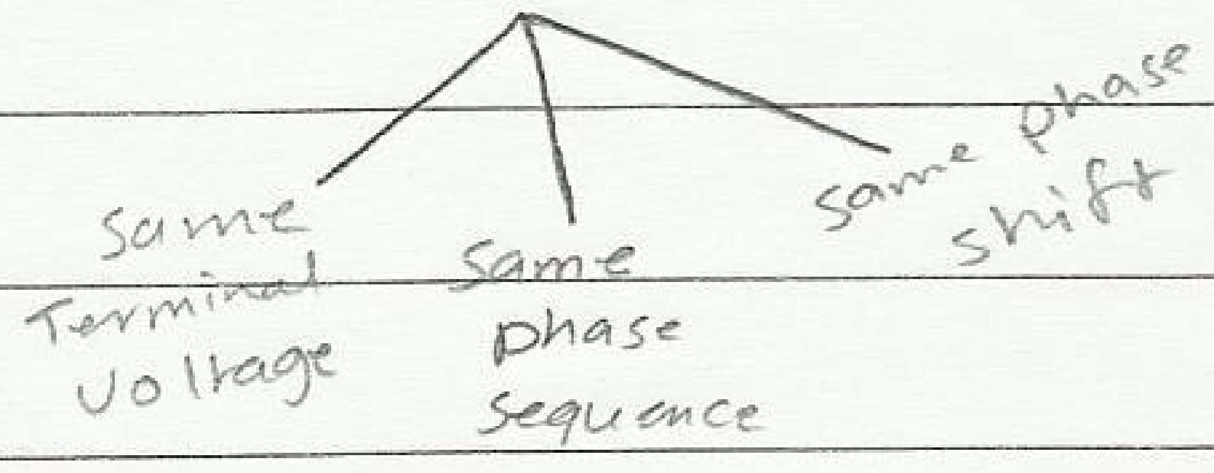
③ - 10.3 %

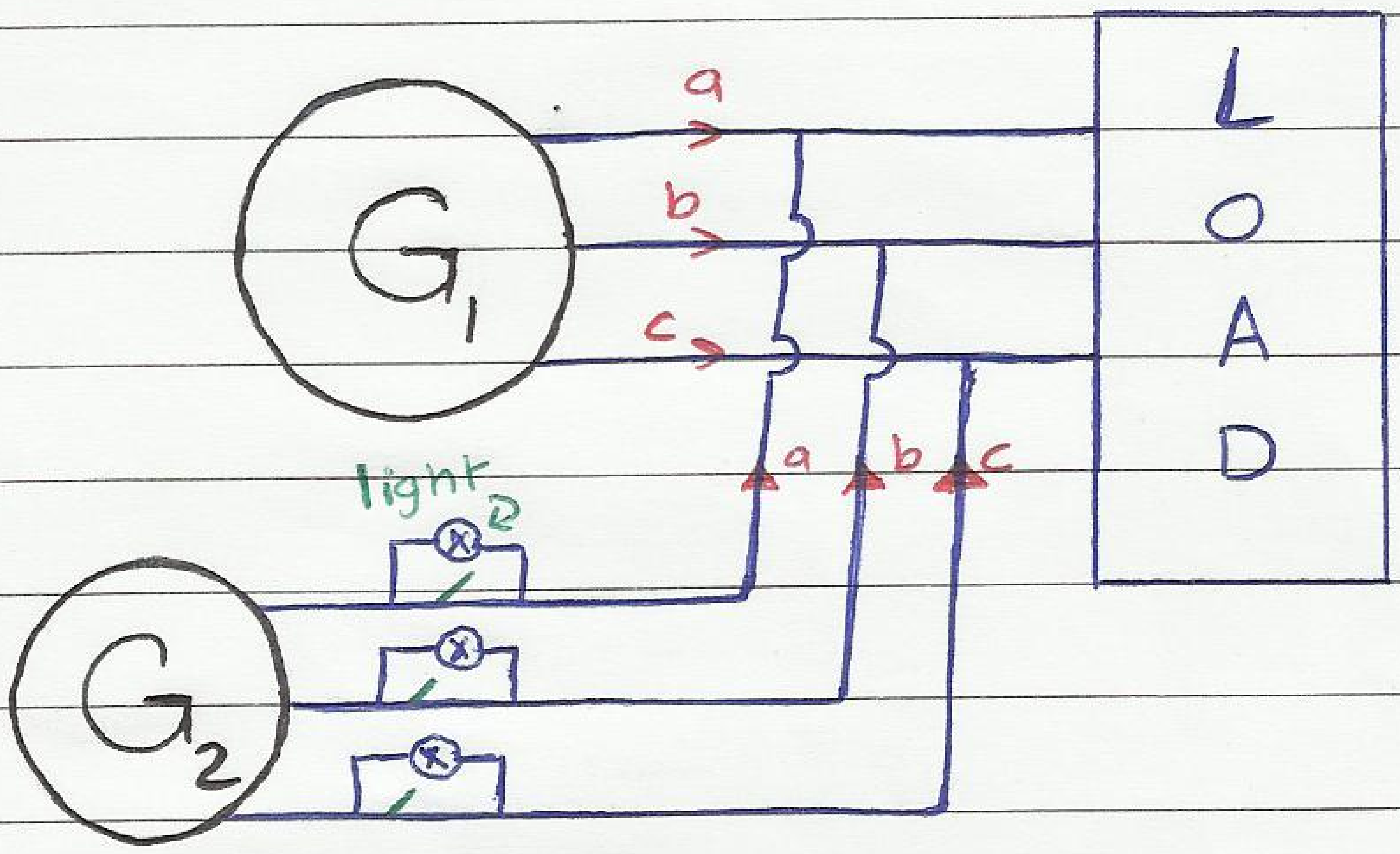
* 5.9 :- parallel operation of Ac generator :-

* advanteges (why?), if the load increases (expanded)
  - increase the reliability of the system. إذا ضرب واحد، الثاني بيضل شغال
  - more power generated.
  - most generator don't have maximum efficiency at Full-load and therefore sharing the power might run them at the maximum efficiency.

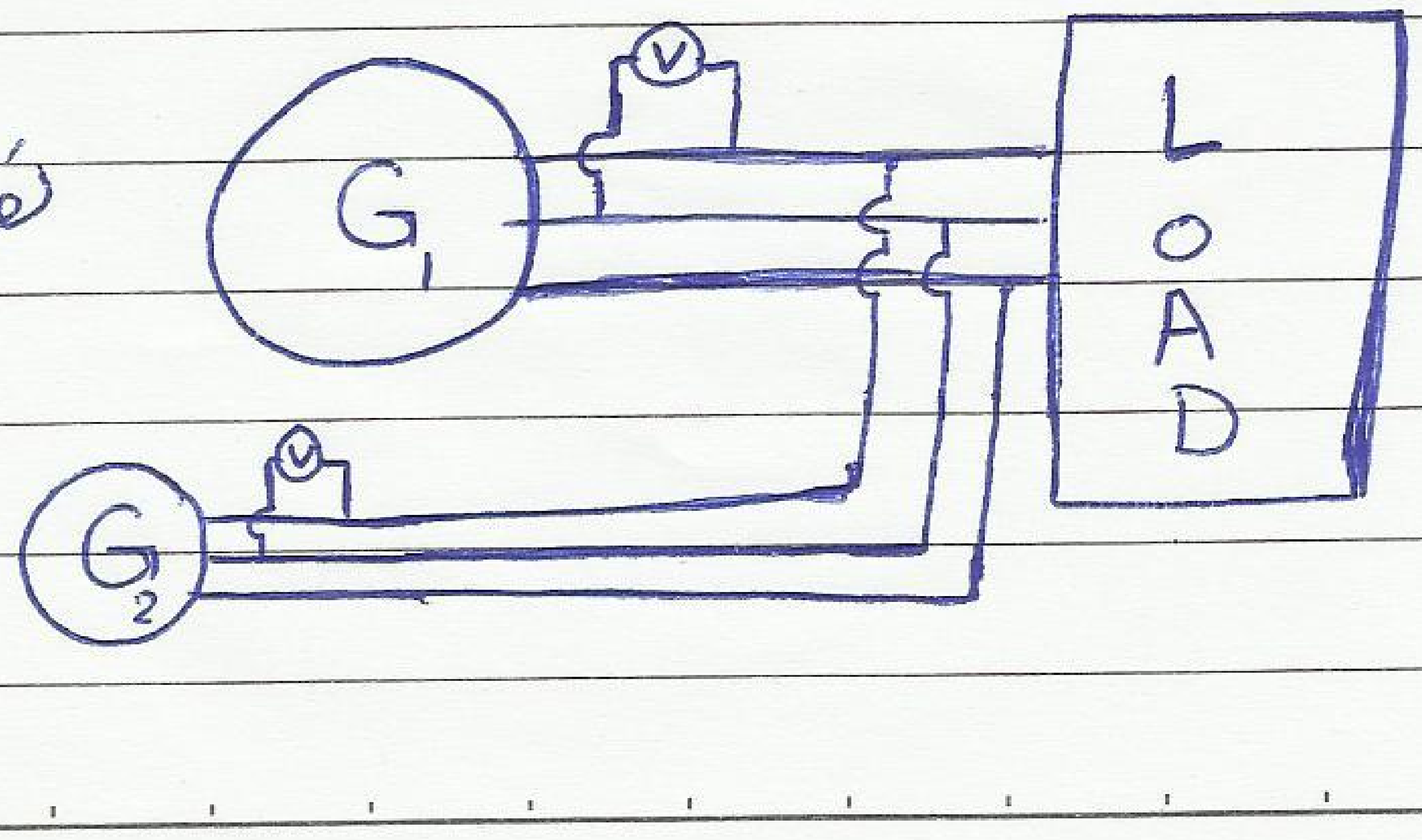
* The conditions required for paralling :-

* إذا الثلاث لمبات بيطفو بيضوا مع بعض بنفس الوقت بيكون:





1] the same rms terminal voltage (line voltage).
2] the same phase sequence.
3] the Freq. of the oncoming generator must be slightly higher than the freq. of the system (the running generator), Because otherwise it will run as a motor.
4] the same phase angle.



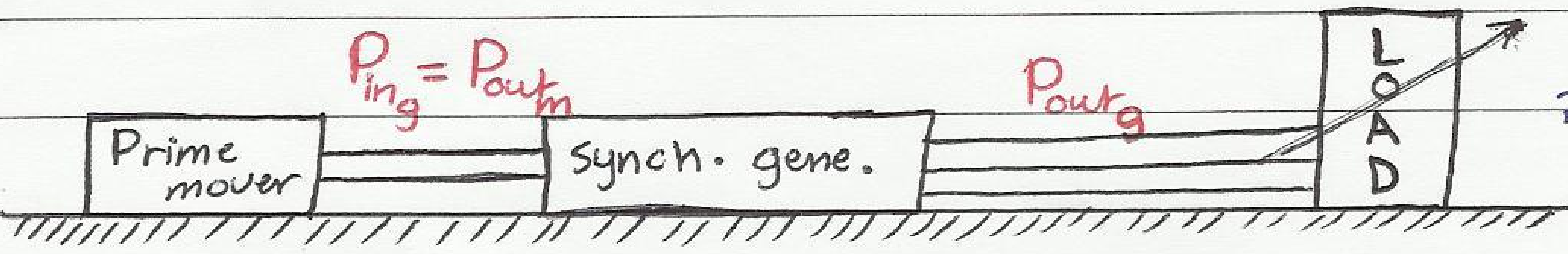
تقريباً نفس الفولتية على الـ Voltmeter

* The General procedure for paralleling generators :-

① lights

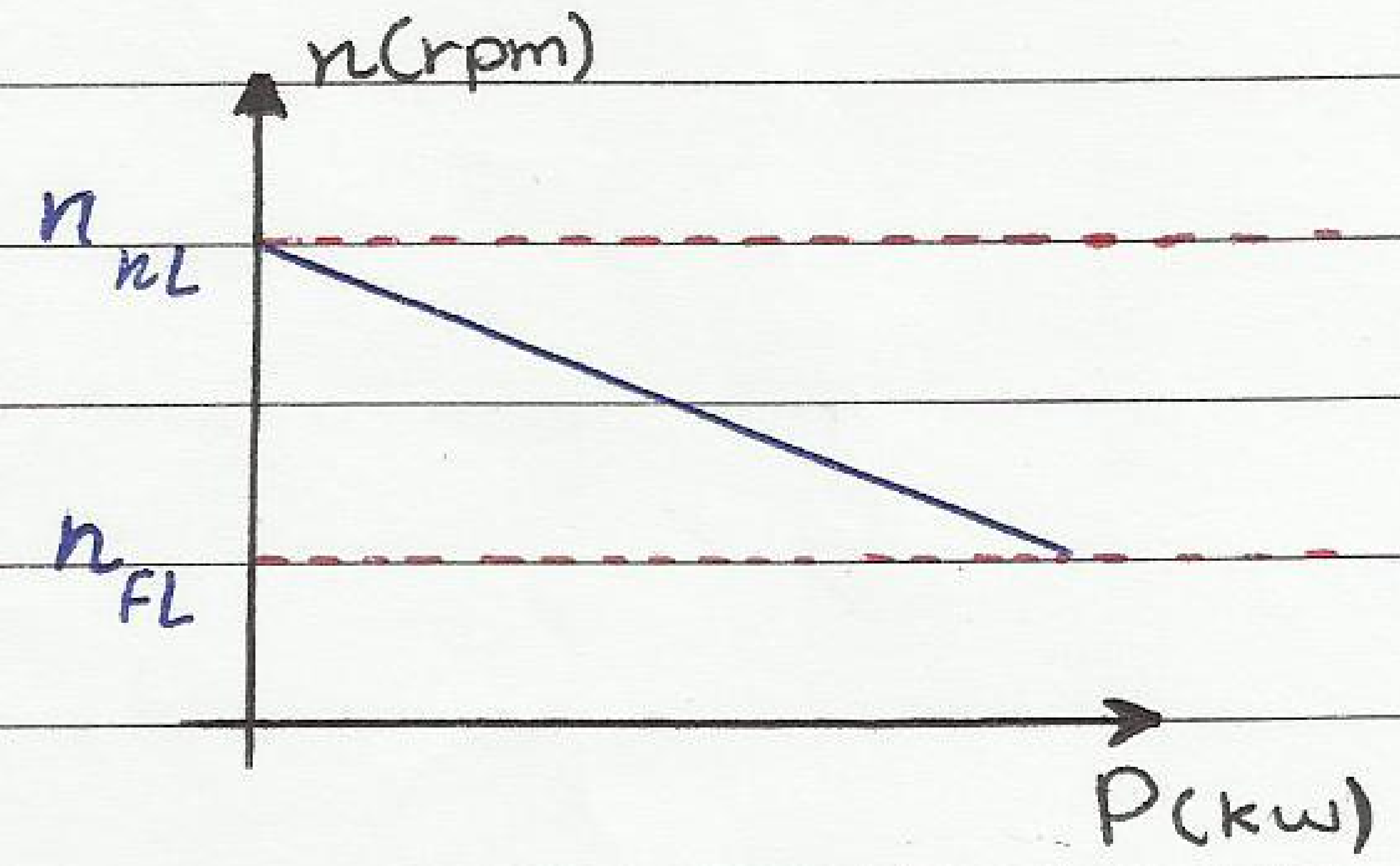
② Another way for paralleling is using what is called "synchroscope".

* Frequency - power and voltage - reactive power characteristics of synchronouns generator :-



كلما زادت ال Pout قلت السرعة

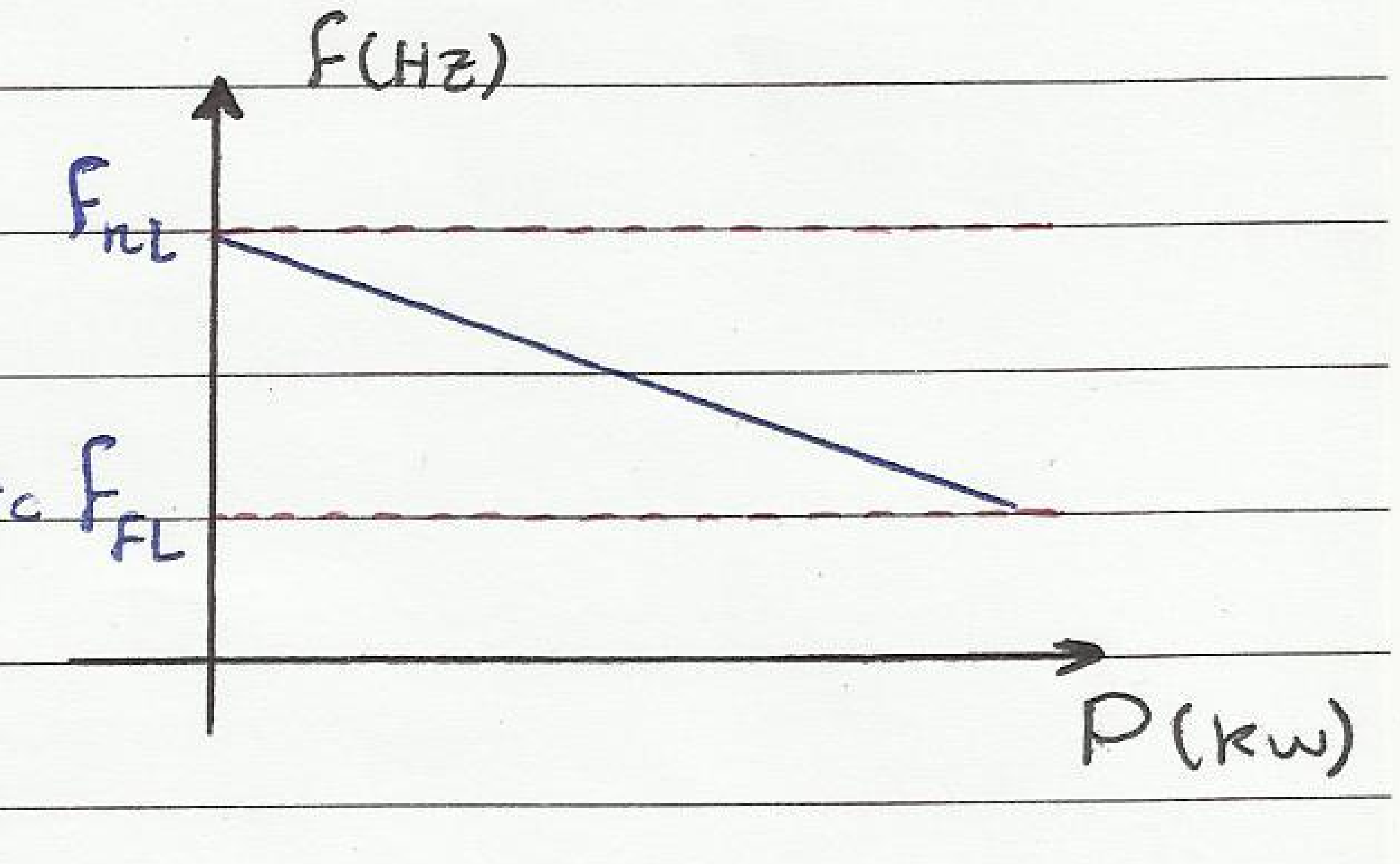
* The speed drop SD or SR% is equal :-



$$SD = \frac{n_{nL} - n_{FL}}{n_{FL}} \times 100\%$$

SD typically 2 to 4 %

- If the load ↑, P_g ↑, n_m ↓.



* Normally, the output power of synch. generator as Function of its Frequency is :-

$P = S_p (f_{nL} - F_{sys})$ ... Freqency - power characteristic

where,

P : output power of the generator.

S_p : slope of the curve KW/Hz or MW/Hz.

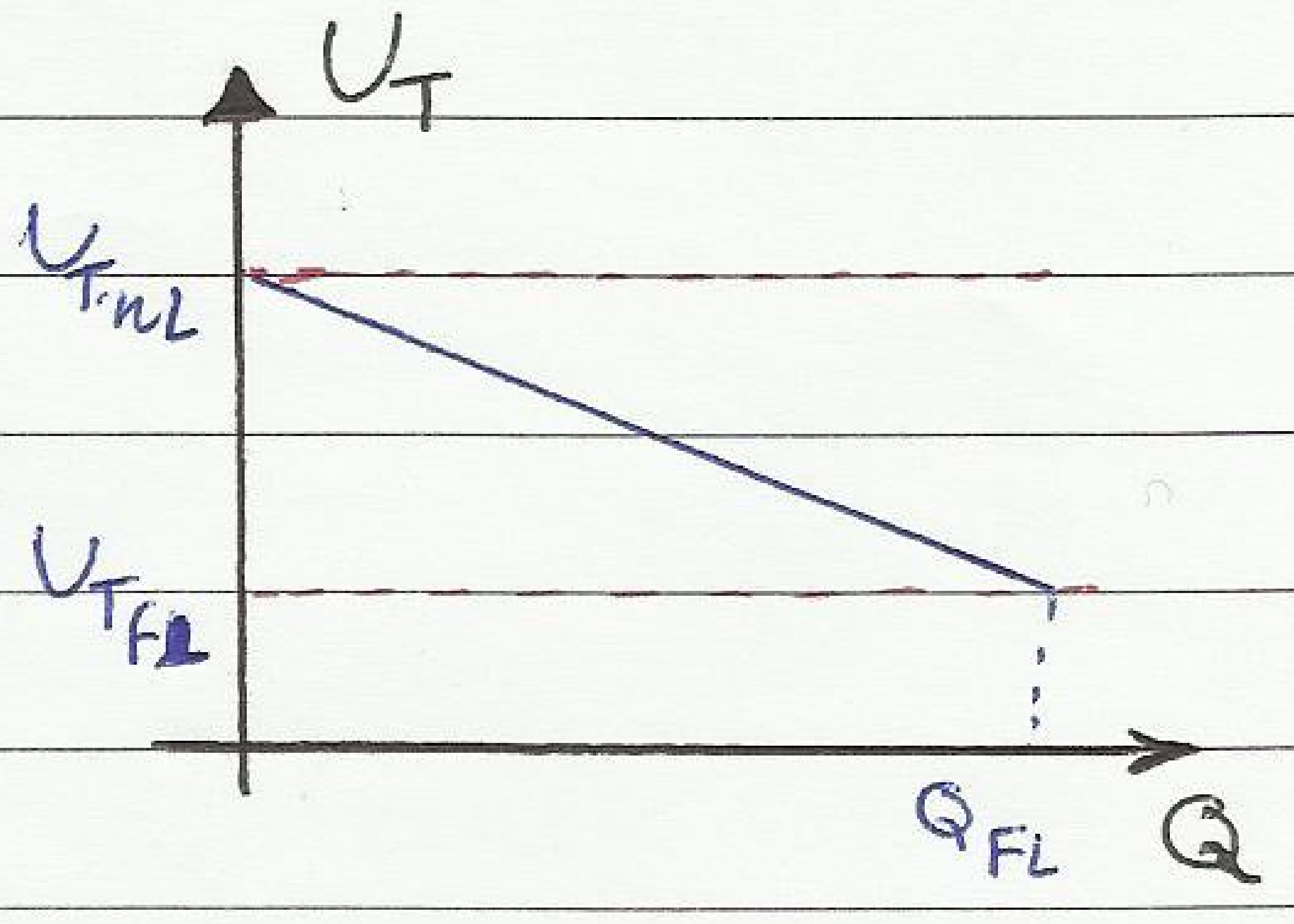
f_{nL} : no-load Frequency.

F_{sys} :- system Frequency 50 or 60 Hz (operating frequency or Full-load frequency).

* A similar relation for the terminal voltage (U_T) has function of the output reactive power (Q) is :-

"p.f lagging"

$$UR\% = \frac{U_{TnL} - U_{TFL}}{U_{TFL}} * 100\%$$



+ UR is typically 15 %

* For any given real power the governer set point control the generators operating frequency and for any given reactive power the field current controls the generators terminal voltage.

* For generators operating alone all the power generated must be consumed by the loads (active, reactive).

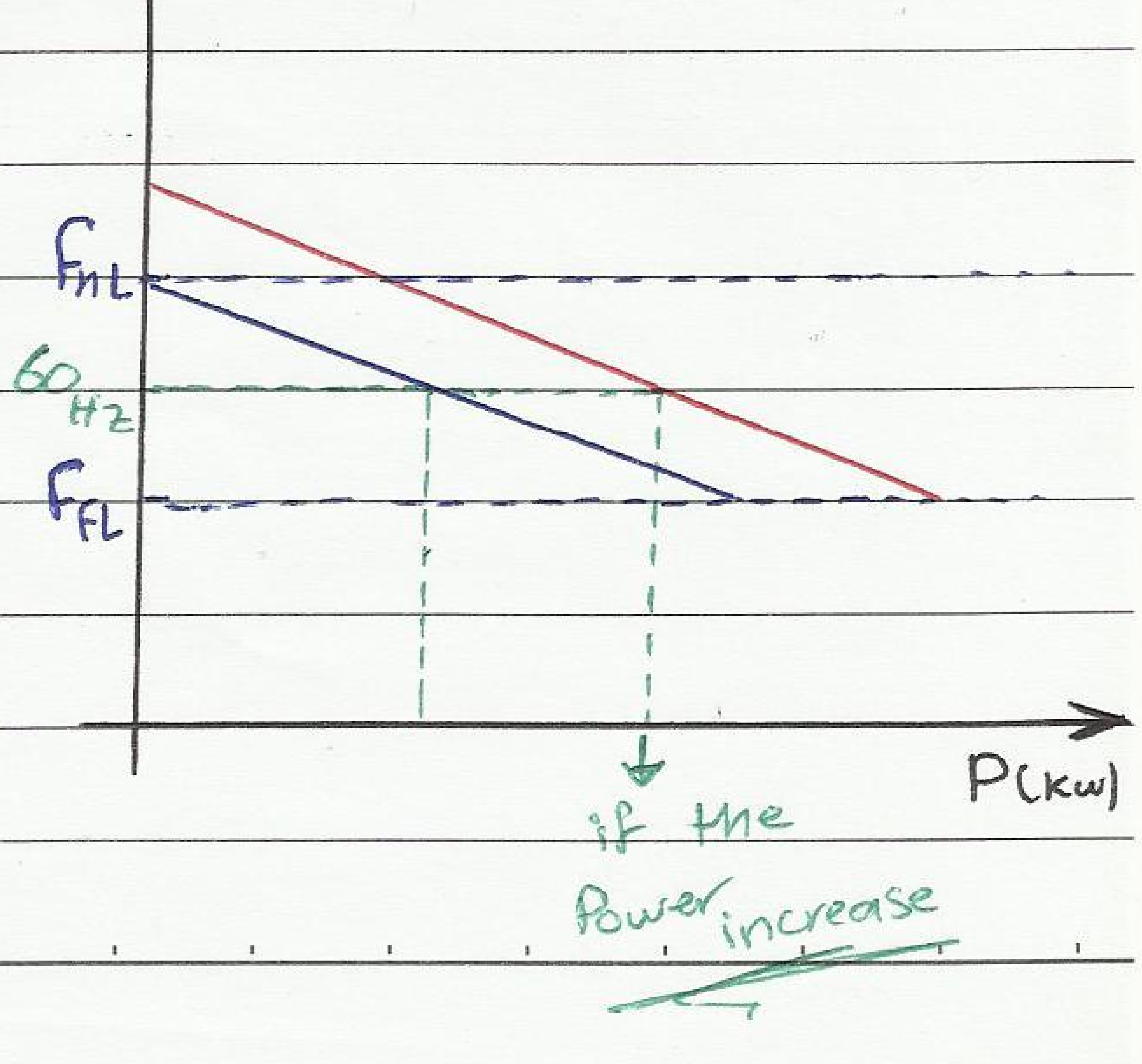
* Summary :-

- the governer set point of generator control the operating frequency of the power system (P).
- the field current I_f control the terminal voltage of the generator (Q).

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

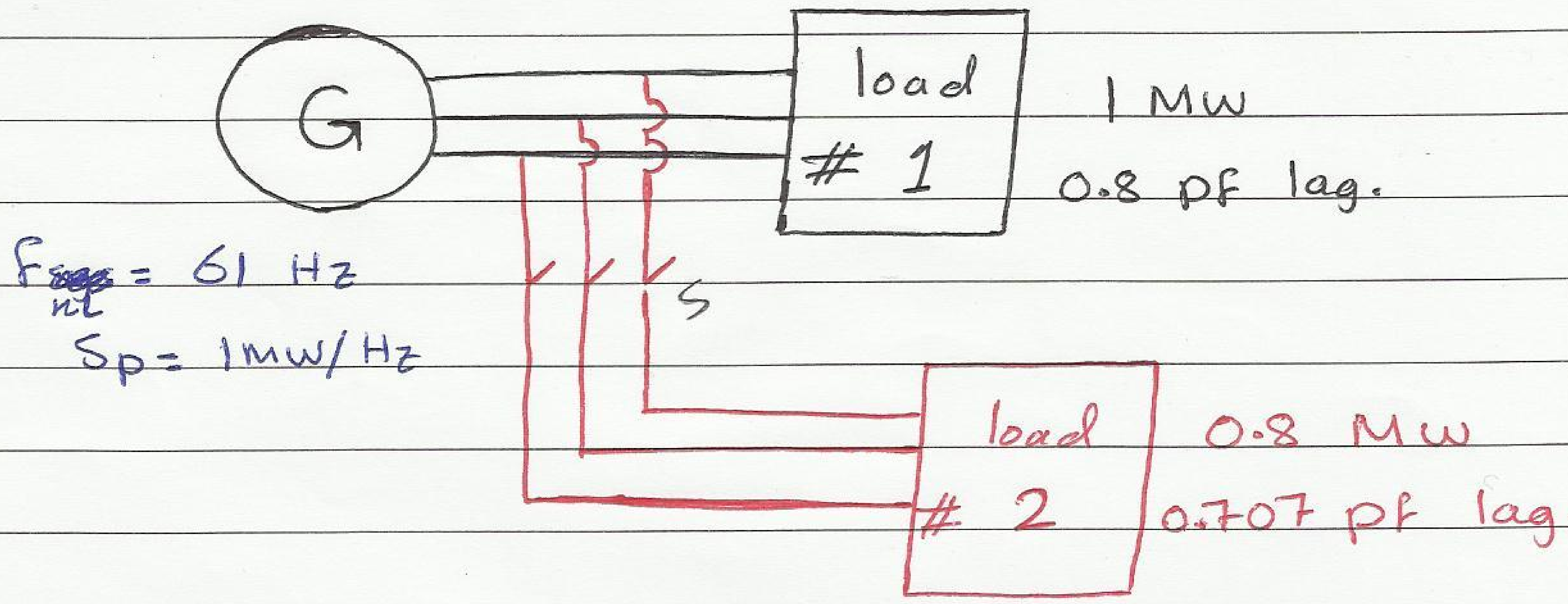
$$1.8 * 10^6 = 1 * 10^6 (f_{nL} - 60)$$

$$f_{nL} = 61.8 \text{ Hz}$$



تابع السؤال التالي
في الصفحة التالية

Ex :



$f_{\substack{\cancel{sys}\\ nL}} = 61\ Hz$

$S_p = 1 MW/Hz$

a) before the switch is closed what is f_{sys}?

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

$1*10^6 = 1*10^6 (61 - f_{sys}) \Rightarrow \underline{f_{sys} = 60\ Hz}$

b) After load # 2 is connected, S closed, find f_{sys}?

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

$1.8*10^6 = 1*10^6 (61 - f_{sys})$

$f_{sys} = 59.2\ Hz$

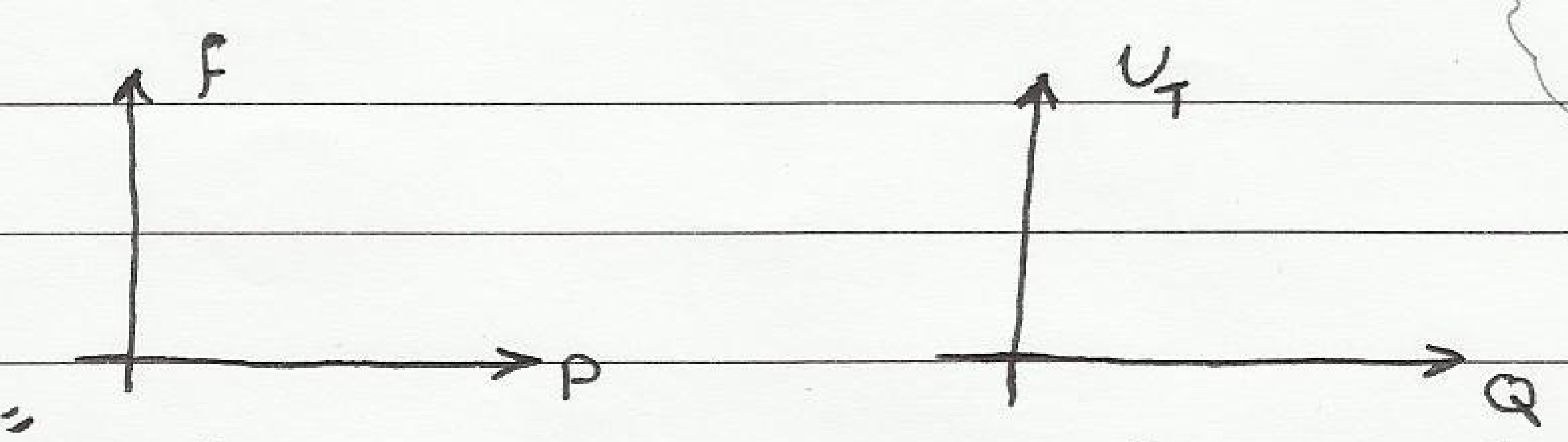
c) what action should be done to restore the frequency to 60 Hz?

↳ the input Fuel of the prime mover must be increased by the governer set point.

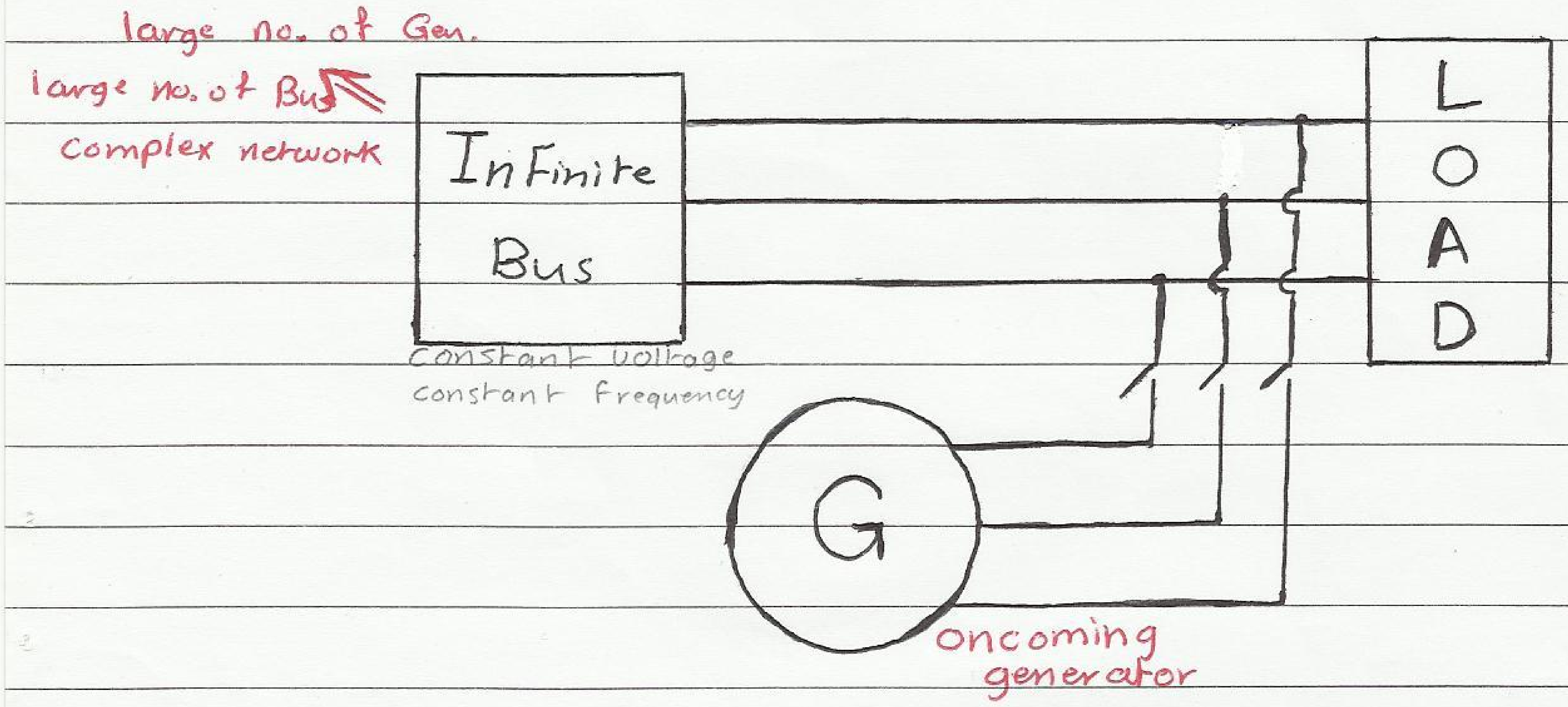
* Operation of Generator in parallel with large power system :-

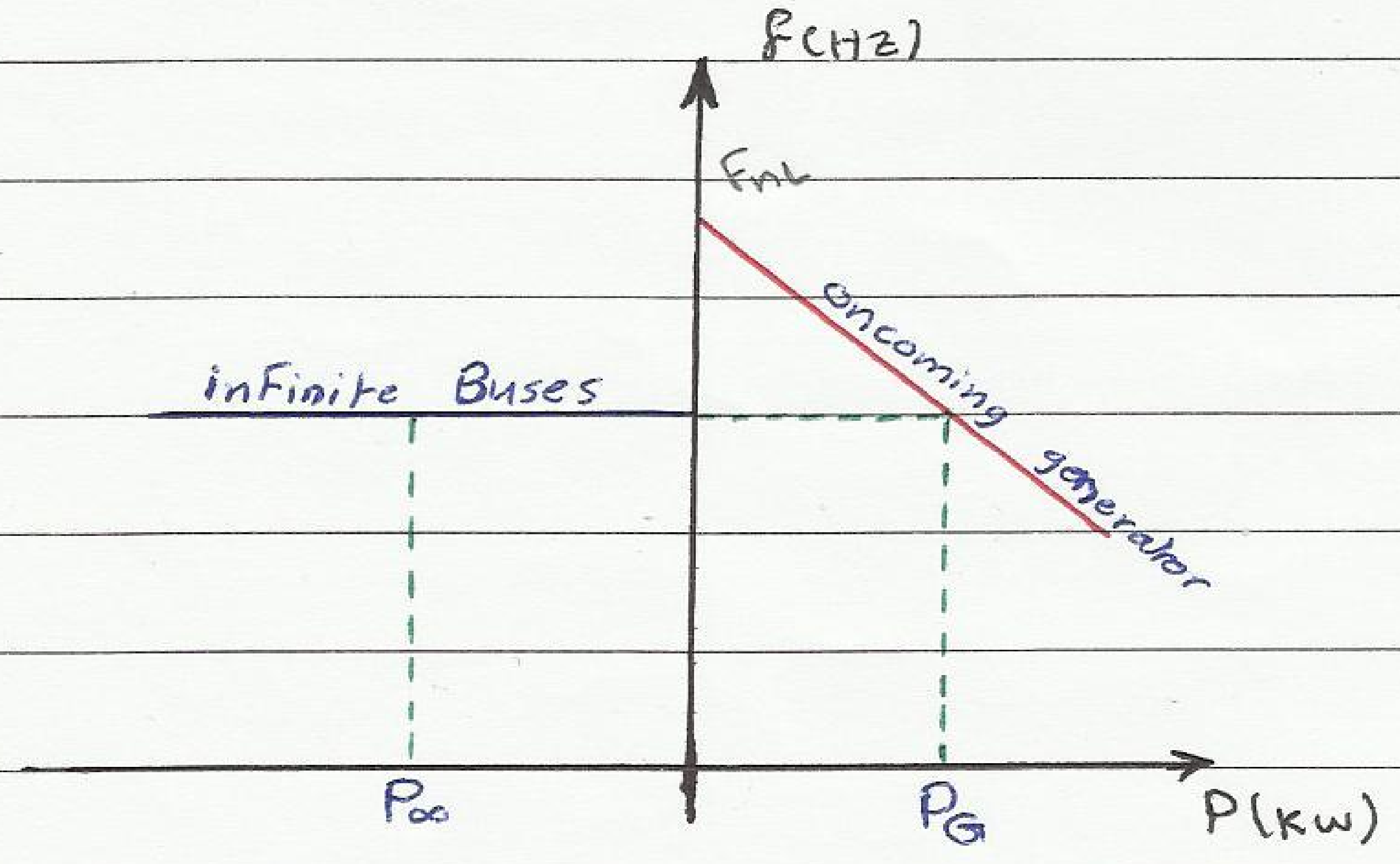
- Infinite Bus :- A so large power system such that it's voltage & frequency are constant irrespective (regardless) of how much active & reactive power are consumed or supplied.

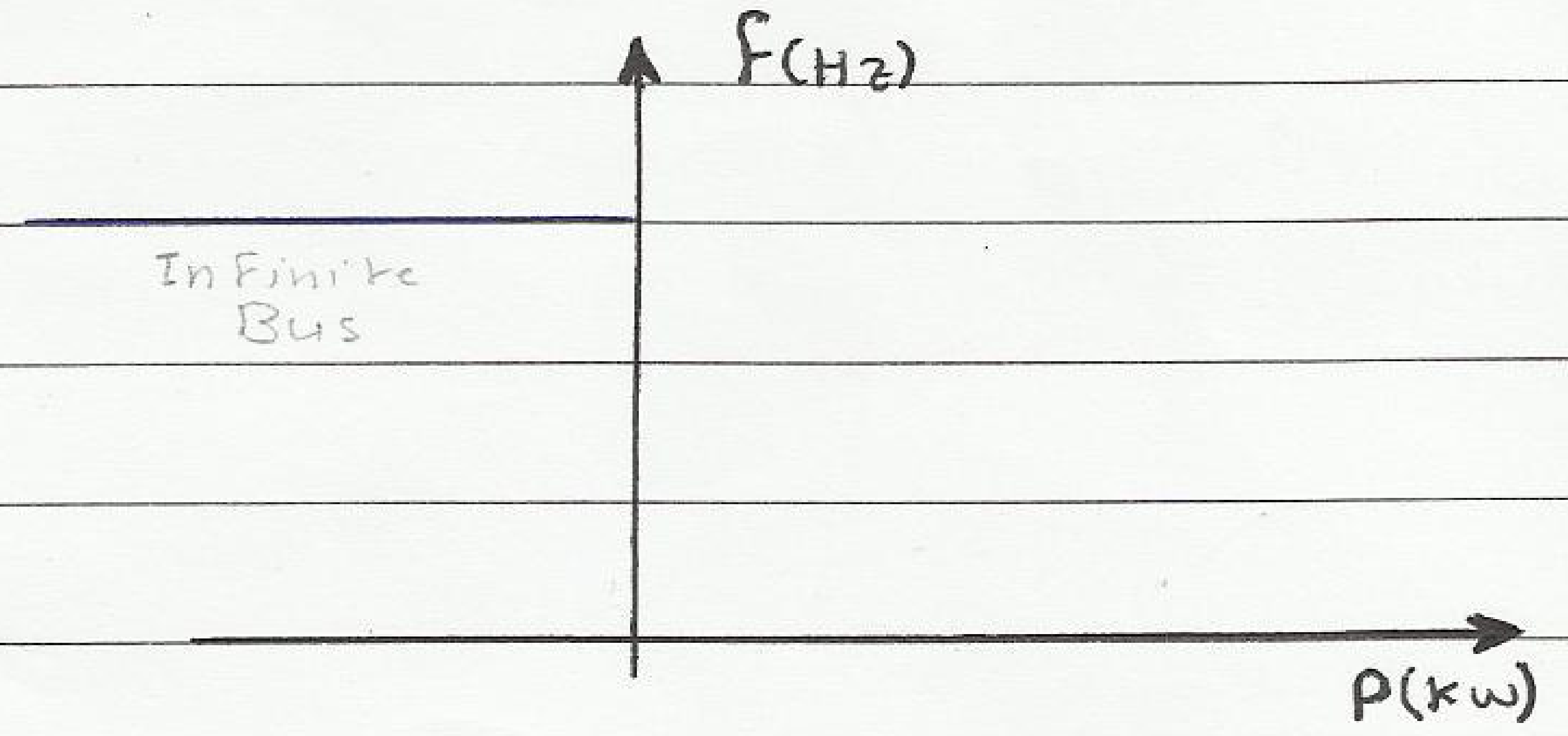
يعطي Infinit Value من
ال P, Q



"constant voltage - constant frequency Bus"

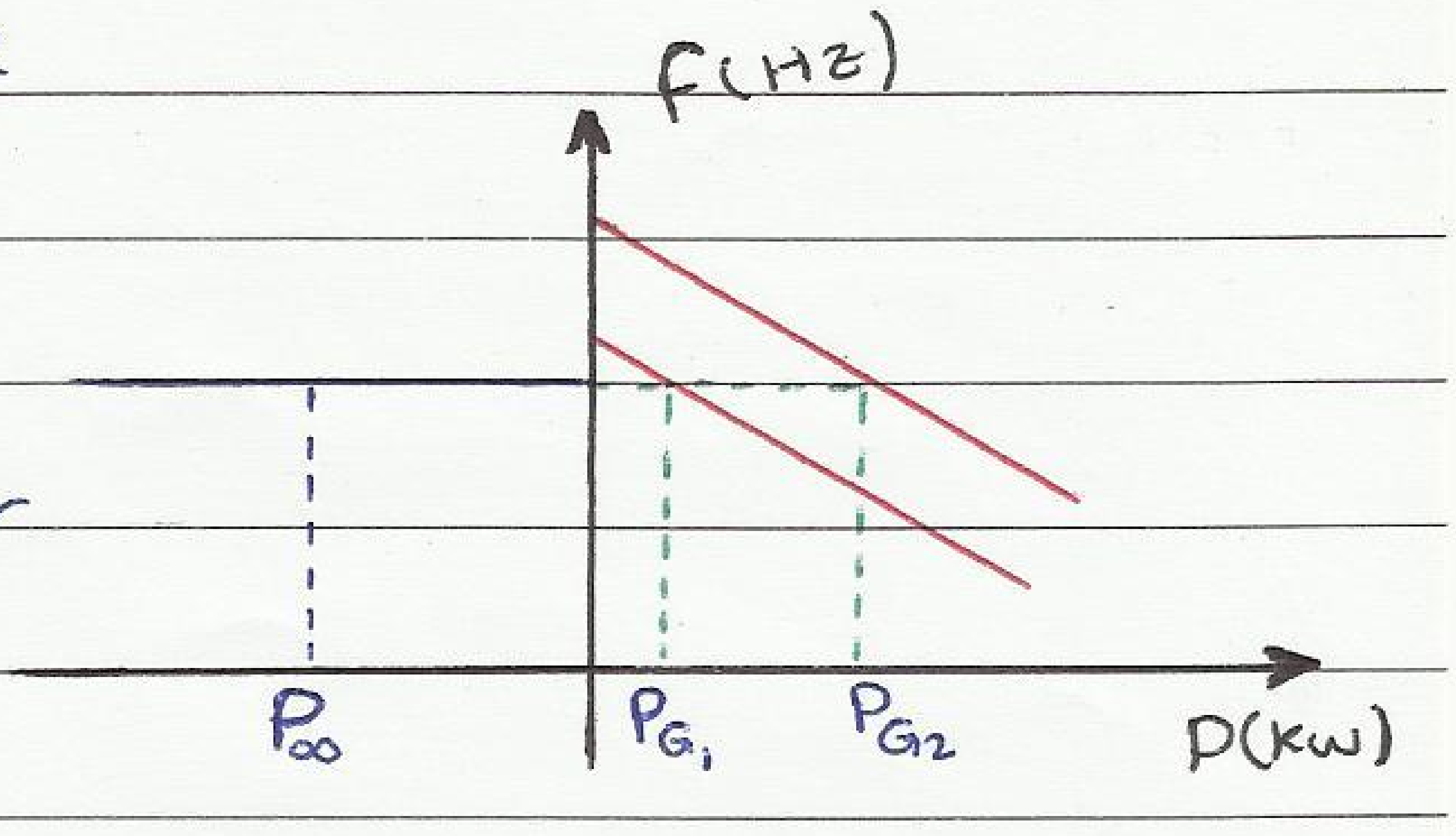






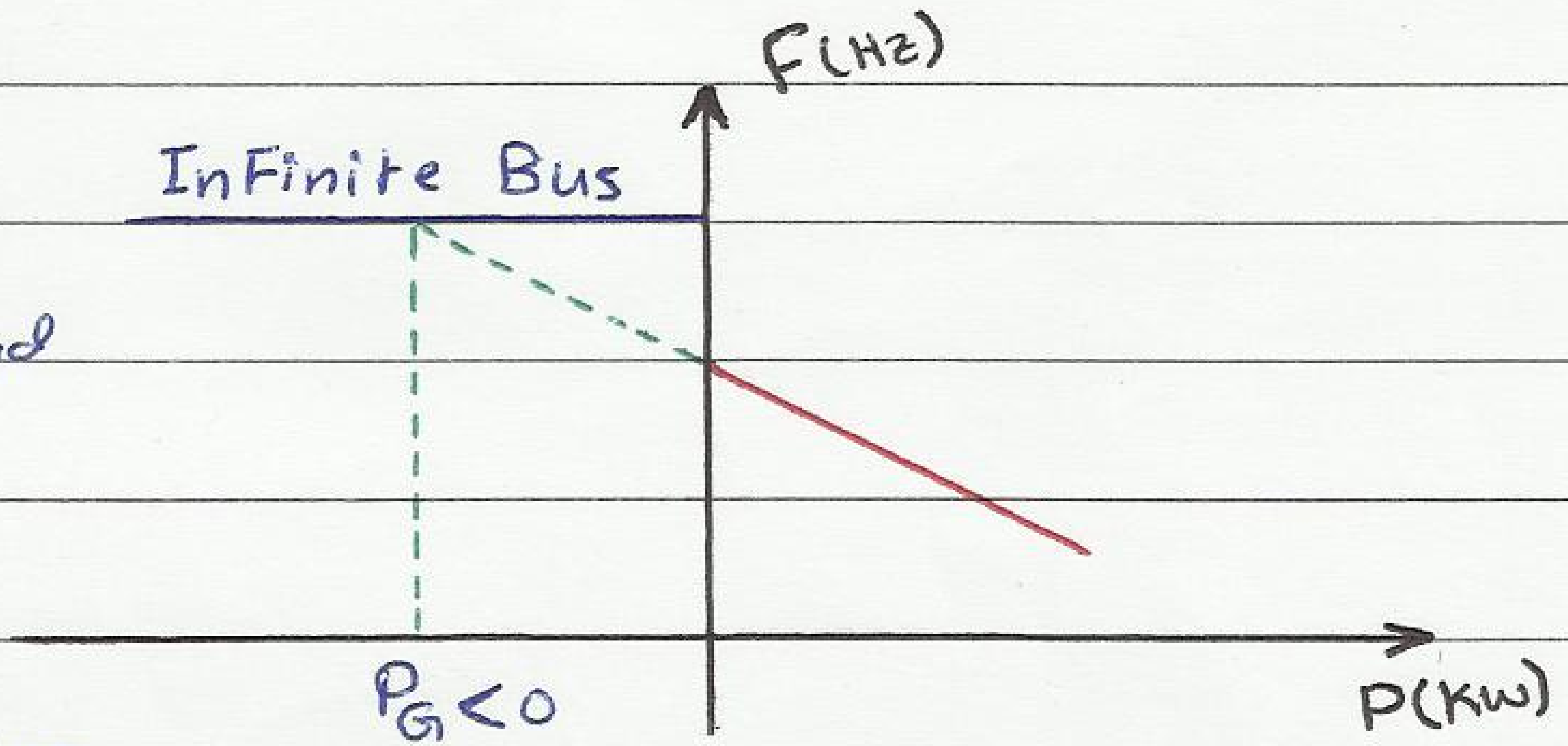
$$P_{tot.} = P_\infty + P_G$$

⇒ to increase the power contribution of the oncoming generator, the governer set point should increase, and therefore the no-load frequency F_{nL} of the generator will increase.



"House diagram"

⇒ assume that the generator has just been parallel with a no-load frequency lower than the system frequency, the output power of the generator will be negative i.e: synchronouns motor.



consumes active power
((motor))

* Effect of increasing the governer set point while keeping $E_A (I_F)$ & ω for synchronouns generator connected to infinite Bus. (constant field current)

↳ If the governer set point increases for the oncoming generator then the no-load freq. will increase. Therefore the output power of the generator increases.

↳ the current limits the output power $p = \sqrt{3}\, V_L\, I_L \cos\phi$.

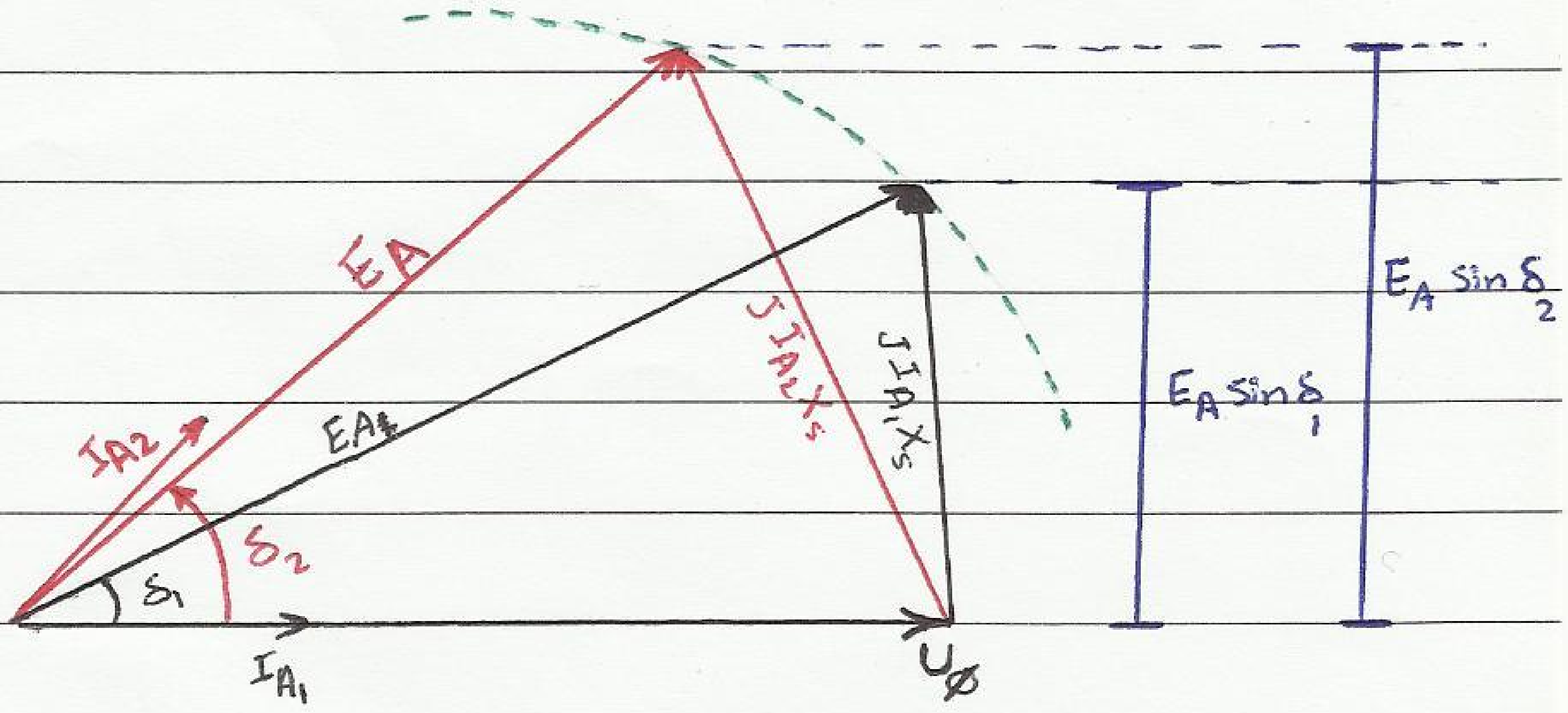
constant ↲ ↳ constant

$\Rightarrow P = 3 U_\phi I_A \cos\phi$

$$P = \frac{3 U_\phi E_A \sin\delta}{X_s}$$

Due to infinit Bus the U_ϕ is constant all time. then,

$P_{out} \propto E_A \sin\delta$



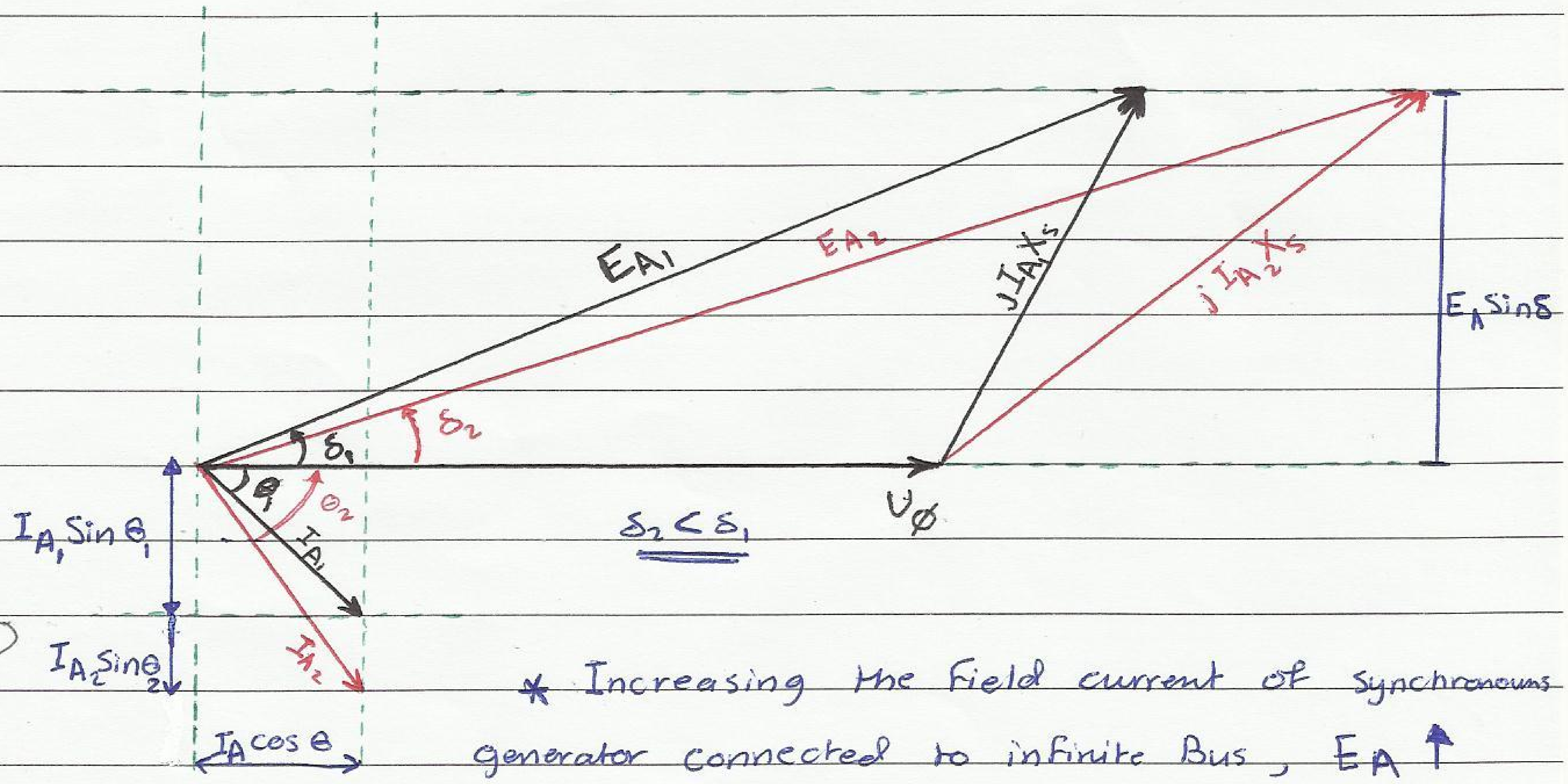
if E_A is constant (fixed I_f), $P_{out} \propto \sin\delta$.

$I_{A_1} \cos\phi_1 \neq I_{A_2} \cos\phi_2$

$\Rightarrow$ when the governer set point of the oncoming generators increases while keeping constant field current, then :-

$P_{out} \uparrow$, $I_A \uparrow$, $\delta \uparrow$, $E_A \sin\delta \uparrow$, $I_A \cos\phi \uparrow$, and the P.F moves from lagging to leading.

* Effect of increasing I_f with constant governer set point for a synchronouns generator connected to infinite Bus :-



$\delta_2 < \delta_1$

Pout fixed

$Q = 3 U_\phi I_A \sin\theta$

$\theta \uparrow$, $Q_{out} \uparrow$

* Increasing the field current of synchronouns generator connected to infinite Bus, $E_A \uparrow$ $\delta \downarrow$, $I_A \uparrow$, $I_A \sin\theta \uparrow$, $Q_{out} \uparrow$, P.F moves from leading to lagging (more lagging).

*Summary :-

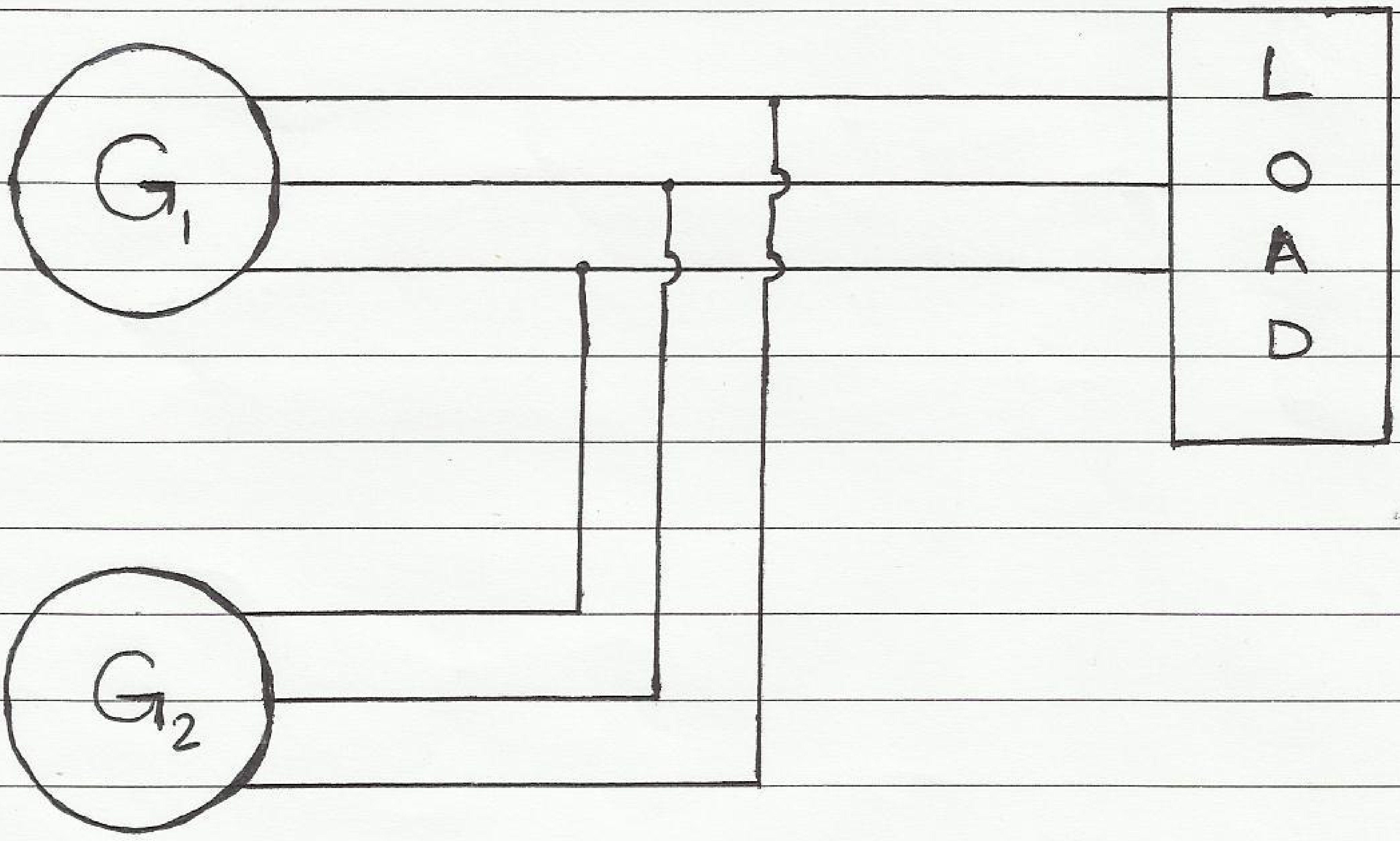
- when a generator is operating in parallel with an infinite Bus :-

1] the frequency and terminal voltage of the generator are controlled by the system to which it is connected.

2] the governer set point of the generator control the real power supply by the generator to the system.

3] the Field current of the generator control the reactive power supply by the generator to the system.

* Operations of generators in parallel with other generators of the Same size :-



Two generators in parallel Feading Loads.
⇓
two generator operating alone.

* The sum of the real and reactive power supplied by the generators must equal that demand by the loads " Total power generated equals total power consumed by the load ".

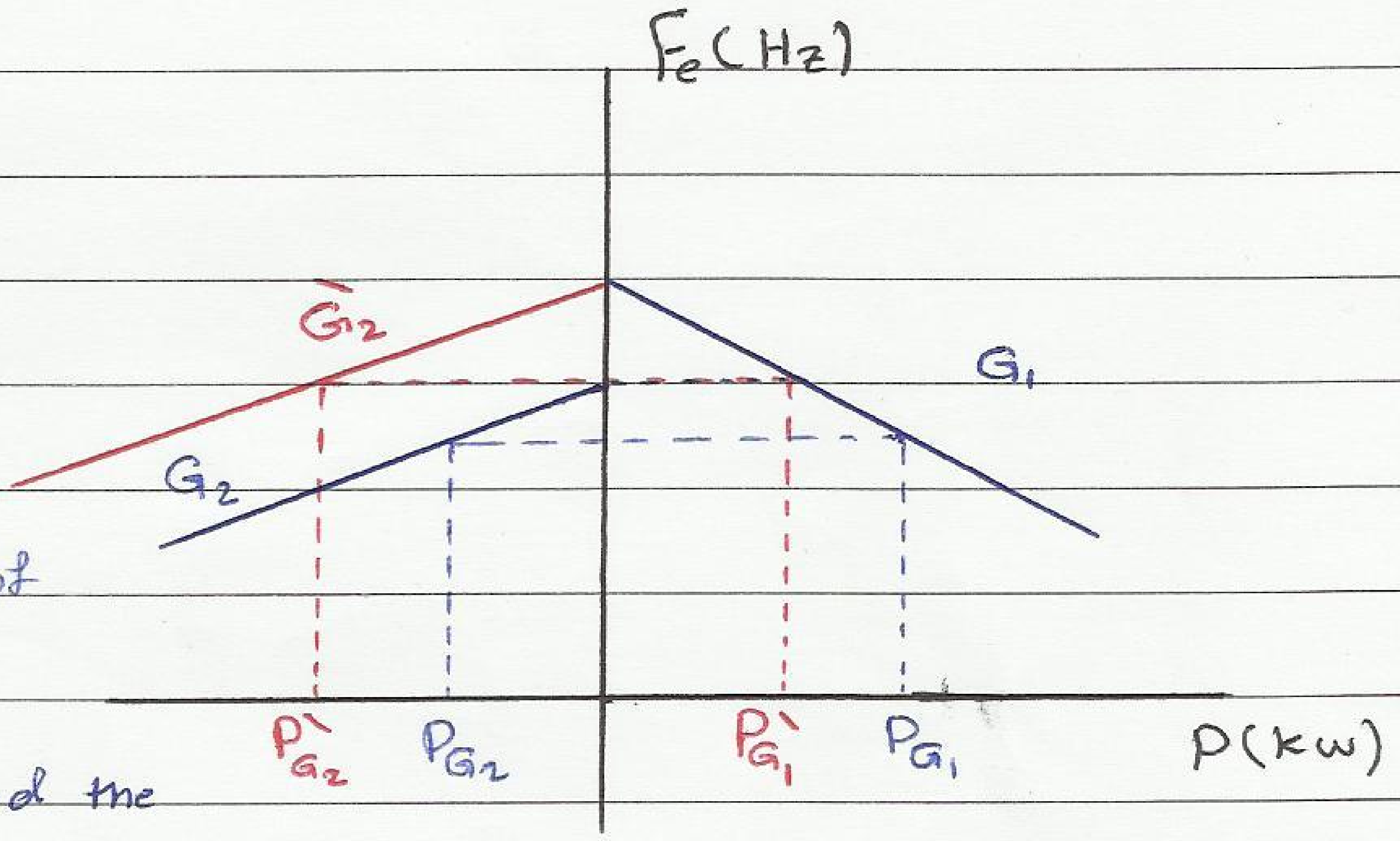
* The power voltage and frequency are not constant.

$$P_{tot} = P_{load} = P_{G_1} + P_{G_2}$$

$$Q_{tot} = Q_{load} = Q_{G_1} + Q_{G_2}$$

* For this Figure :-

$$P_{G_1} + P_{G_2} = P'_{G_1} + P'_{G_2}$$



⇒ If the governer set point of any one increases, then the power supply by it increase, and the power supplied by the other one decrease and the Frequency of the system increase provided that the same load.

نفس الجواب

↳ what happen if the governer set point to any of the generators is increased ?

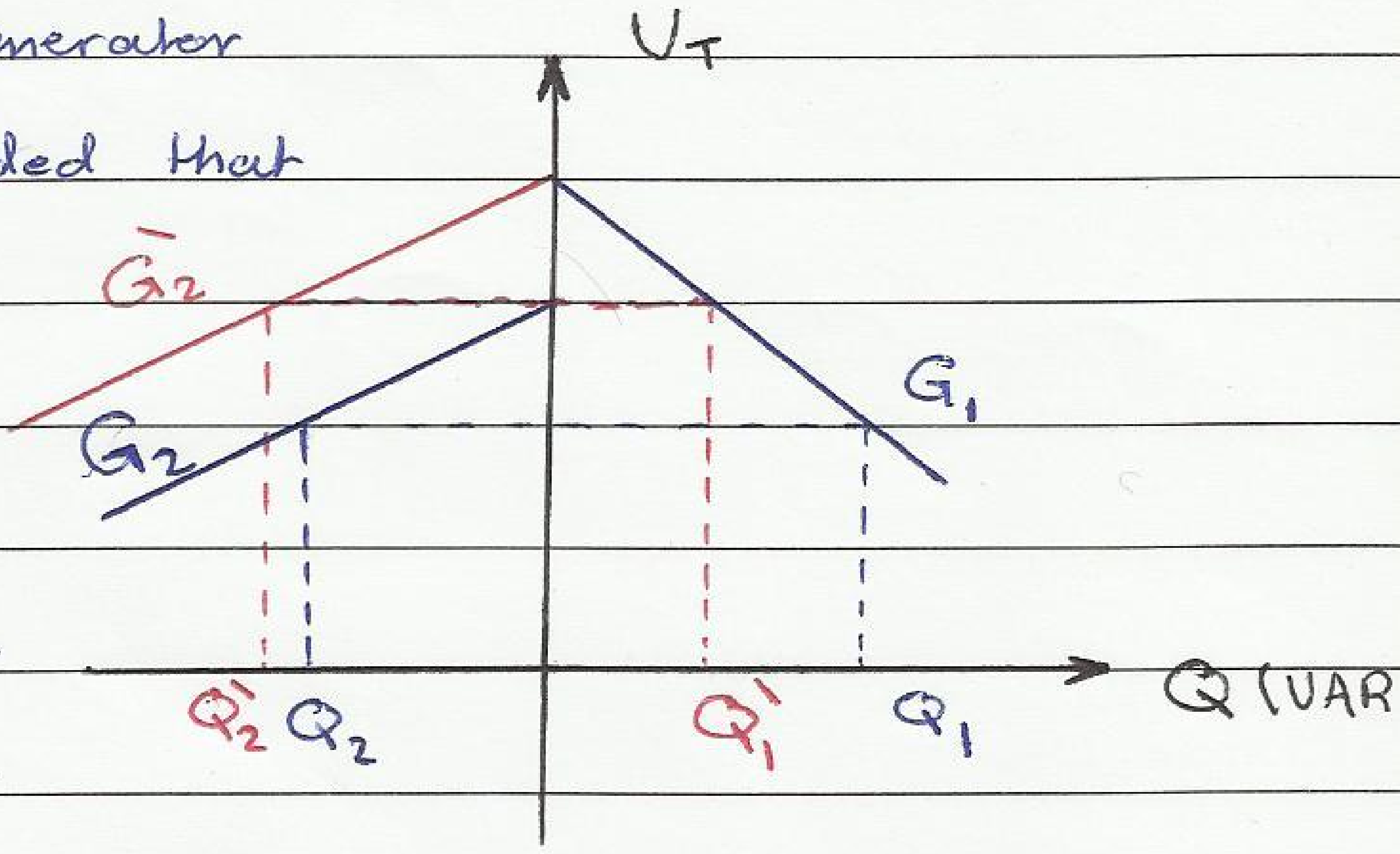
- For the same load if the governer set point of the second, then this no-load Frequency will increase, it's power contribution increases the first generator power contribution decreases at a higher system frequency and vic versa.

* what happens if the Field current of the ~~second~~ Second generator increase ?

1- the system terminal voltage increase.

2- the reactive power supplied by one generator increase and the other decrease, provided that the same load.

⇒ For the same Reactive power load, the reactive power contribution of the second generator increases, the reactive power of the First power generator decrease at a higher terminal voltage.



Ex:- two generators are supplying a load $G_1 \Rightarrow f_{nL} = 61.5$ Hz, $Sp_1 = 1MW/Hz$
$G_2 \Rightarrow F_{nL} = 61$ Hz, $Sp_2 = 1 MW/Hz$, $P_{tot} = 2.5MW$ at 0.85 p.f lag.?

a) $P_{tot} = Sp_1(f_{nL_1} - f_{sys}) + Sp_2(f_{nL_2} - f_{sys})$

$$2.5*10^6 = \underbrace{1*10^6(61.5 - F_{sys})}_{P_1 = 1.5MW} + \underbrace{1*10^6(61 - F_{sys})}_{P_2 = 1MW}$$

$F_{sys} = 60$ Hz

b) suppose that additional 1MW load is connected, what is the Freq, P_1, P_2 ?

$$P_{tot} = Sp_1(f_{nL_1} - F_{sys}) + Sp_2(f_{nL_2} - f_{sys}) \Rightarrow 3.5*10^6 = \underbrace{1*10^6(61.5 - f_{sys})}_{P_1 = 2MW} + \underbrace{1*10^6(61 - F_{sys})}_{P_2 = 1.5MW}$$

$F_{sys} = 59.5$ Hz

c) with the operation conditions with part b, what will be F_{sys}, P_1, P_2 ? if the governer set point of g_2 is increase by 0.5 Hz ?

$$3.5*10^6 = \overbrace{1*10^6(61.5 - F_{sys})}^{1.75 MW} + \overbrace{1*10^6(61.5 - F_{sys})}^{1.75 MW}$$

$F_{sys} = 59.75$ Hz

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* Summary :-

- to summarize in the case of two generators operating together :-

1] The total power generated by the generator must be equal the total power consumed by the load.

2] niether (f_{sys}) nor (V_T) is constant.

3] To adjust the real power sharing between the both generators without changing (f_{sys}) increase the governer set point in one generator and decrease the governer set point of the other.

4] To adjust (F_{sys}) without changing the real power sharing simultaneously increase or decrease both generators governer set point.

5] as ③ real power ⇒ reactive power

f_{sys} ⇒ V_T

6] as ④ F_{sys} ⇒ V_T

real ⇒ reactive

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* 5.10 :- Synchronouns Generator Transients :-

- transients of synchronouns generators come as a result of :-

1- shaft torque is applied (shaft power change) الوزن ، الاحتكاك ، مقاومة الهواء

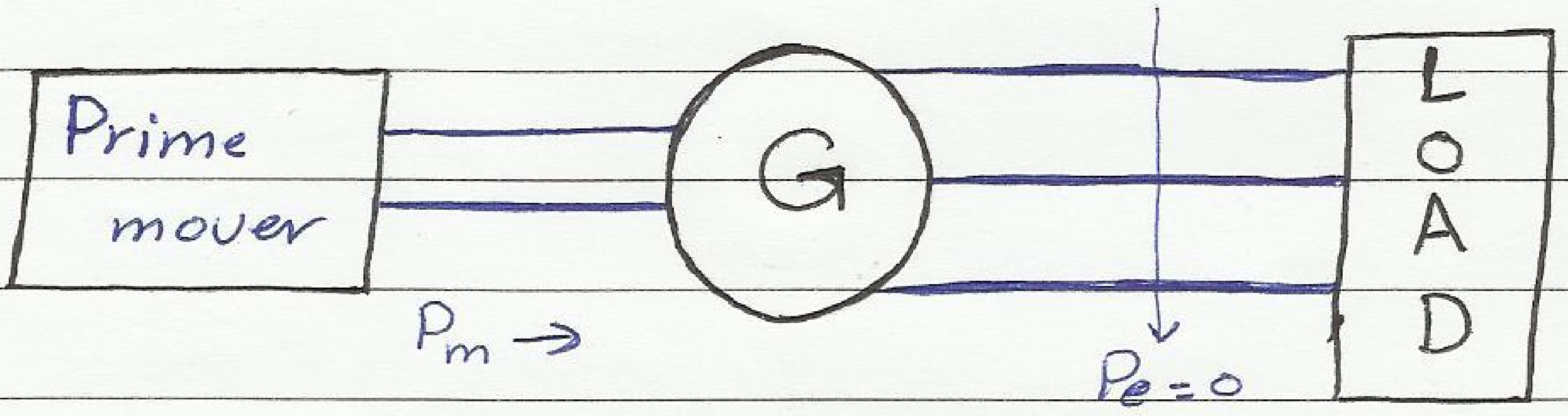
2- output load suddenly changes.

3- the generator is paralleled with another one or connected to the grid or with running power system.

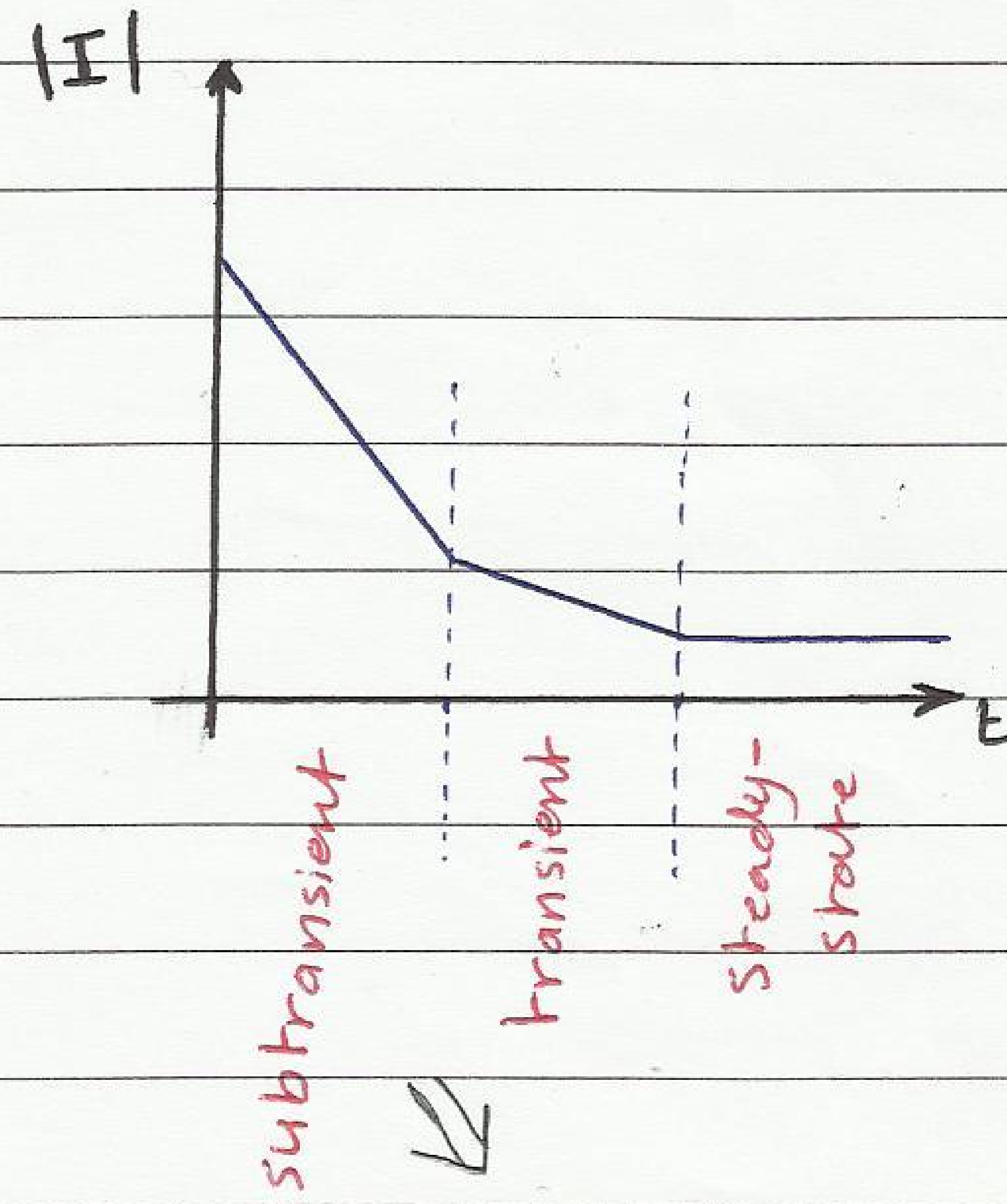
4- short circuit across the terminals of the generators.

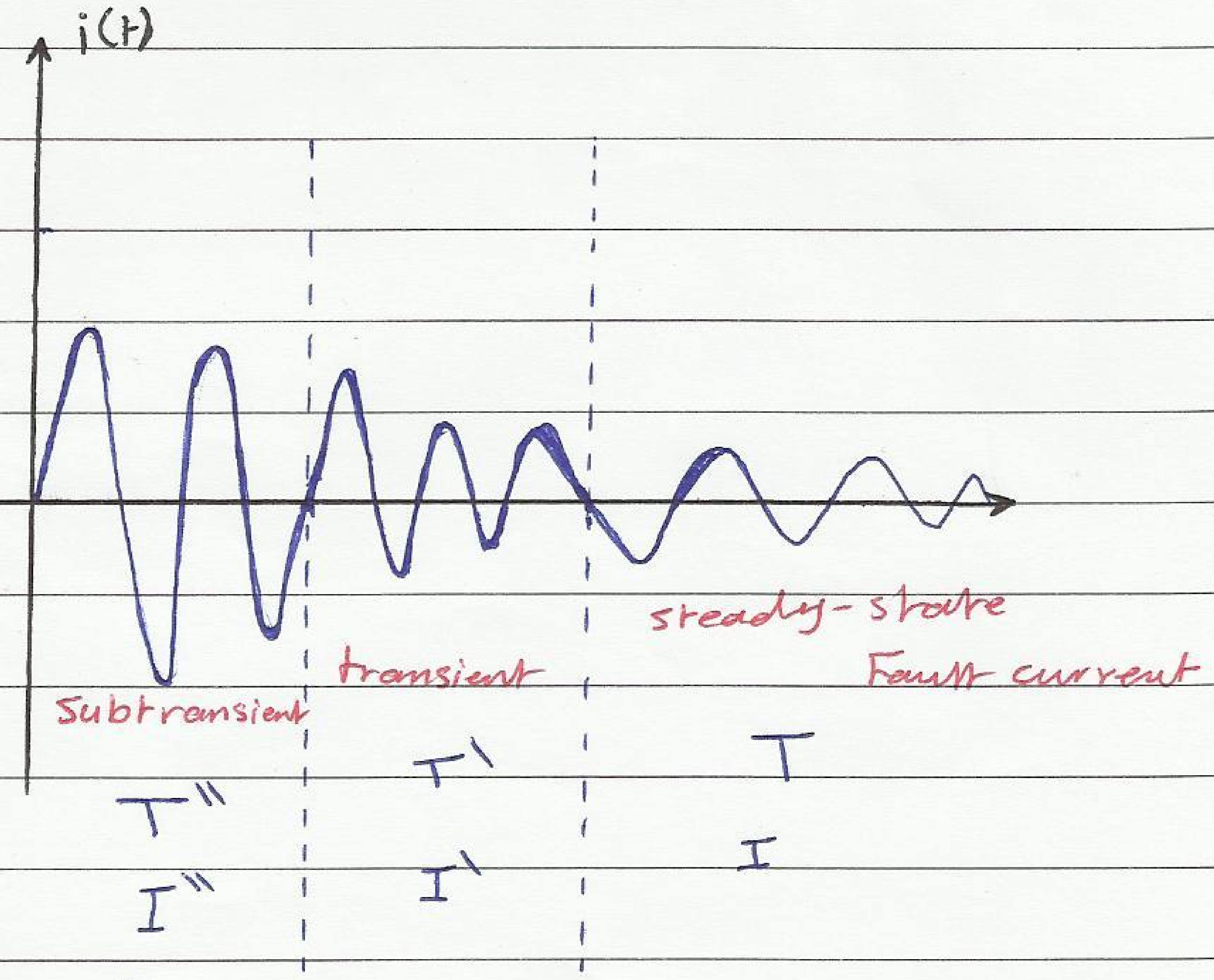
5- Surges (الصواعق)

* Short - circuit transient in synchronouns generator :-



$P_m \gg P_e \Rightarrow$ acceleration $\omega\uparrow$, $\delta\uparrow$, $\delta \angle 90^\circ$





response of the synchronouns generator after symmetrical 3-∅ short circuit a cross its terminals

$$\underbrace{X'' = \frac{E_A}{I''} \quad X' = \frac{E_A}{I'} \quad X = \frac{E_A}{I_A}}_{\text{Provided by the manufactorer}}$$

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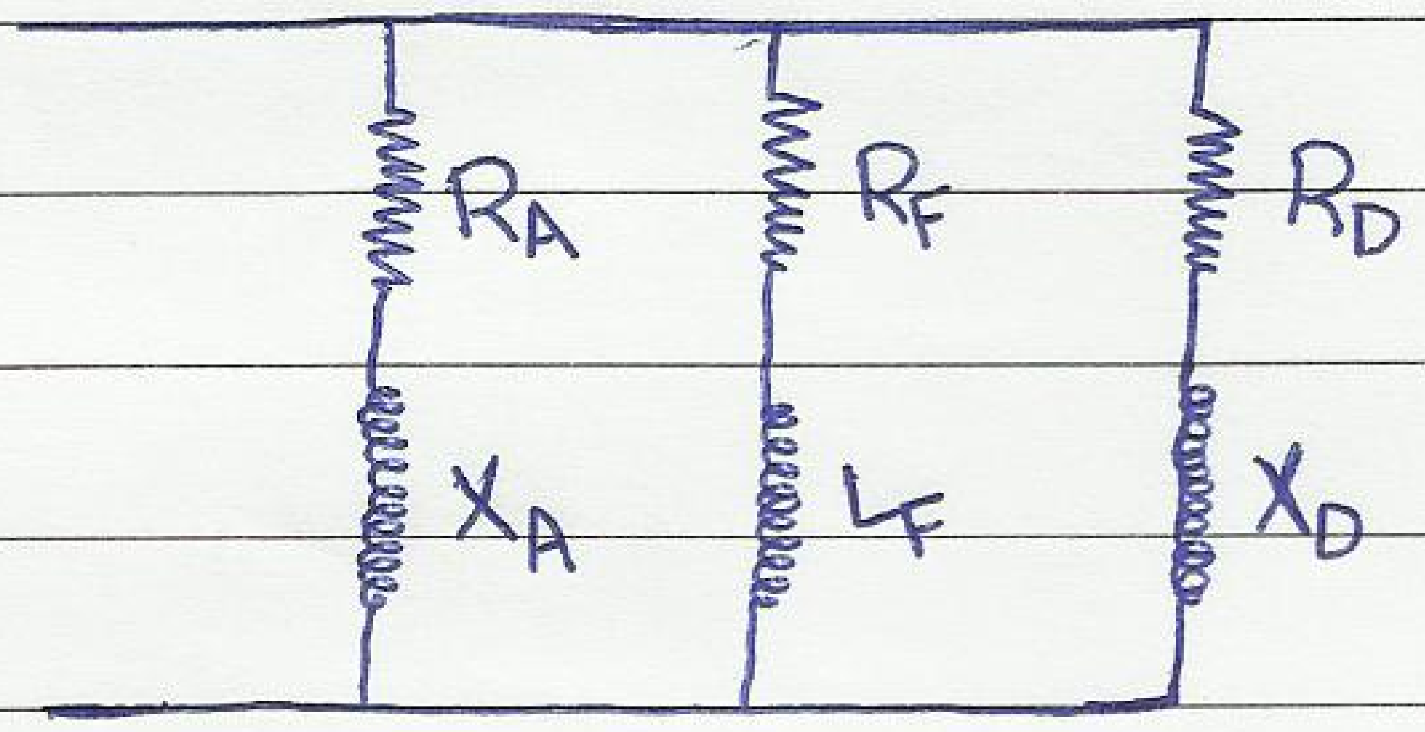
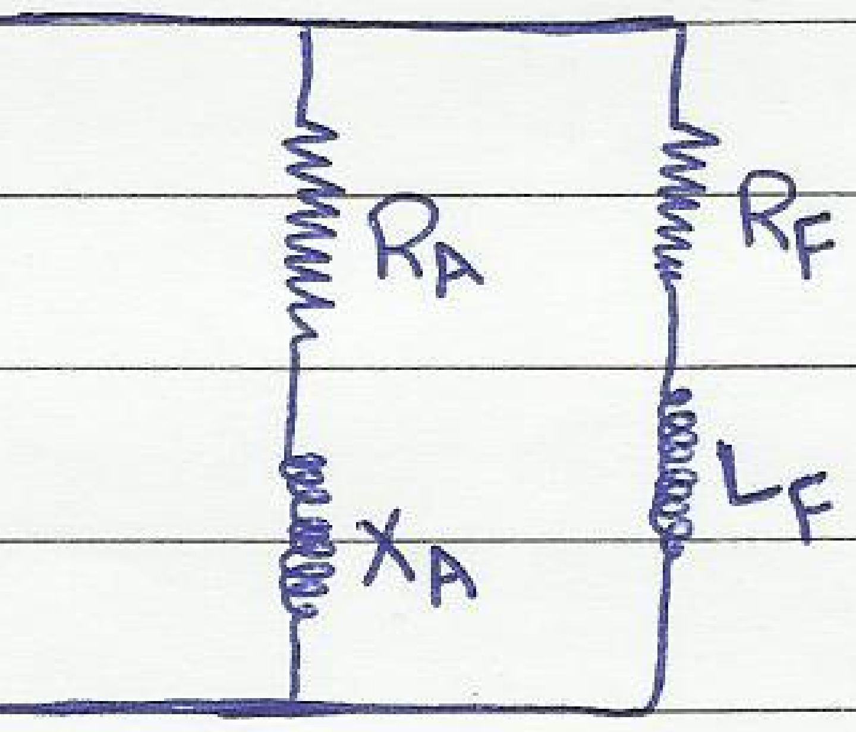
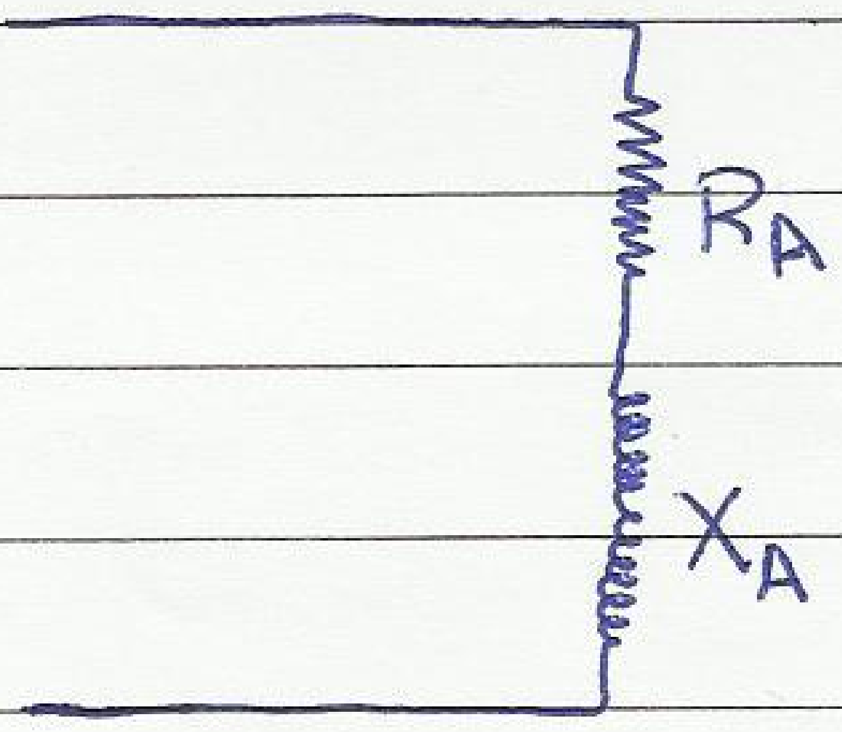
* In subtransient interval, the damper windings and DC Field windings and the phase armature windings are all connected in parallel having the subtransient time constant T''.



* In transient interval, DC Field windings and phase armature windings are connected in parallel having the transient time constant T'.



* In steady-state interval, only the phase armature winding appears in the analysis with a current $I = \frac{E_A}{X_A}$



$I'' = 10 I$ (I'' is a bout 10 times the steady state Fault current I)

$I' = 5 I$

$$I(t) = (I'' - I')e^{-t/T''} + (I' - I)e^{-t/T'} + I$$

- 5.11 :- Synchronouns Generator ratings :-

ratings :- certain basic limits that may be obtained from the system to protect the system from improper operation (maximum limit which should not be exceeded).

* Typical ratings :-

1] Voltage

2] Frequency $f = \frac{nP}{120} \Rightarrow$ Infinite Bus system.

3] speed ⇒ bearings (friction)

4] $S(KVA) \Rightarrow I \Rightarrow I \geq 1.2\, I_{rated}$

5] p.f

6] I_f (field current)

copper losses / saturation

* 7] Service Factor :- the ratio of the actual maximum power to its name plate rating.

- a generator with a service factor of 1.15 can operate at 115% of the rated load without harm.

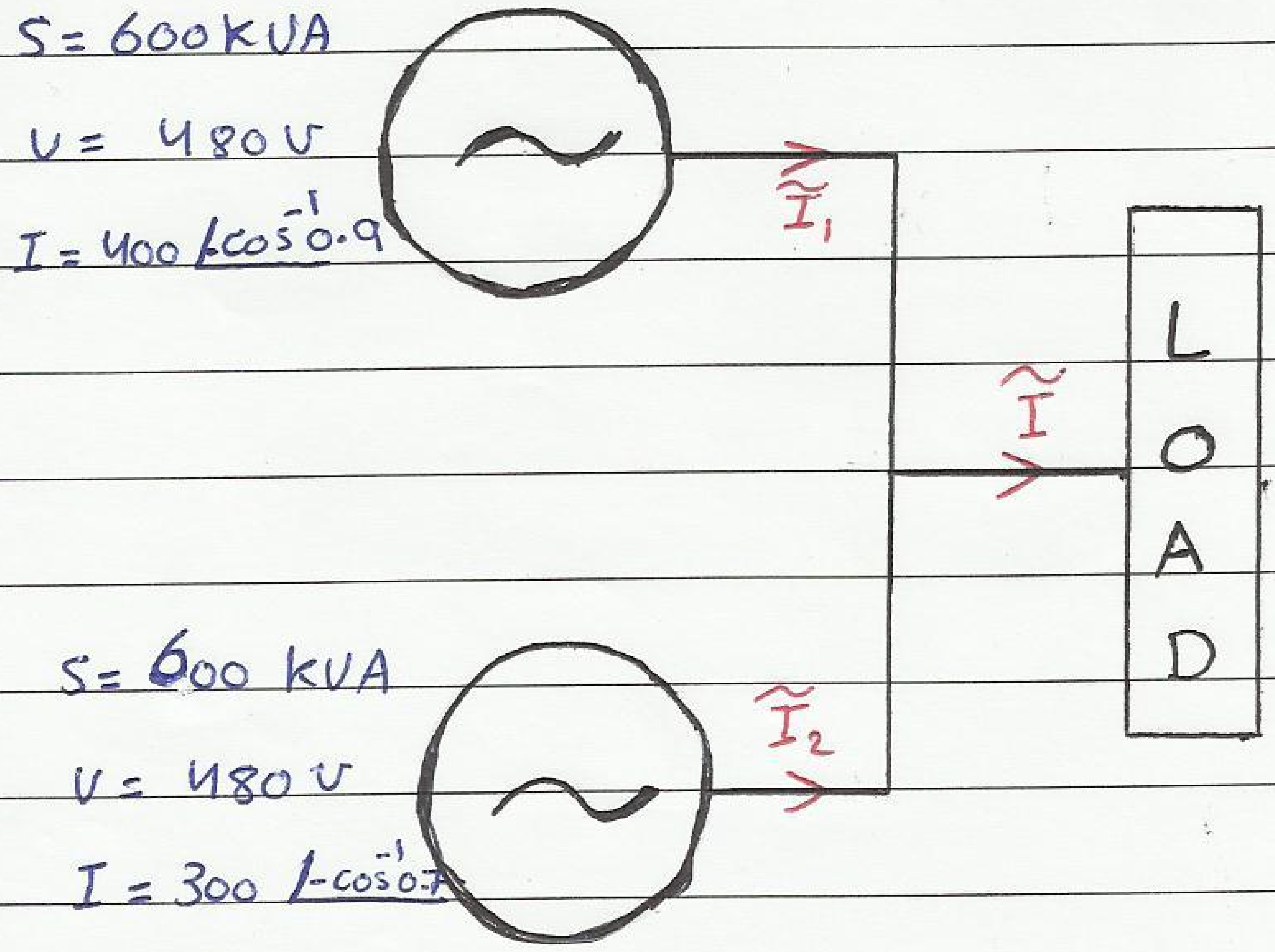
Ex:

a) P_1, P_2, Q_1, Q_2?

$P_1 = \sqrt{3}\, V_L I_L \cos\phi_1$

$= \sqrt{3}(480)(400)(0.9)$

$= 0.3$ MW



$P_2 = \sqrt{3}\, V_L I_L \cos\phi_2$

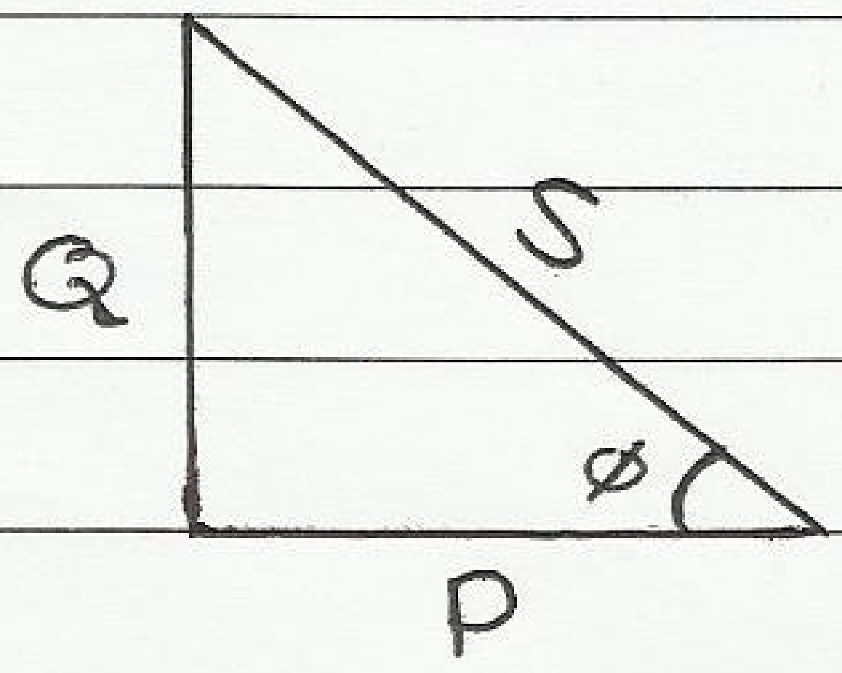
$= \sqrt{3}(480)(300)(0.72)$

$= 0.18$ MW

⇒ $Q_1 = \sqrt{3}\, V_L I_L \sin \phi_1$

$= \sqrt{3}(480)(400)(\sin(\cos^{-1}0.9))$

= 0.145 MVAR



$Q_2 = \sqrt{3}\, V_L I_L \sin \phi_2$

$= \sqrt{3}(480)(300)(\sin(\cos^{-1}0.72))$

= 0.173 MVAR

$Q = P * \tan \phi$

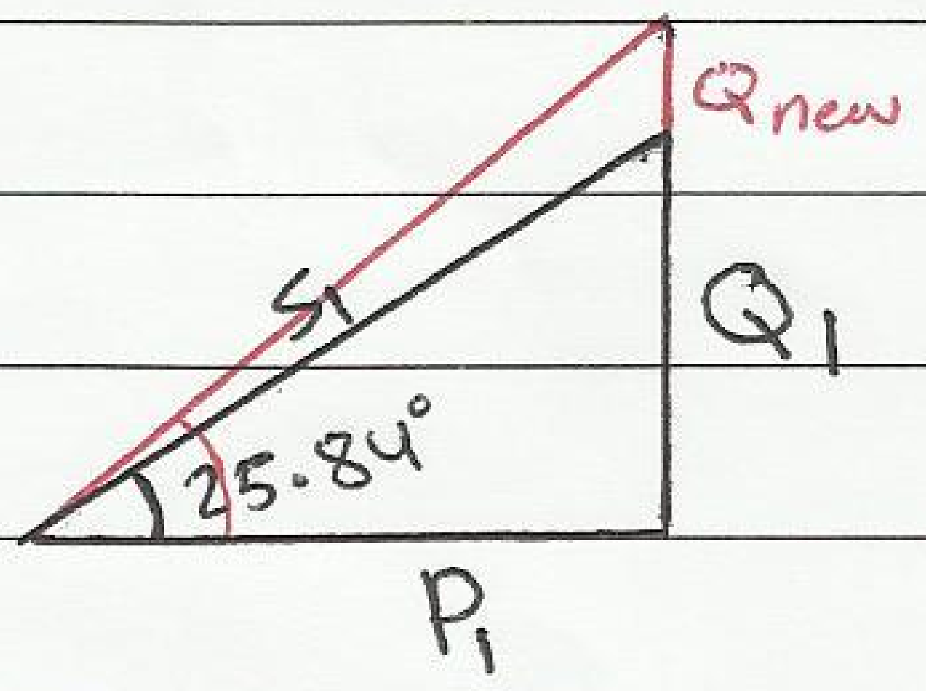
b) overall p.f ? (p.f of the load)

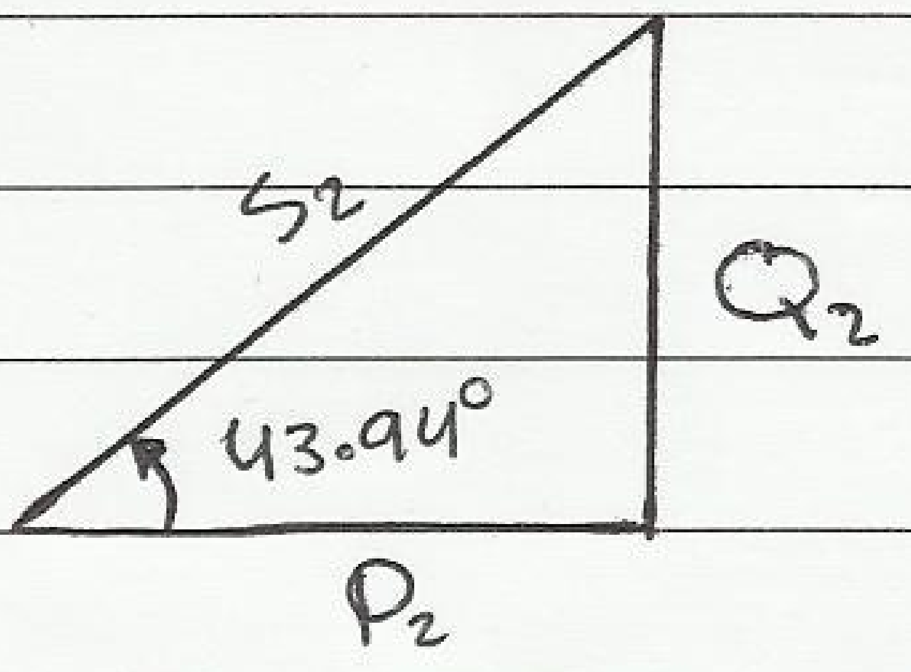
$\tilde{I} = \tilde{I}_1 + \tilde{I}_2 = 400 \angle -\cos^{-1}0.9 + 300 \angle -\cos^{-1}0.72$

$\tilde{I} = 691.5 \angle -33.6$

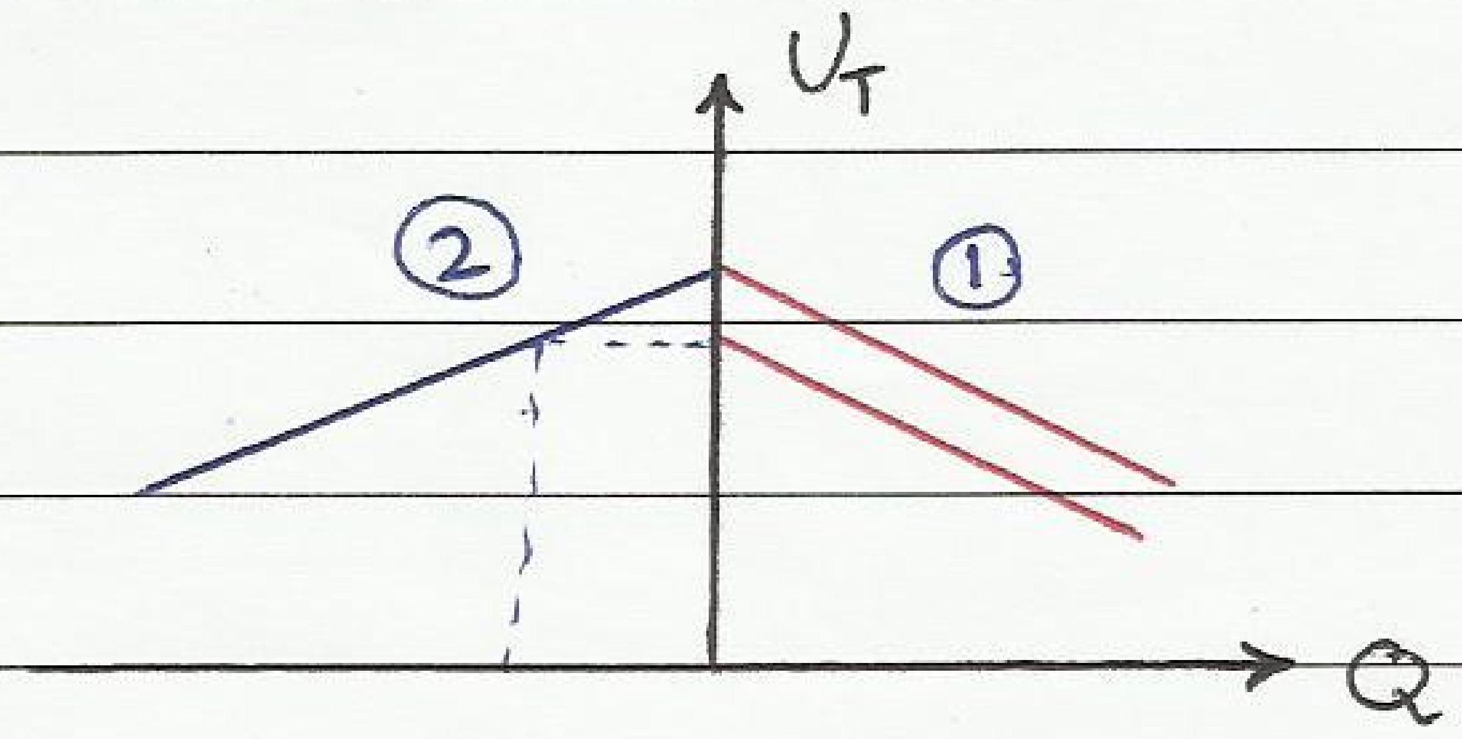
P.F = cos(-33.6°) = 0.833 lagging

c) In what direction must the Field current on each generators be adjusted in order For them to operate at the same P.F ?





* The Field current of G_1 to be increased, such that its Q increase and the field current of the second generator has to be decrease such that it's Q decrease.



Ex2: 20 MVA, 13.8 kV, 0.8 pf lagging Y-connection synchronouns Generator, $R_A = 0$, $X_s = 0.7$ pu.

a) X_s ?

$$S_{base} = \sqrt{3}\, U_{L_{base}}\, I_{L_{base}}$$

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

$$I_{L_{base}} = 836.7 \text{ A}$$

$$Z_{base} = \frac{U_{\phi\, base}}{I_{\phi\, base}} = \frac{(13.8 * 10^3)/\sqrt{3}}{836.7} = 9.5$$

$$X_s = (0.7)(9.5) = 6.66$$

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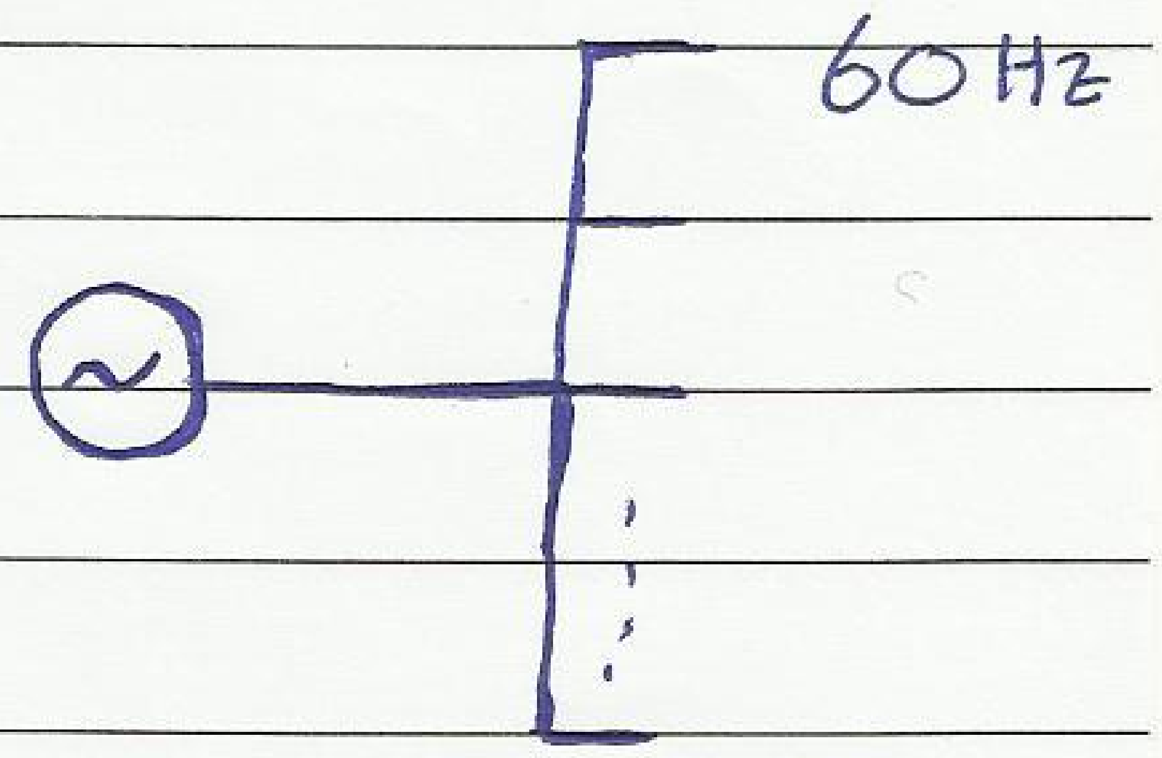
(11.55) ??



Infinite Bus
constant voltage
constant freq.

b) E_A in pu ?

$$\tilde{E}_A = \tilde{U}_T + j X_s \tilde{I}_A$$

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

$$= 1.52 \angle 21.5° \text{ pu}$$

c) E_A in V ?

$$E_A = (1.52)(13.8 * 10^3) = 210.64 \text{ V}$$

d) if the internal generated voltage is reduced by a factor of 0.05 (the new value is 0.95 of the previous one), what will be the new armature current ?

$$E_{A_1} \sin\delta_1 = E_{A_2} \sin\delta_2$$

$$\cancel{E_{A_1}} \sin(21.5) = 0.95\, \cancel{E_{A_1}} \sin\delta_2$$

$$\delta_2 = \sin^{-1}\left(\frac{\sin(21.5)}{0.95}\right)$$

$$\tilde{E}_{A_2} = \tilde{V}_T + j\tilde{I}_A X_s$$

$$0.95 E_{A_1} = 1\angle 0 + j(0.7)\tilde{I}_A$$

$$0.95(1.52)\angle\delta_2 = 1 + j(0.7) I_A$$

$$\tilde{I}_A = \text{----}$$

e) Repeat the previous part for (10, 15, 25, 20)% reduction E_A ?

f) plot the magnitude of Armature current as a Function of E_A?

problems :-

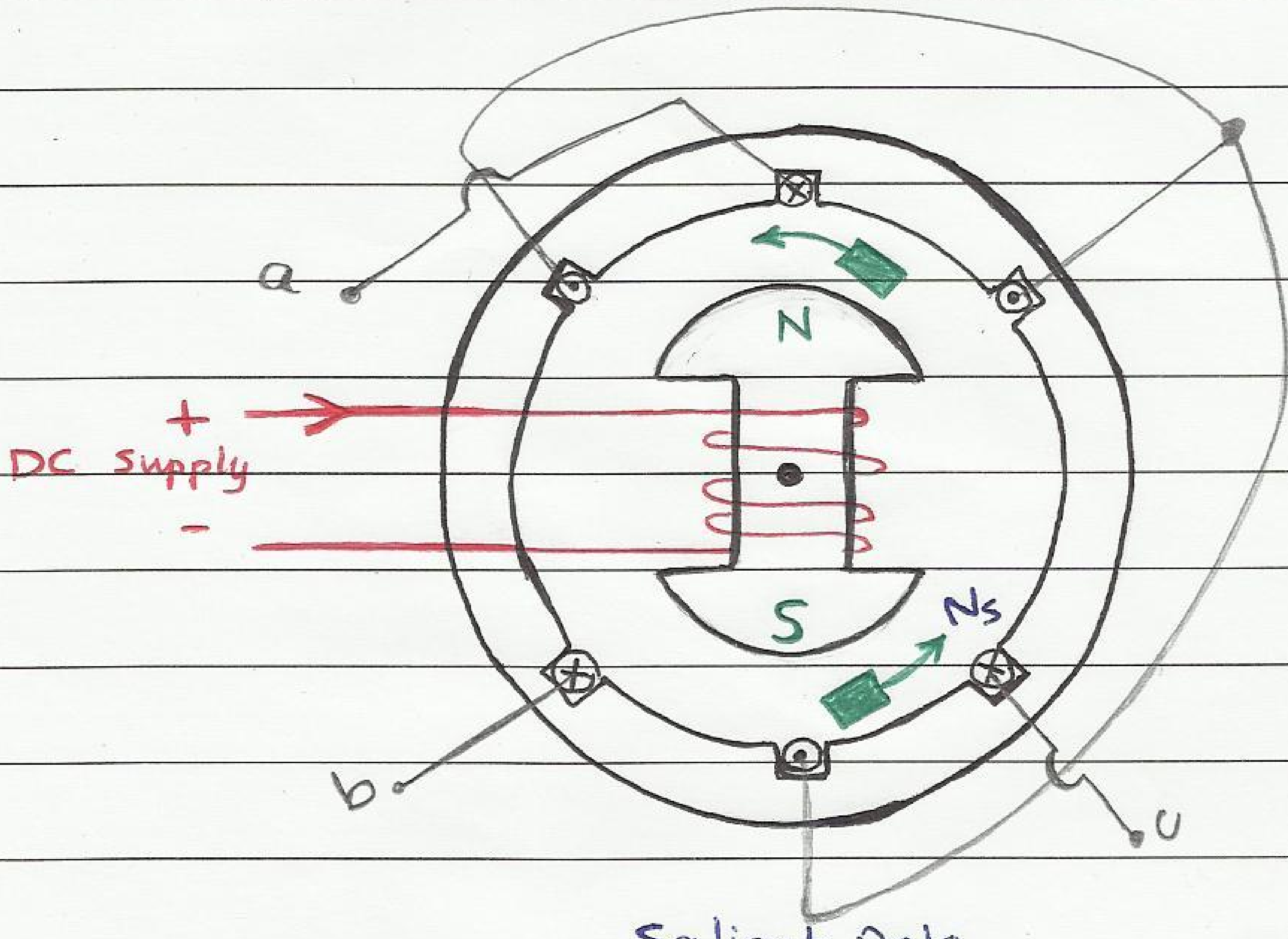
5-6, 5-7 ✓second, 5-8, 5-9, 5-10, 5-22, 5-24, 5-25
5-26, 5-28

CHAPTER
6

SYNCHRONOUS MOTORS

6.1 :-

* construction and principle of operation :-



Salient pole

$n_r = n_s$

ملاحظة :-

الـ Synch. Motor يعتبر
not-self-starting
وهاي مشكلة في جميع الـ mechanical engine ,
فقط الـ 3-ϕ Induction Motor الذي يحوي كـ self-starting

* The Field current I_f of the motor produces a steady-state magnetic field B_R. A three phase set of voltages is applied to the stator of the machine, which produces a three phase current flow in the windings this three phase set of currents in an armature windings, produces a uniform rotating magnetic field B_S, therefore there are two magnetic fields present in the machine, and the rotor field will tend to line up with the stator field.

* starting :- (سيتم شرحها مفصلة في نهاية الشابتر)

- $f = \frac{n_s P}{120}$

- Damper winding

ملاحظة ٢ :-

at no-load the angle between stator mmF and rotor mmF (δ) equals zero $\delta = 0°$

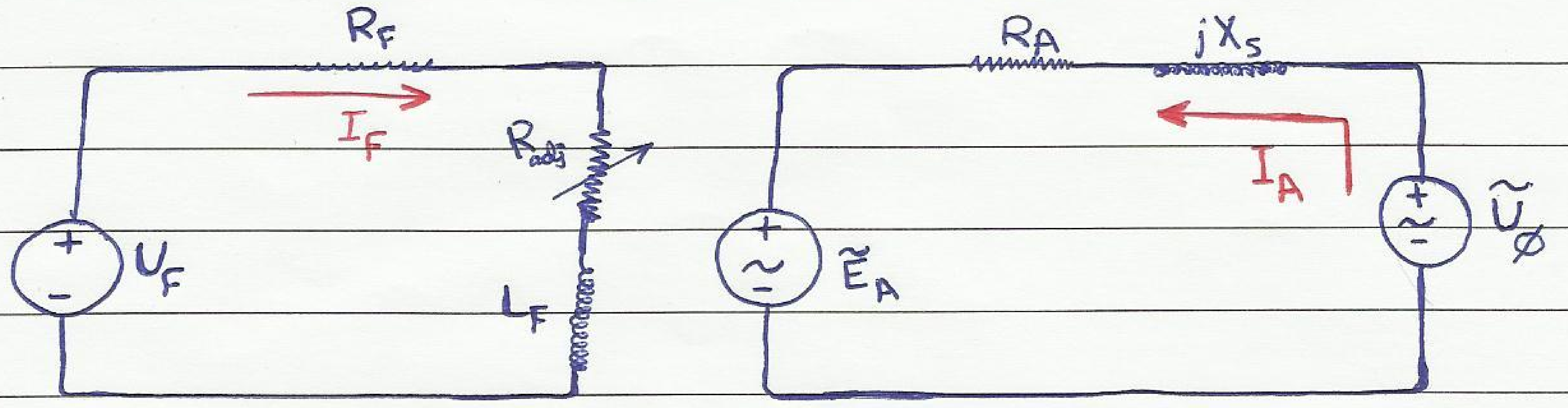
والعلاقة بينهم ستكون دائماً (sin δ) حسب القانون التالي:-

$$P = \frac{3V_\phi E_A}{X_s} \sin\delta$$

* كلما زاد الـ load زادت قيمة δ

• أكثر ما يمكن نصل له δ هو 90° لأنه اذا زادت عن 90° بيصير عنا الـ system ⟸ "unstable system"

- The equivalent circuit of a Synchronouns **Motor** :-



" per-phase equivalent circuit of synchronouns Motor. "

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

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

$$I_F = \frac{V_F}{R_F + R_{adj}}$$

* Synchronouns Motor Application :-

- constant speed loads.
- speed control is possible via changing the Frequency of the supply voltage.

* Synchronouns Motor advanteges :-

- constant speed
- Power Factor (PF) corrector.
- controllabel.

كمان تعتبر Application

* Synchronouns Motor disadvanteges :-

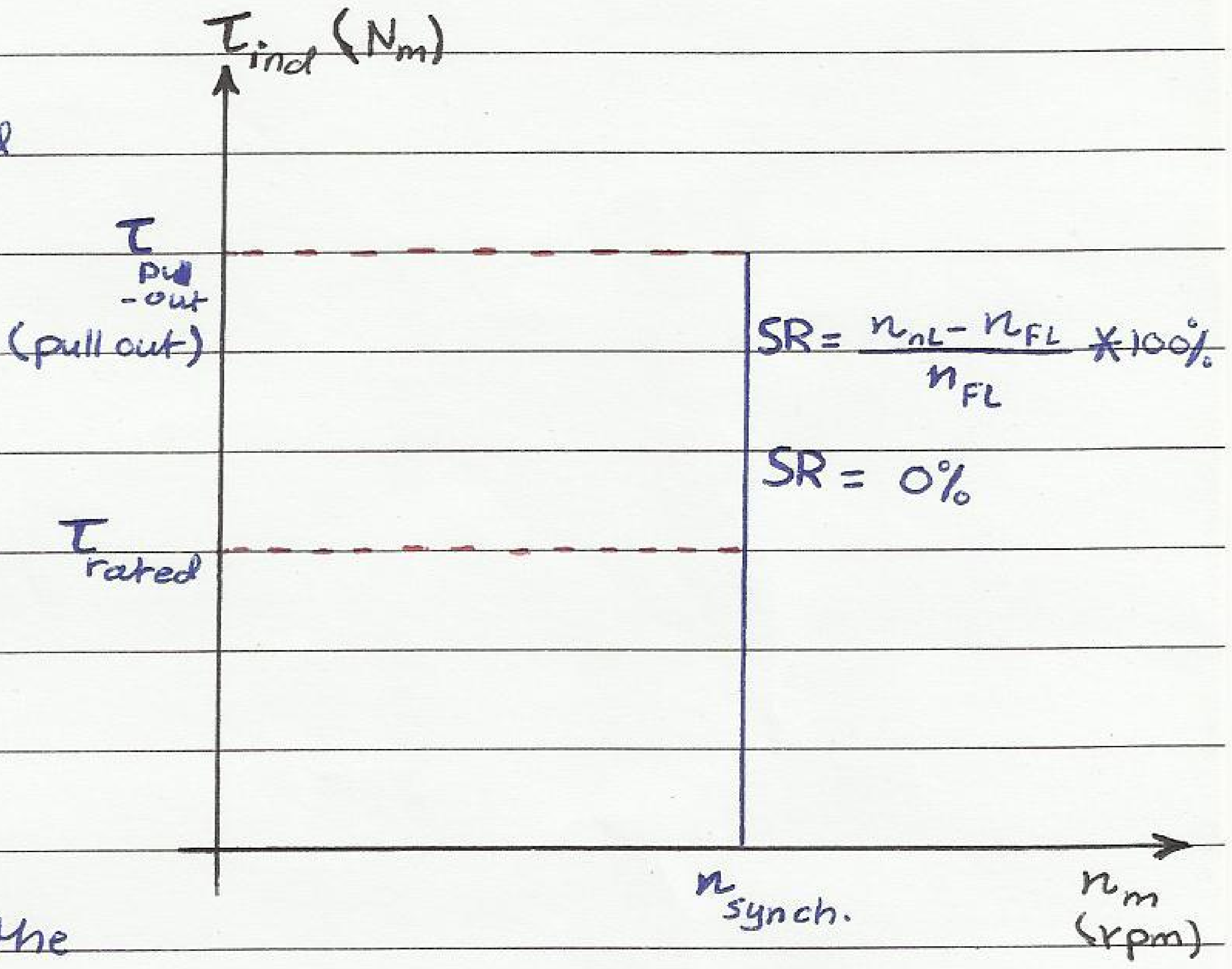
- not-self starting.
- Oscillation if the load increase.

* 6.2 :- Steady-state synchronous motor operation :-

- In steady-state the rotational speed of synchronous motor is constant Irrespective of the value of the load torque.

$\tau_{ind} = \frac{P_{out}}{\omega_s}$, $P_{out} = \frac{3\, V_\phi E_A}{X_s} \sin\delta$, then :-

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



* Synchronouns motors supply power to loads that are basically constant-speed devices. They are usually connected to power systems very much larger than the individual motors, so the power systems appears as infinite Buses to the motors. This mean that the terminal voltage and the system Frequency will be constant regardless of the amount of power drawn by the motor. The speed of rotation of the motor is locked to the applied electrical Frequency, so the speed of the motor will be constant regardless of the load. The steady-state speed of the motor is constant From no load all the way up to the maximum torque that the motor can supply (pull-out torque), so the speed regulation of the motor is 0 percent.

$$\tau_{pullout} = \tau_{ind}\Big|_{\delta=90^\circ} = \frac{3\, V_\phi E_A}{\omega_s X_s}$$

* $\delta = 90^\circ$ (marginally stabie pt.)
unstable يعني أي تأثير بسيط يخليها

$\tau_{rated} < \tau_{pull-out}$

$\tau_{pullout} \approx 3\, \tau_{rated}$ (the pull-out torque may typically be 3 times the Full load torque of the machine)

* When the load torque applied on the shaft of synchronous motor exceeds the pull-out Torque the rotor can no-longer remain locked to the stator rotating magnatic Field and the rotor start Oscillations which called of " Synchronism" .

* The effect of load changes on a Synchronous Motor :-

- In this part , $|\tilde{E}_A|$ is constant , i.e I_f is constant (magnetic Flux constant)
- The applied voltage & frequency are also assumed constants (Infinite Bus).
- When the load torque (external torque) increases , the induced torque (τ_{ind}) must increase to match this change (torque needed).

this point is applied on all type of machines ليس فقط على ال synchronous motor.

* Because it is Synchronous motor , then the rotor speed ω_r is principally constant = ω_s .

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

$$\tau_{ind}\uparrow \Rightarrow (E_A \sin\delta)\uparrow$$

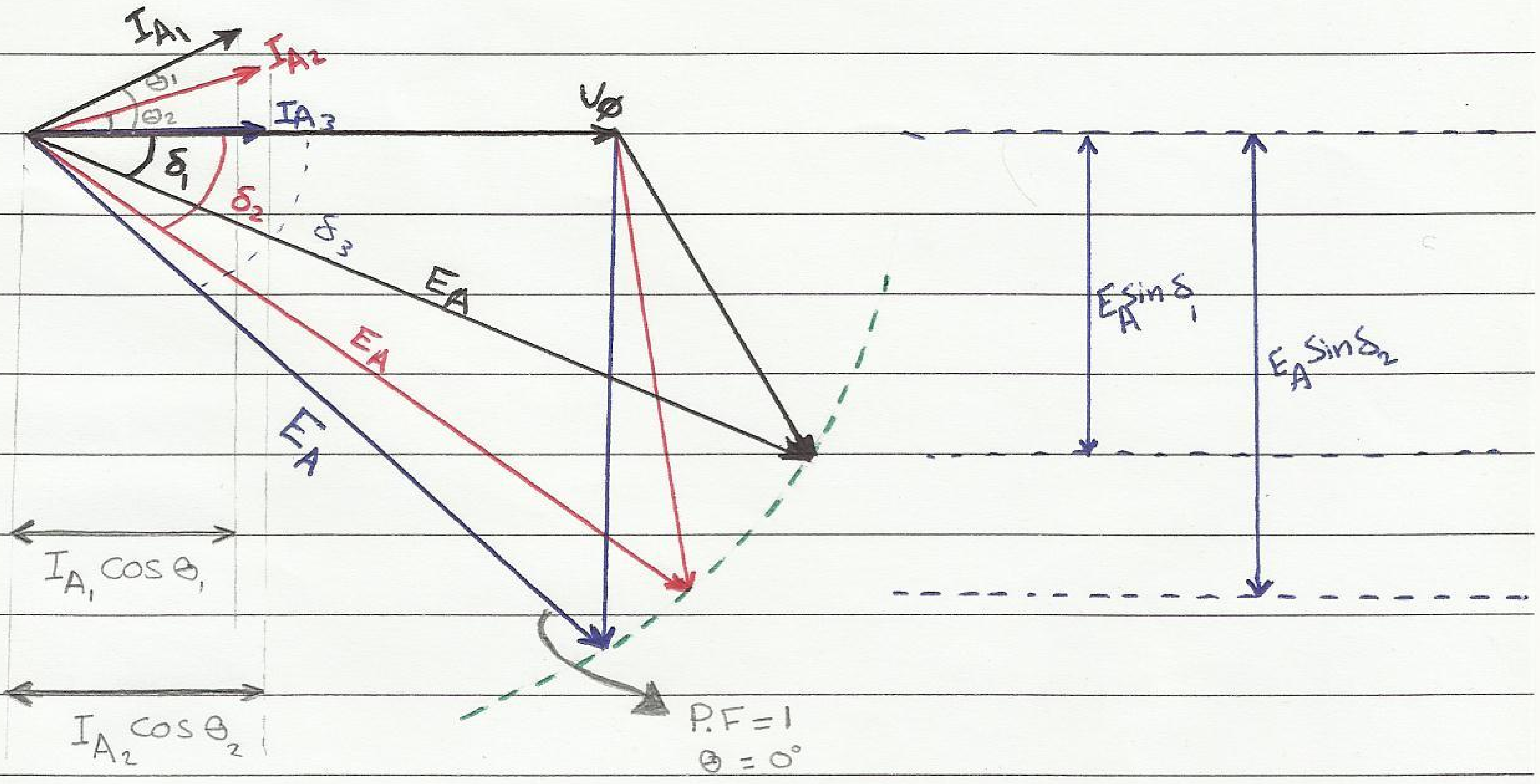
- if I_f is Fixed $\delta\uparrow \Rightarrow \sin\delta\uparrow$ only
- if I_f is not Fixed $E_A \sin\delta\uparrow$

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

$$P_{out}\uparrow \Rightarrow \tau_{ind}\uparrow \Rightarrow P_{in}\uparrow$$

$$P_{in}\uparrow \Rightarrow I_A \cos\theta\uparrow$$

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



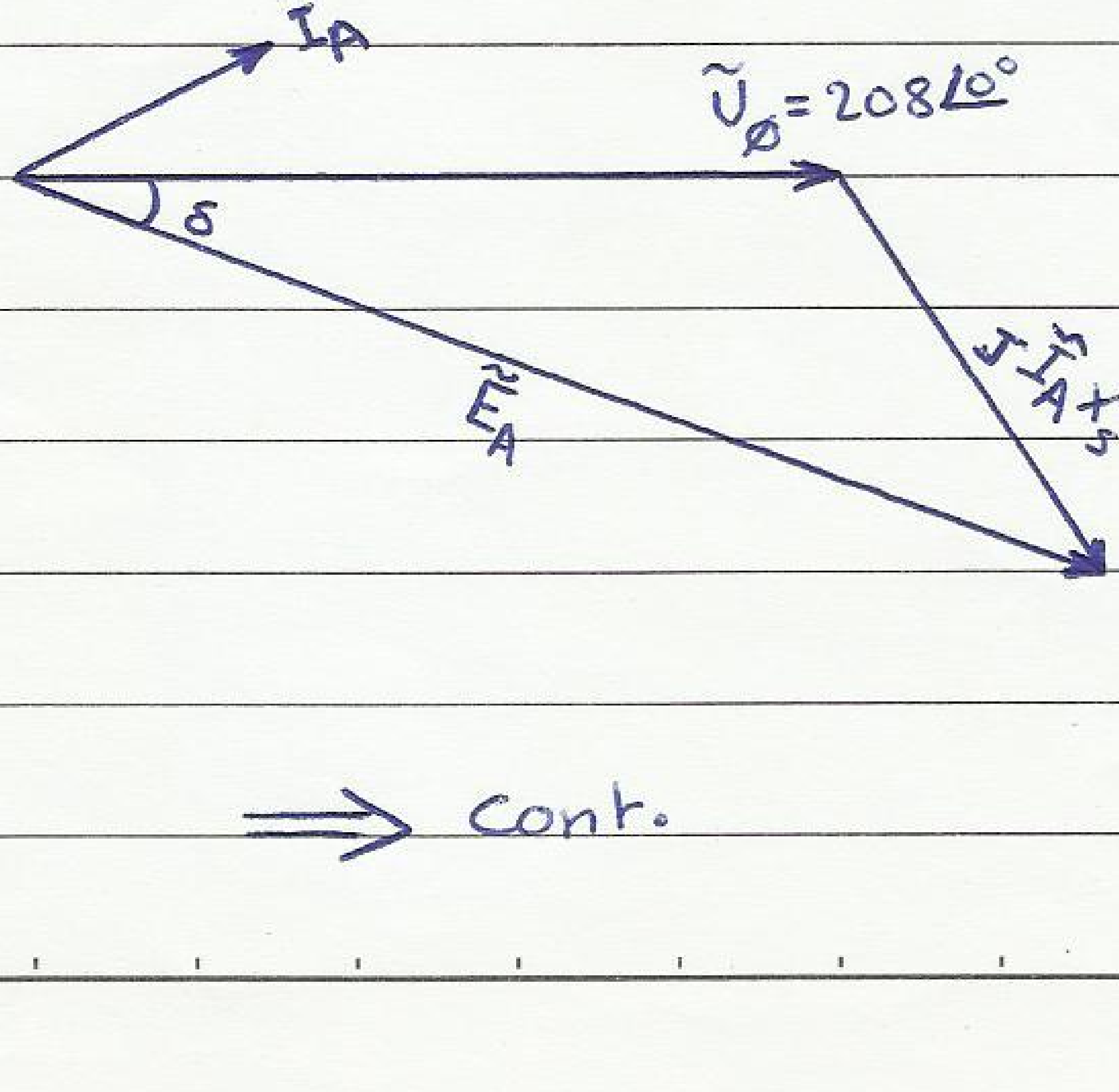
* Conclusion :-

- As the load increases ⇒ P_{in} ↑, P_{out} ↑, τ_{ind} ↑, I_A ↑, $I_A\cos\theta$ ↑ $E_A \sin\delta$ ↑, $\sin\delta$ ↑, δ ↑ and the motor becomes more and more lagging P.F.

89.9°

* **Ex** : 208 V, 45 kVA, 0.8 p.F leading, 60 Hz, Δ-connection stator $X_s = 2.5\,\Omega$, $R_A = 0$, $P_{Fract\,win.} = 1.5$ kw, $P_{core} = 1$ kw, Initially the shaft is supplying 15 hp (P_{out}), and p.F = 0.8 leading.

a) Draw the phasor diagram?



⟹ cont.

Sub. Date: / /

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

$P_{out} = 15\ hp = 15(746) = 11.2\ kw$

$P_{in} = P_{out} + P_{friction+winding} + P_{core} + P_{cu}$

$= 11.2k + 1.5*10^3 + 1*10^3 + 0 = 13.7\ kw$

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

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

$I_L = 47.5\ A$

$I_A = I_\phi = \frac{I_L}{\sqrt{3}} = \ = \frac{47.5}{\sqrt{3}} \angle 36.8^\circ$

$= 27.4 \angle 36.8^\circ$

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

$208 \angle 0 = \tilde{E}_A + j(27.4)\angle 36.8 * (2.5)$

$E_A = 255 \angle -12.4^\circ$

$|\tilde{E}_A| = 255$

$\delta = -12.4^\circ$

b) Assume that the shaft load is increased to 30 hp, and the field current is keeped constant.

$P_{out} = (30)(746) = 22.38\ kw$

$P_{in} = 22.38k + 1.5*10^3 + 1*10^3 = 24.9\ kw$

$\Rightarrow$

$$\Rightarrow P_{in} = \frac{3 V_\phi E_A \sin\delta}{X_s}$$

$$24.9\,k = \frac{(3)(208)(255)}{2.5}\sin\delta$$

$$\boxed{\delta = 23^\circ}$$

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

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

$$\tilde{I}_A = 41.2\angle 15^\circ \text{ A}$$

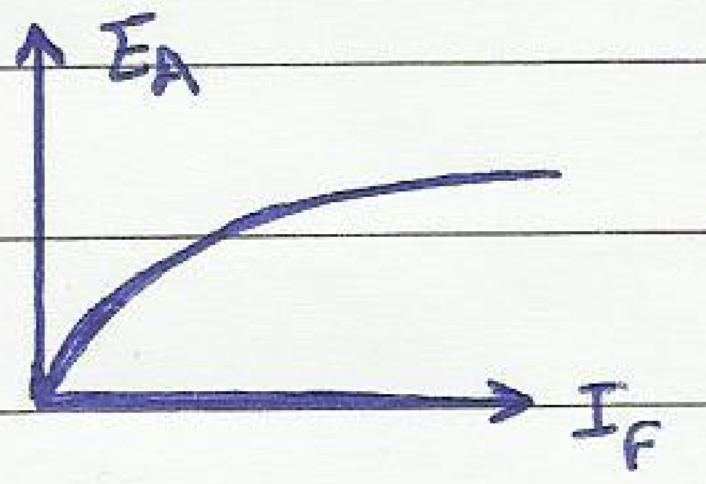
$$I_L = \sqrt{3}\,(41.2) = 71.4 \text{ A}$$

$$PF = \cos 15^\circ = 0.966 \text{ leading}$$

* The effect of field current changes on the synchronous motor :-

$V_\phi, P_{out}, P_{in}, \omega_m \Rightarrow$ constants

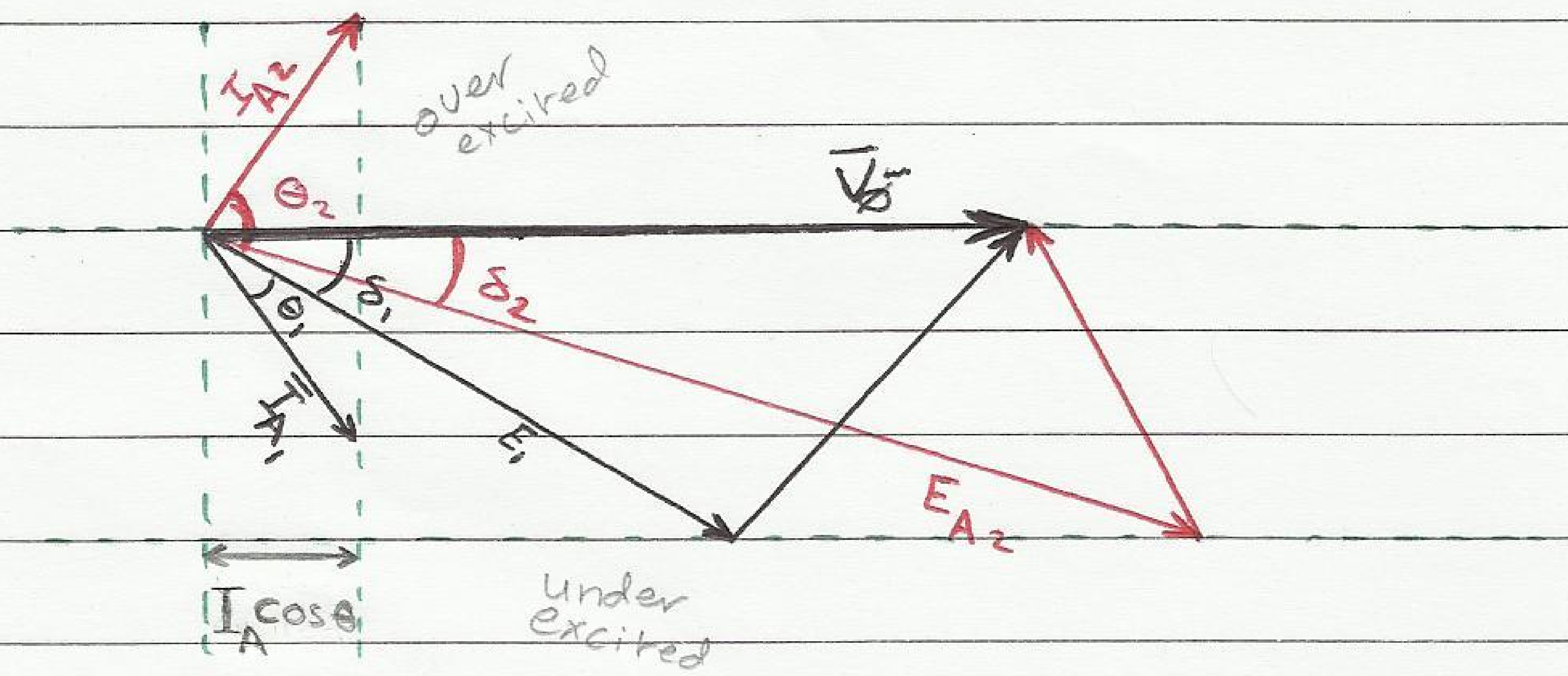
$I_F \uparrow$, $E_A \uparrow$ and vice versa



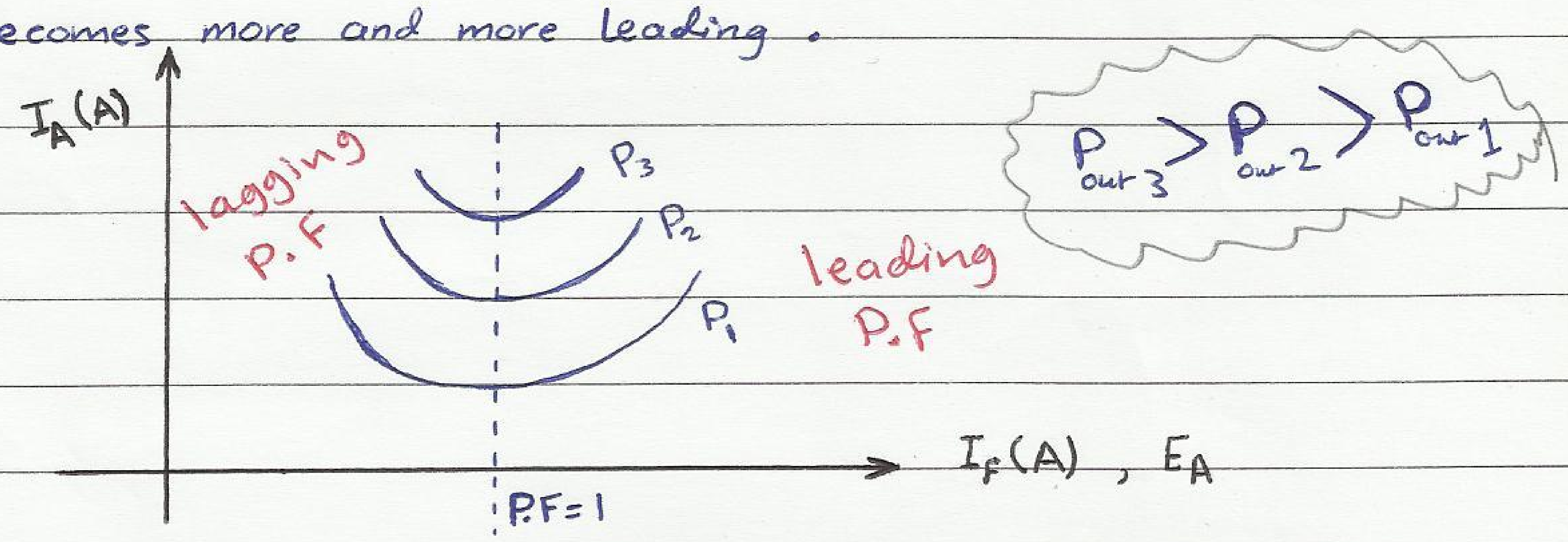
$$P_{in} = 3 V_\phi \underbrace{I_A \cos\theta}_{\text{Fixed}}$$

$$P_{in} = \frac{3 V_\phi \overset{\text{Fixed}}{E_A \sin\delta}}{X_s}$$

- The effect of I_f changes :-



* For constant input and output power of synchronouns motor, as I_f ↑ for Fixed P_{out}, E_A ↑, $E_A \sin\delta$ constant, $I_A \cos\theta$ constant, I_A ↓ and the P.F becomes less lagging until unity P.F (moves from lag to lead), on Fertheir I_f ↑, E_A continuously increasing ↑, I_A start increasing and the P.F becomes more and more leading.



="V-curves of synch. Motor"=

* notes :-

- controlling the I_f of S.M changes it's P.F, over excited S.M are used as controllable P.F corrector.
- lagging P.F motor consumes reactive power (Q) like Induction Motor.
- leading P.F motor supplies reactive power (Q) like capacitors.
- Induction Motor always lagging

capacitor ← شغلة نزيلها

synch. Motor

Ex: 208 V, 45 kVA, 0.85 p.F leading Synchronous Motor, Δ-connected stator, 60 Hz, P_{out} = 15 hp, with an initial pF of 0.85 lagging

From last Example.

a) Sketch the phasor diagram of this operating point.

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

$$P_{out} + P_{loss} = 3 V_\phi I_A \cos\theta$$

$$(15)(746) + 15*10^3 + 1*10^3 = (3)(208)\, I_A\, (0.85) \Rightarrow \boxed{I_A = 25.8\ A}$$

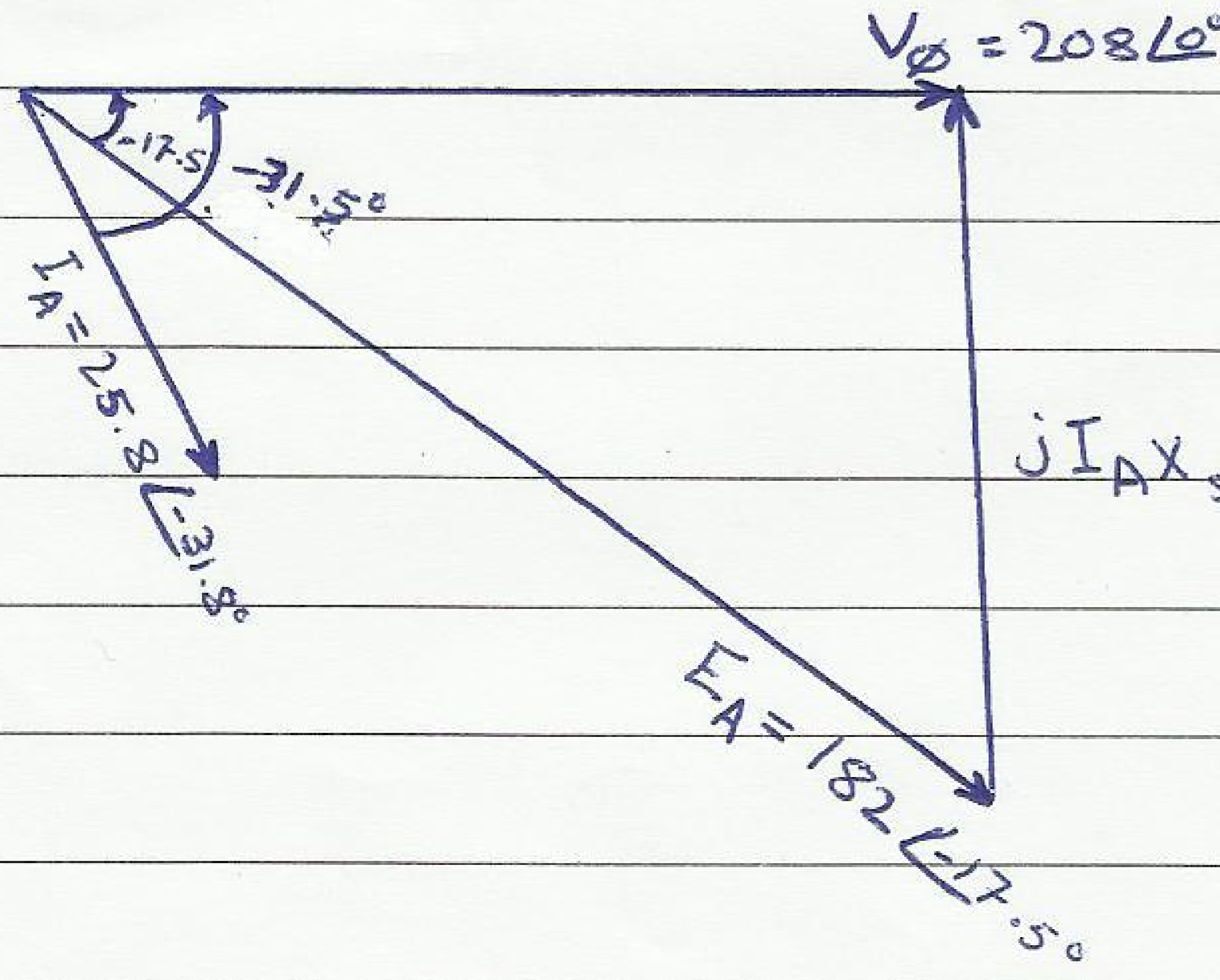
phase current

$$\bar{I}_A = 25.8 \angle -\cos^{-1}(0.85) = 25.8 \angle -31.8^\circ\ A$$

$$\bar{E}_A = \bar{V}_\phi - j\bar{I}_A X_s$$

$$= 208 \angle 0 - j(25.8 \angle -31.8^\circ)(2.5)$$

$$= 182 \angle -17.5^\circ$$



b) If the motor Flux is increase, by 25% sketch the new phasor diagram of the motor, what is the value of E_A, I_A, P.F ??

$$E_{A_1} \sin\delta_1 = E_{A_2} \sin\delta_2$$

ملاحظة: -

هناك طريقة أخرى للحل باستخدام التيار

$$I_{A_1} \cos\theta_1 = I_A \cos\theta_2$$

not necessarily linear

$$\cancel{E_{A_1}} \sin(-17.5) = 1.25 \cancel{E_{A_1}} \sin\delta_2$$

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

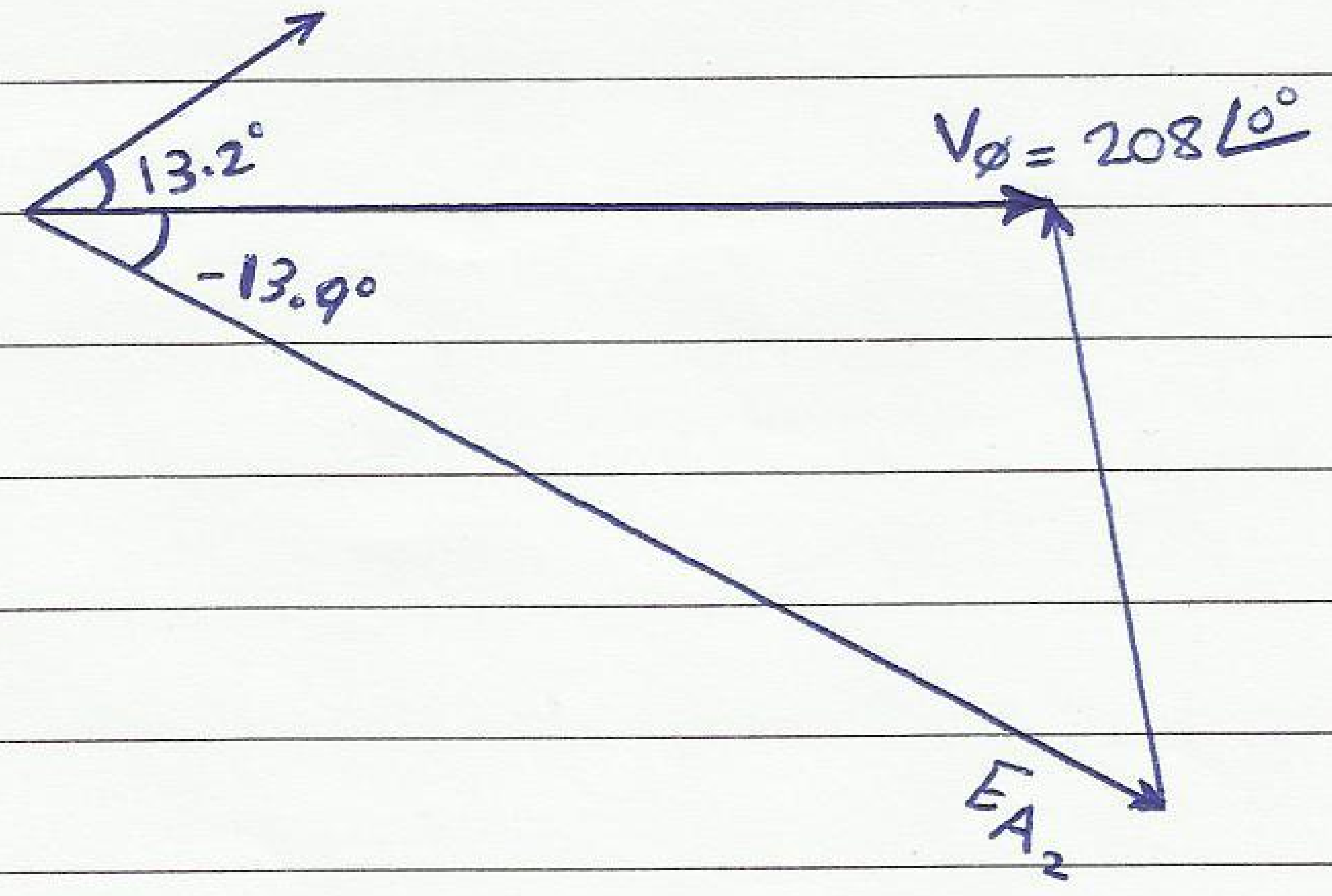
$\delta_2 = -13.9°$ ⇒ δ is decreased as a magnitude

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

$$208\angle 0° = (1.25)(182)\angle{-13.9°} + j(2.5)\,\overline{I}_A$$

$$\overline{I}_A = 22.5\angle 13.2° \text{ A}$$

P.F = cos (13.2°) = 0.974 leading



c) What is the increase in Flux such that to have a unity p.F motor ?
(refer to part a).

$$I_A \angle 0 = \frac{208 - y(182)\angle \delta_2}{2.5j}$$

حيث أن y = الزيادة + 1

$$(2.5j)\, I_A = 208 - y(182)\angle \delta_2$$

$$(2.5j)\, I_A = 208 - y(182)\cos\delta_2 - jy(182)\sin\delta_2$$

$$208 = y(182)\cos\delta_2 \quad \ldots\ldots (1)$$

$$(2.5j)\, I_A = -jy(182)\sin\delta_2 \quad \ldots\ldots (2)$$

$$\cancel{E}_{A_1}\sin\delta_1 = y\,\cancel{E}_{A_2}\sin\delta_2$$

$$\sin\delta_2 = \frac{\sin(-17.5)}{y} \quad \ldots\ldots (3)$$

* Solve these equations :-

$I_A = 21.891$

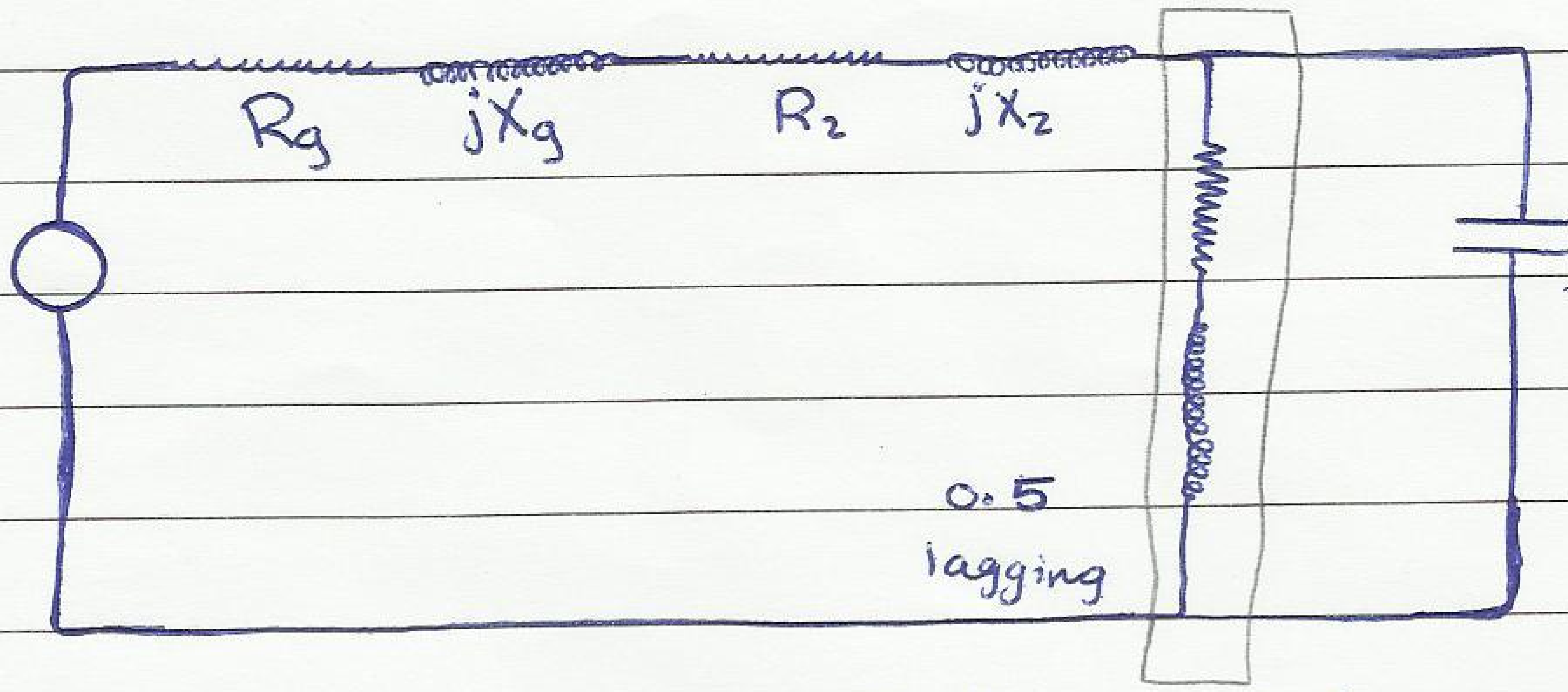
$\delta_2 = -14.7$

$y = 1.1817$

$\% = 18.17\%$

لأن y = الزيادة + 1

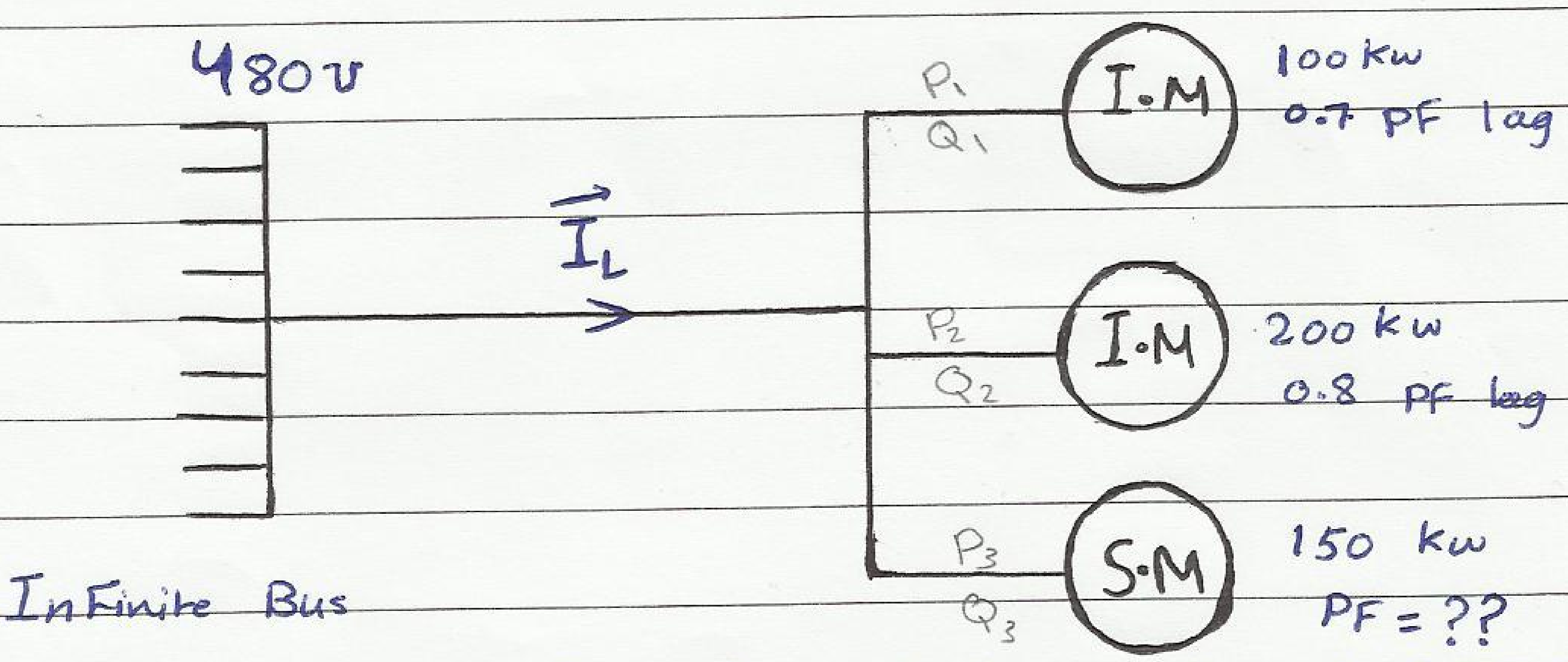
* The synchronous Motor and power Factor correction :-



* consume same power with less current.

* over excited synchronous Motor run at leading power Factors. This power Factor is controllable via changing the value of Field current for a given mechanical load coupled to the motor.

Ex :

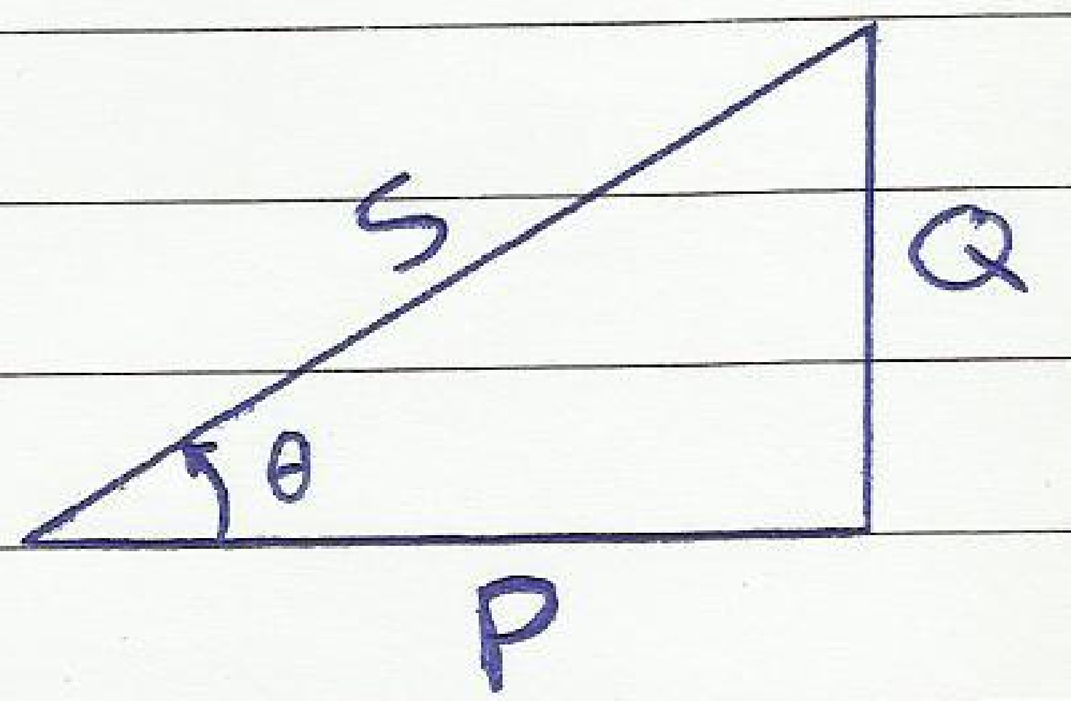


a) If the synchronous motor is adjusted to operate at 0.85 pf lag, Find the value of $\bar{I_L}$?

$Q_1 = \tan\theta_1 P_1 = \tan(\cos^{-1}(0.7)) * (100*10^3) = 80.2$ KVAR

$Q_2 = \tan\theta_2 P_2 = \tan(\cos^{-1}(0.8)) * (200*10^3) = 150$ KVAR

$Q_3 = \tan\theta_3 P_3 = \tan(\cos^{-1}(0.85)) * (150*10^3) = 93$ KVAR



$P_{tot.} = P_1 + P_2 + P_3 = 100 + 200 + 150 = 450$ kw

$Q_{tot.} = Q_1 + Q_2 + Q_3 = 80.2 + 150 + 93 = 323.2$ KVAR

$\Rightarrow \theta_{tot.} = \tan^{-1}\left(\frac{Q_{tot}}{P_{tot}}\right) = \tan^{-1}\left(\frac{323.2}{450}\right) = 35.68^\circ$

$\cos(\theta_{tot}) = \cos(35.68) = 0.812$ lagging For all

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

$450 * 10^3 = \sqrt{3}(480)\, I_L (0.812) \Rightarrow \boxed{\bar{I}_L = 667 \angle -\cos^{-1} 0.812}$

b) If the synchronous motor is adjusted to 0.85 pf leading, Find I_L ??

$P_{tot.} = 450$ kw (same as before)

$Q_{tot} = Q_1 + Q_2 - Q_3 = 80.2 + 150 - 93 = 137.2$ KVAR

leading deliver reactive power.

$\theta_{tot} = \tan^{-1}\left(\frac{Q_{tot}}{P_{tot}}\right) = 16.95$

$P.F_{tot} = \cos(\theta_{tot}) = 0.957$ lagging

$I_L = \frac{P_{tot}}{\sqrt{3}(480)(PF)_{tot}} = 566A \Rightarrow \bar{I}_L = 566 \angle -\cos^{-1} 0.957$

c) What is the ratio of line copper losses between both cases?
(calculate the percentage reduction in the copper losses of the transmission line).

$P_{cu} \propto I^2 \Rightarrow \frac{(566)^2}{(667)^2} = 0.72 \Rightarrow$ reduction = 28%

* Conclusion :-

The losses in the second case has been reduced by a factor of 28% despite the fact of the real power consumed has not changed.

* 6.3 :- Starting Synchronous Motor :-

- synchronous motor it's not self-starting motor.
- It's impossible For the rotor of synchronous motor to line up with the stator magnetic field by itself due to inertia (huge mass), three basic approaches are used to start synchronous motor :-

1] reduce the speed of the rotating mmF by reducing the frequency by inverters or cycloconverters and then increasing it gradually.

2] using external prime mover to accelarate the rotor up to (n_s), then we disconnect the prime mover and connect it with the field circuit.

3] using damper windings, in this case starting as induction motor up to almost n_s, and then running as synchronous motor after switching on the field circuit.

Ex_1: 480 V, 375 kVA, 0.85 pF lag Y-connection synchronous Generator

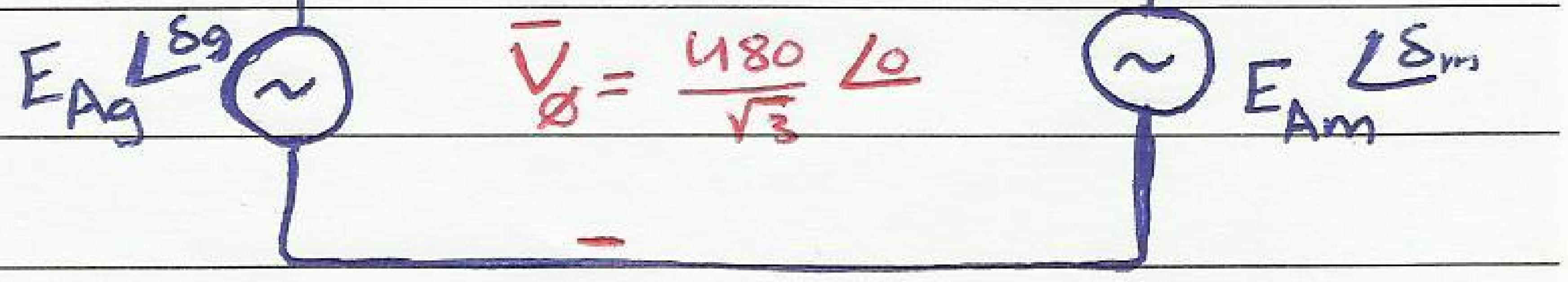
$X_s = 0.6\,\Omega$, $R_A = 0$

480 V, 100 kVA, 0.8 pF leading Y-connected Synchronous Motor

$X_s = 2.3\,\Omega$, $R_A = 0$

operating point { The generator is adjusted to supply a terminal voltage of 480 V at the rated current of the motor at unity power factor?

a) E_{Ag} & E_{Am}?



at unity pF $\cos\theta = 1$

then $P = S$

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

$100 * 10^3 = \sqrt{3}\,(480)\, I_L$

$I_L = 120.3\ A$ $\Rightarrow$

$\Rightarrow \bar{I}_L = 120.3\angle 0$ A

$\bar{I}_\phi = \bar{I}_L = 120.3\angle 0$ A

$$\bar{E}_{Ag} = \bar{V}_\phi + j\bar{I}_\phi X_s$$

$$= \frac{480}{\sqrt{3}}\angle 0 + j(120.3\angle 0)(0.6)$$

$$\boxed{\bar{E}_{Ag} = 286.4\angle 14.6^\circ \ V}$$

$$\bar{V}_\phi = \bar{E}_{AM} + jI_\phi X_s$$

$$\frac{480}{\sqrt{3}}\angle 0 = \bar{E}_{AM} + j(120.3\angle 0)(2.3)$$

$$\boxed{\bar{E}_{AM} = 392\angle -45^\circ \ V}$$

b) If the Flux of the motor is increased by 10% then calculate the new values of δ and I_ϕ ?

$$E_{AM_1}\sin\delta_1 = E_{AM_2}\sin\delta_2$$

$$\cancel{E_{AM_1}}\sin(-45^\circ) = 1.1\,\cancel{E_{AM_1}}\sin\delta_2$$

$$\delta_2 = -40$$

$$I_\phi = \frac{(480/\sqrt{3})\angle 0 - (1.1)(392)\angle -40}{j2.3} = 122.4\angle 10.9^\circ \text{ A}$$

$PF_{new} = \cos(10.9) = 0.98$ leading

Ex 2 :- 440 V 3-Ø Y-connected Synchronous Motor $X_s = 1.5\ \Omega$, The Field current is adjusted so that the torque angle δ is 30° when $P_{out} = 90\text{kW}$

- load angle
- delta angle

a) $|\bar{E}_A| = ?$

$$P = \frac{3 V_\phi E_A \sin\delta}{X_s}$$

$$90 * 10^3 = \frac{3(440/\sqrt{3}) E_A}{1.5} \sin 30^\circ$$

$$E_A = 354.3\ \text{V}$$

b) $$\tilde{I}_\phi = \frac{(440/\sqrt{3})\angle 0 - 354.3\angle -30^\circ}{j\,1.5} = 123.2\ \angle 16.5^\circ\ \text{A}$$

$$\text{PF} = \cos(16.5) = 0.96 \text{ leading}$$

c) $$P_{max} = \frac{3 V_\phi E_A}{X_s} = 18020\ \text{W}$$ ⇒ max. power (static stability power limit).

problems :-

please solve all problems, it's very important

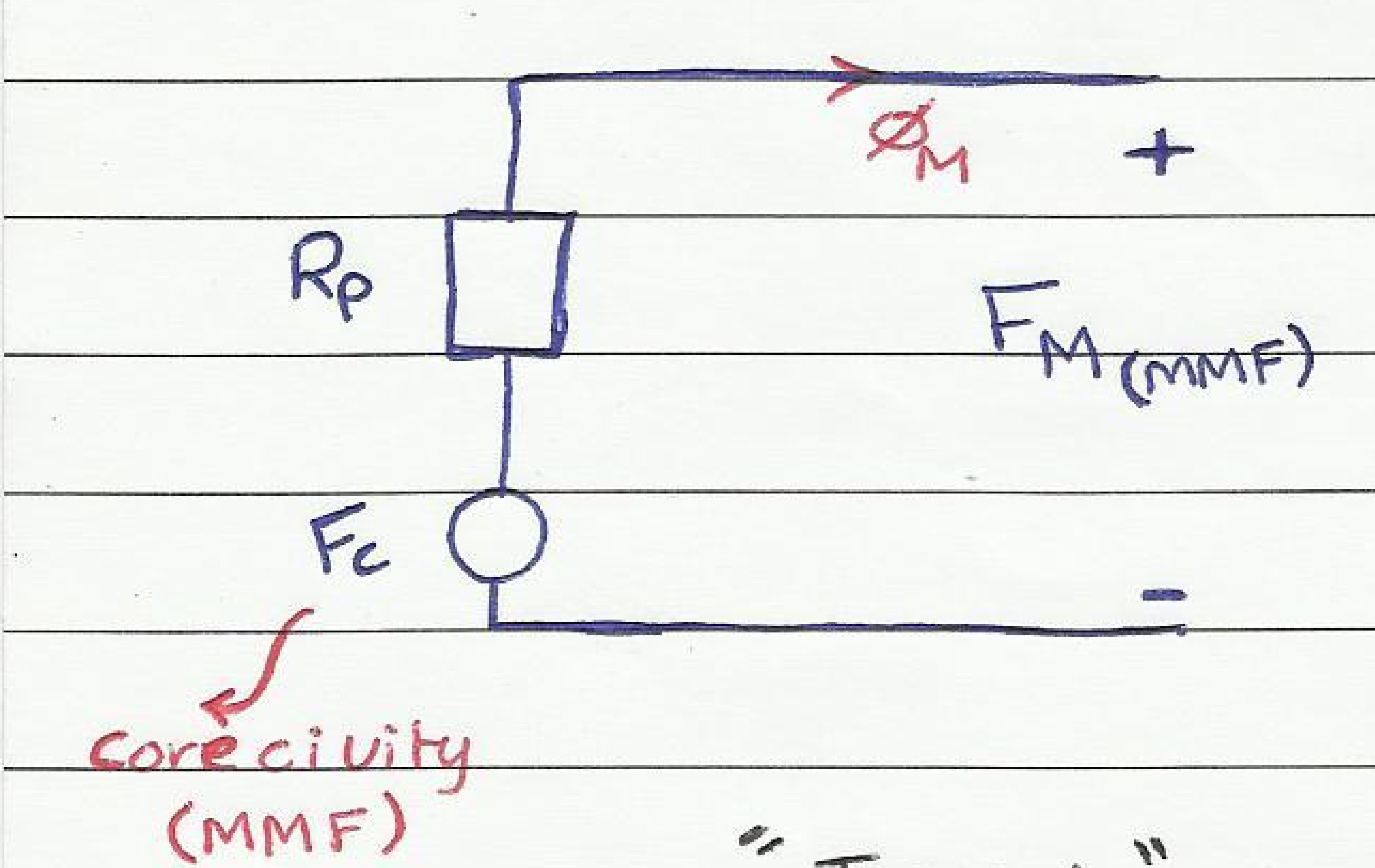
V.V.V.I (6.6 & 6.15)

* Perment _ Magnet Materials and Perment _ Magnet Machines :- (PM)

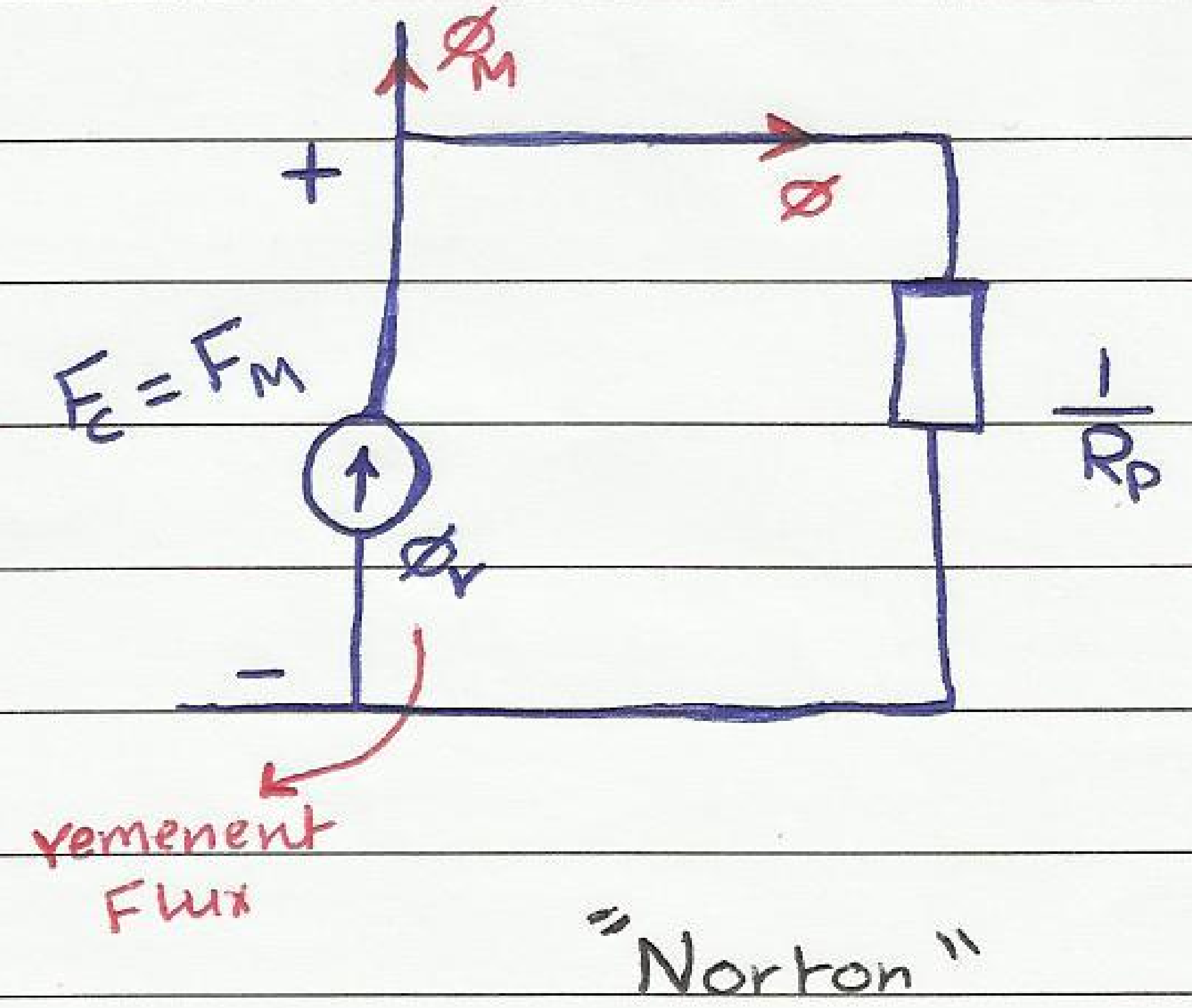
_ The Flux in a PM machine is established by the magnets. Both the internal generated voltage E_A and the induced torque depends on the Flux. $E_A = K\phi\omega$, $\tau = K\phi I_A$. A PM can be consided as source of flux and the magnetic Field is calculated by magnetic circuit approach analogues to a simple electric circuit.

Magnetic circuit Parameter	Electric circuit Parameter
Flux (wb)	current (A)
MMF (A or A.turn)	voltage (V)
Reluctance (A/wb)	Resistance (Ω)

_ A permenent _ magnet can be represented by a Thevenin Equivalent which comprises ~~an~~ MMF source in series which an internal reluctance R_p or by Norton Equivalent comprissing a Flux source in paralel with an internal permence $\left(\frac{1}{R_p}\right)$.



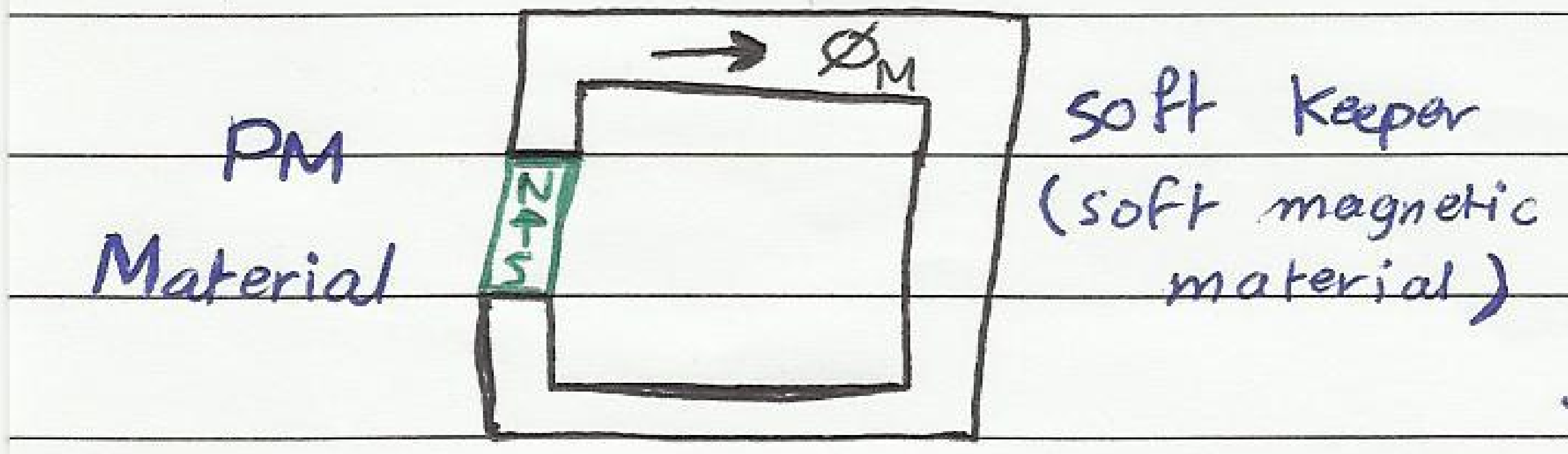
" Thevenin"



"Norton"

inFinite Permeable material

* The magnet can be short circuited by connecting a soft iron Keeper a cross it poles. This makes the mmF across its terminals (Poles) equal to Zero and the magnet operates at short circuit conditions.



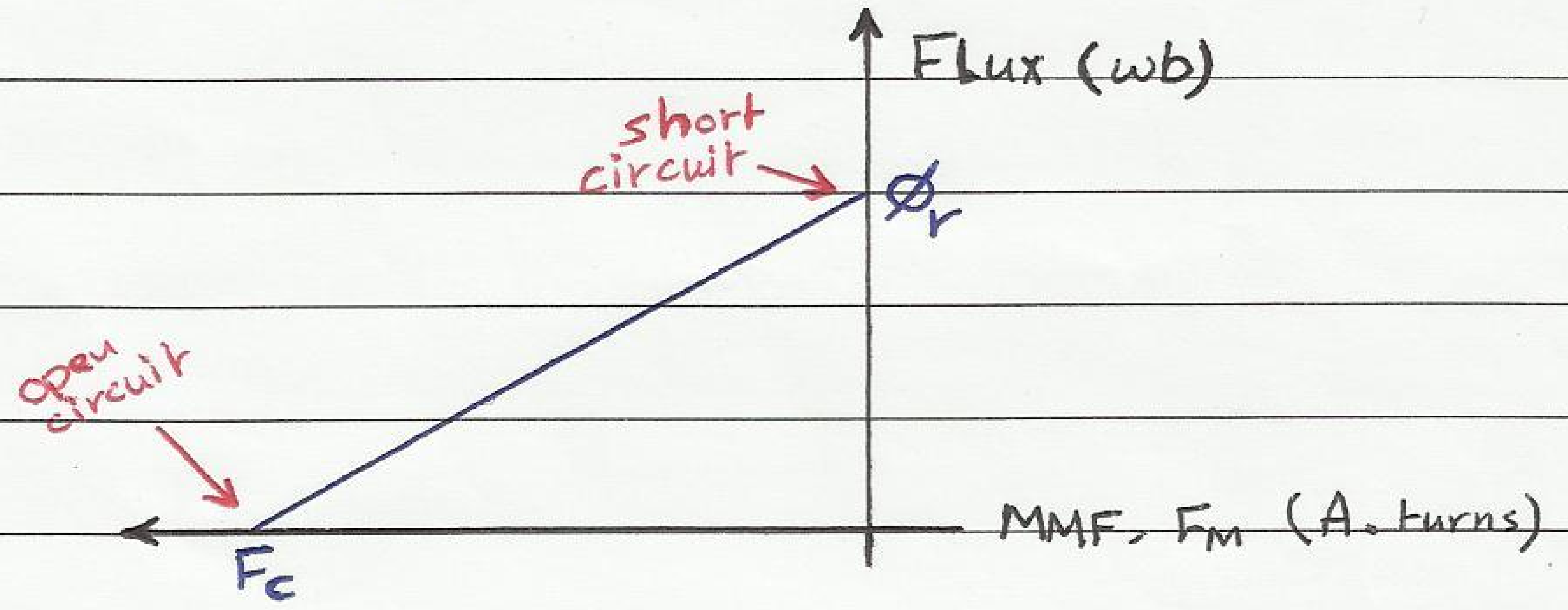
⇒ if the soft magnetic material is inFinity Permeable, then :- $\phi_M = \phi_r = \frac{F_c}{R_p}$

$R = 0 \Rightarrow \mu_r \rightarrow \infty$

* The magnet is open circuit if the Flux leaving it is Zero.

$\boxed{S \longrightarrow N}$ $\phi_M = 0$ (open circuit)

* F_c is called corecive MMF because it is the MMF required to coerce the magnet to produce Zero Flux. It directly expresses the resistance of the magnet to demagnetization. The characteristics of a permenet magnet can be expressed graphically in terms of Flux/MMF at the terminals of the pole Faces as:-



* The remanent Flux ϕ_r and coercive MMF depent not only on the Material properities but also on the dimensions of the Magnet.

$$\phi_r = B_r \cdot A_m$$

material Properity

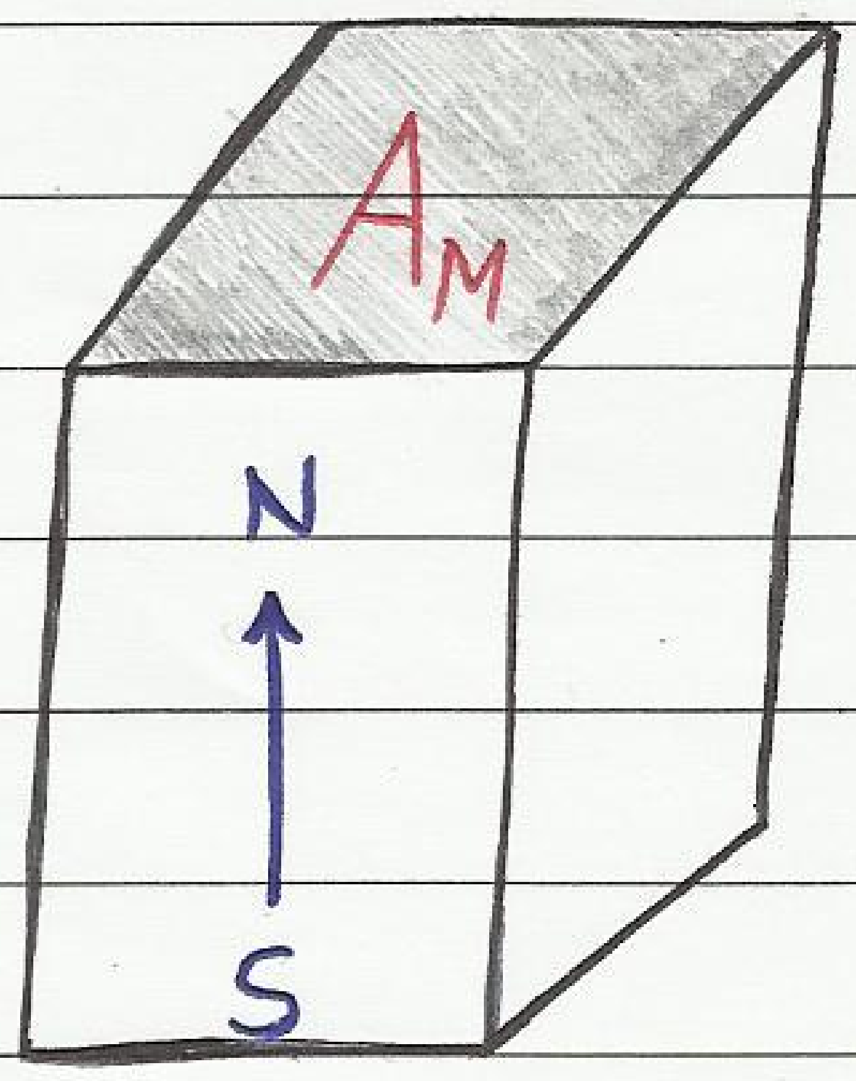
magnet cross sectional area dimension

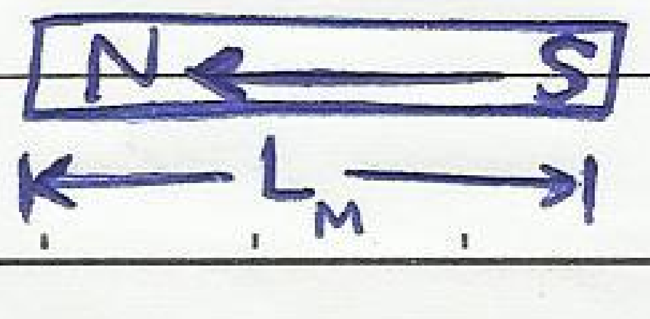
corecivity

$$F_c = H_c \cdot L_M$$

corecivity Force

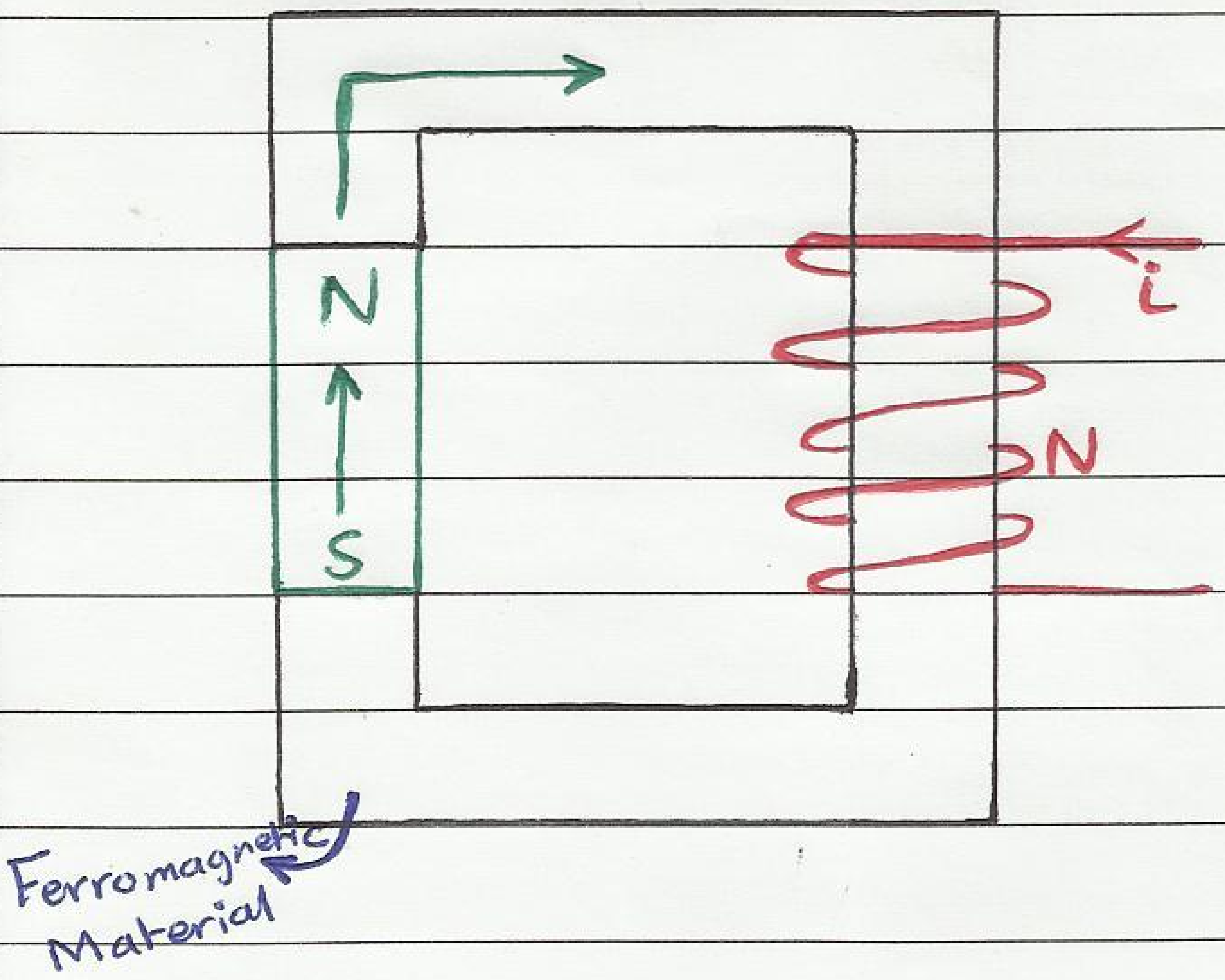
length of the material in the direction of magnetization

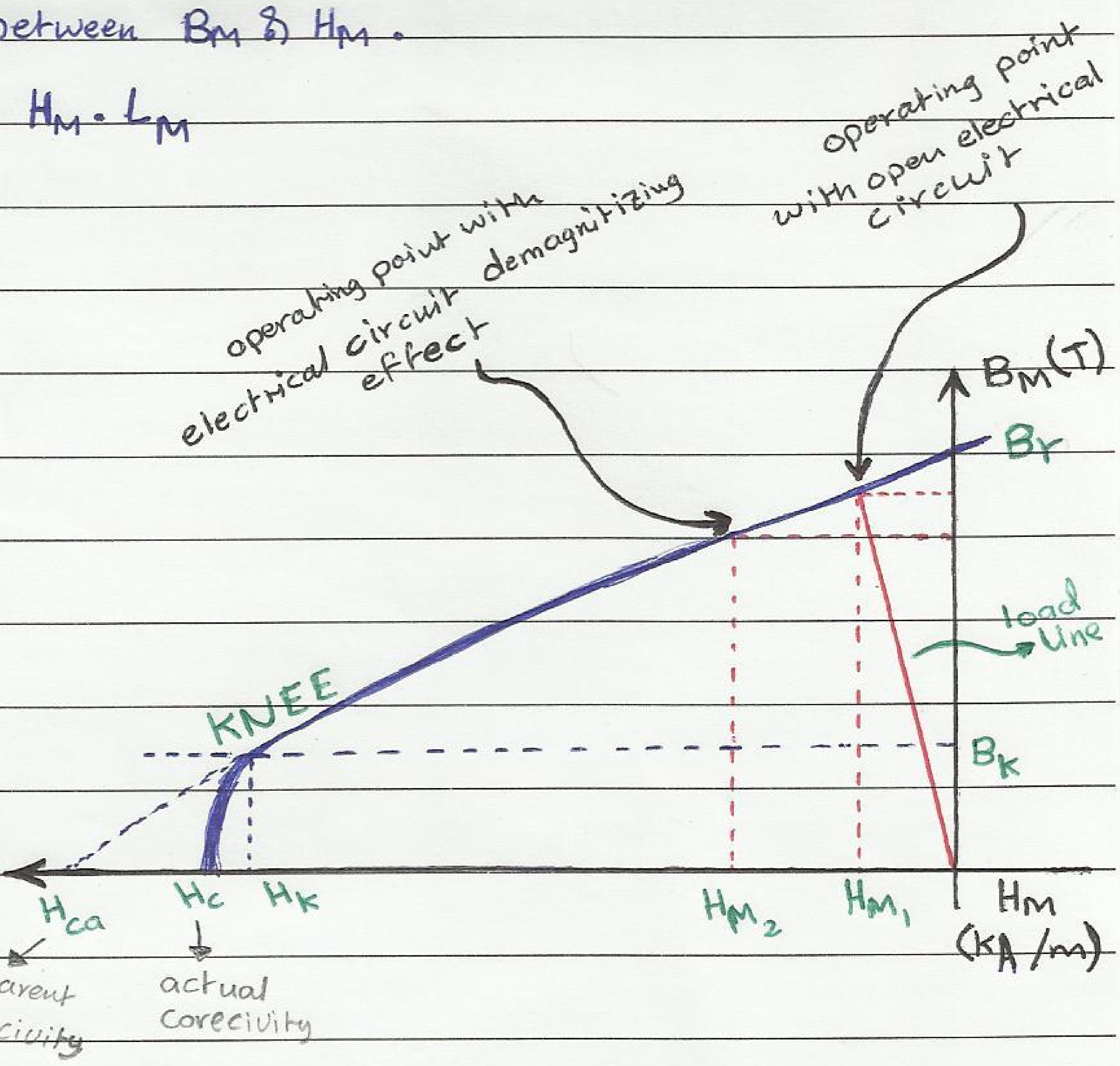




* If the vertical axis is scaled by $1/A_M$ and the horizontal axis by $1/L_M$, then the result will be a relationship between B_M & H_M.

$$\phi_M = B_M \cdot A_M \qquad F_M = H_M \cdot L_M$$



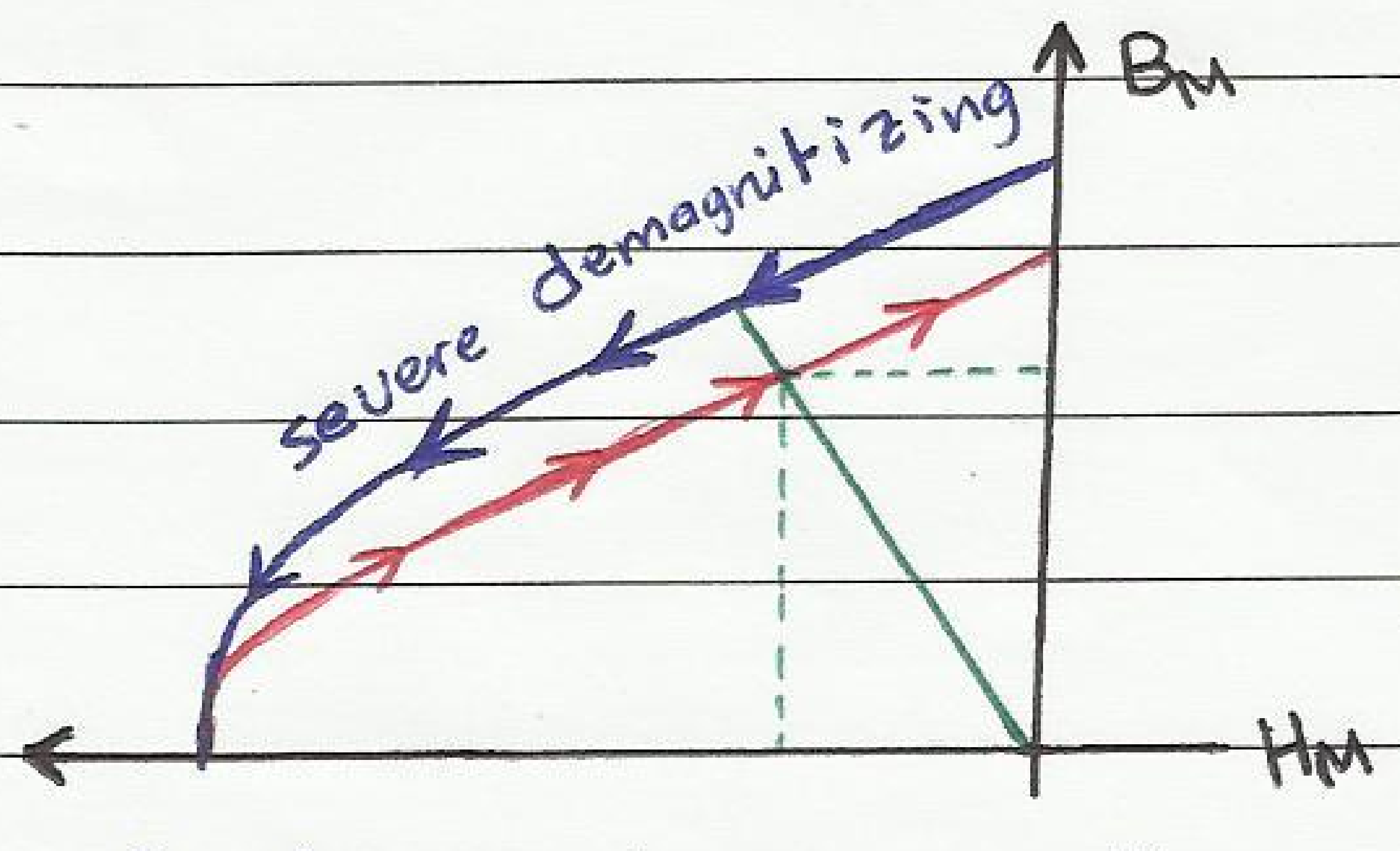


* If the current is AC, then the operating point will move slightly at the characteristic line and therefore the energy extracted from the PM will be changing which represent one of the sources of vaibration in PM machine.

$$B_M = \mu_{rec} \cdot H_M$$

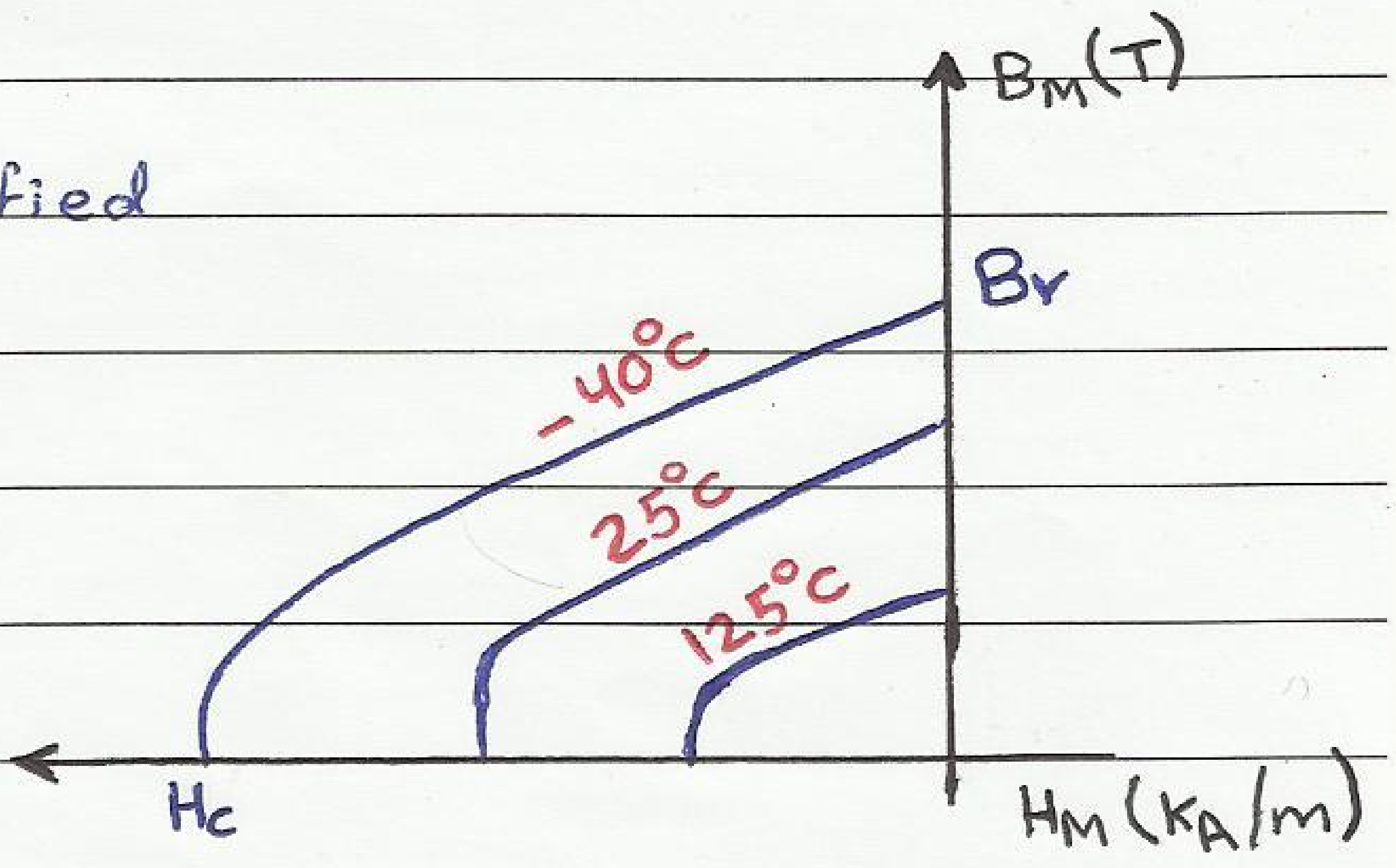
recoil permability of the PM material

* If the operating point is forced below the KNEE by severe demagnitizing force then the magnet recovers along allower recoil line when it's removed.



Effect of demagnitizing on the characteristics of the PM materials

* The effect of temperature on the B/H curve characteristics of PM material :-



⇒ The effect of temperature is normally specified by α_{B_r} ⇒ reversible temperature coefficient.

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

* Shapes of perment magnets :-

cheapest

most expensive

* Types of permanent magnets :-

① Ferrites

Aluminum Nickel cobalt ← ② ALNico

→ inexpansive

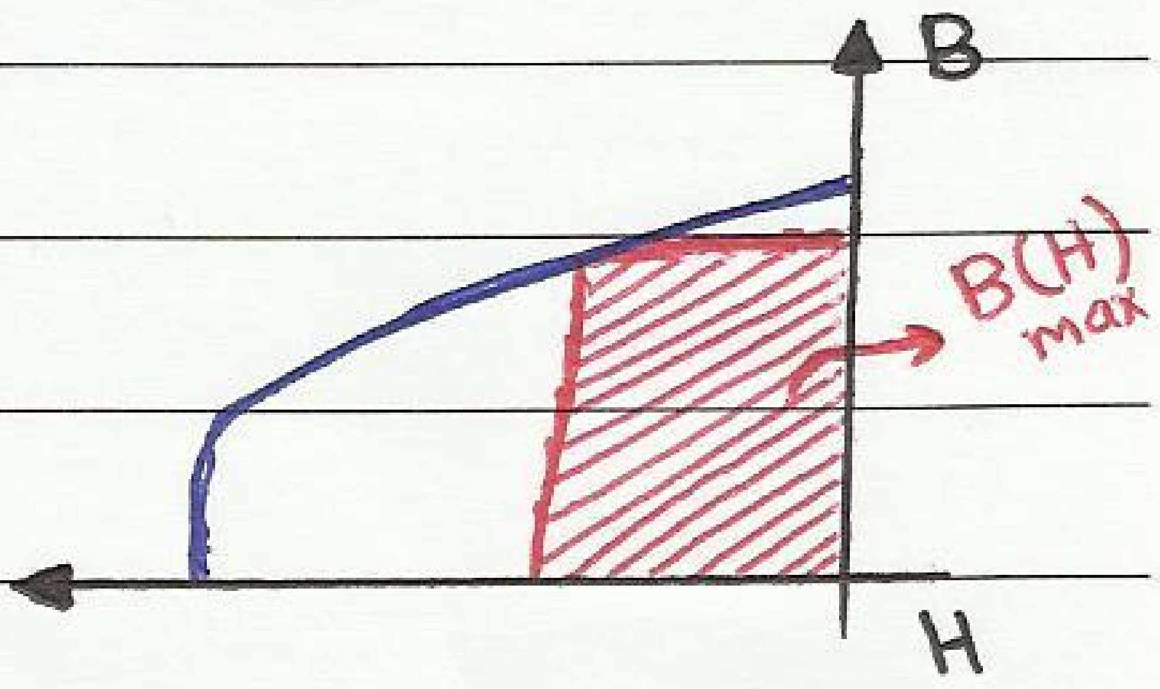
samarium cobalt ← ③ SmCo

Nedymium Iron Boron ← ④ Nd FeB

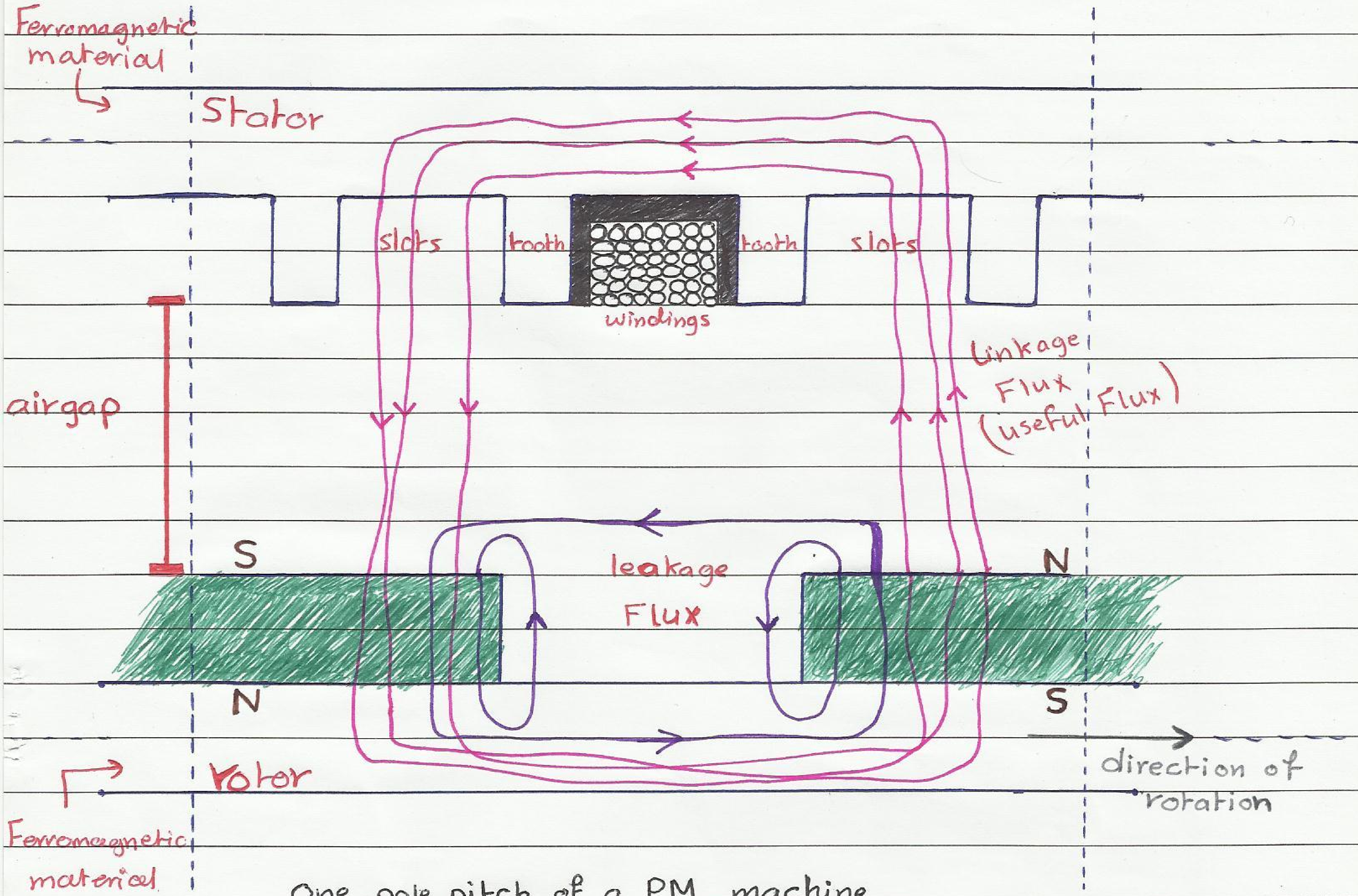
→ rare-earth materials

→ highest $(B(H))_{max}$ → indicates the energy stored in the magnet

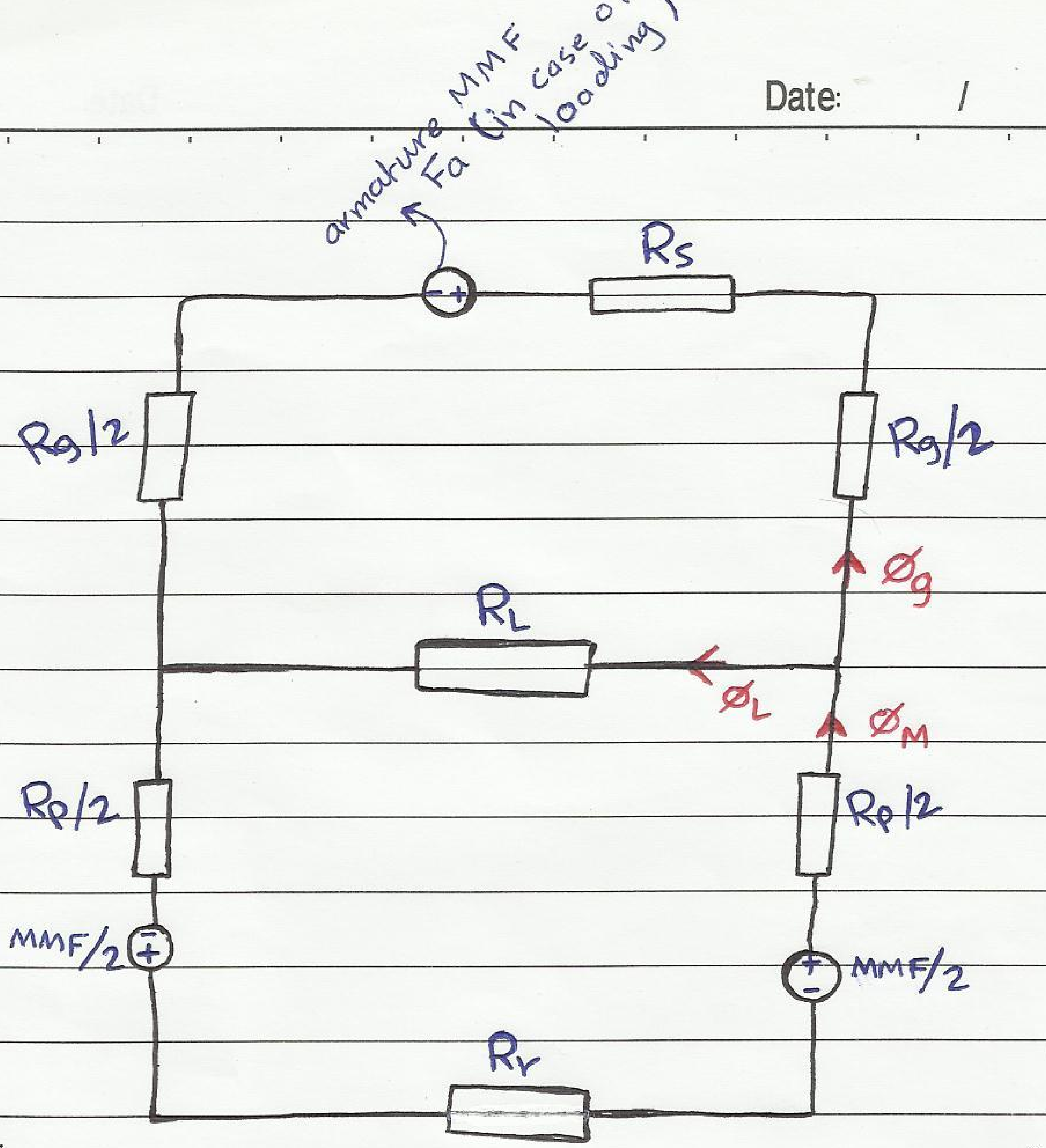
* $B(H)_{max}$: maximum energy product.



* Approximate calculations of Flux :-



One-pole pitch of a PM machine



"one-pole pitch magnetic equivalent circuit"

$$E = 4.44\, \phi_g\, f\, N\, K_w$$

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

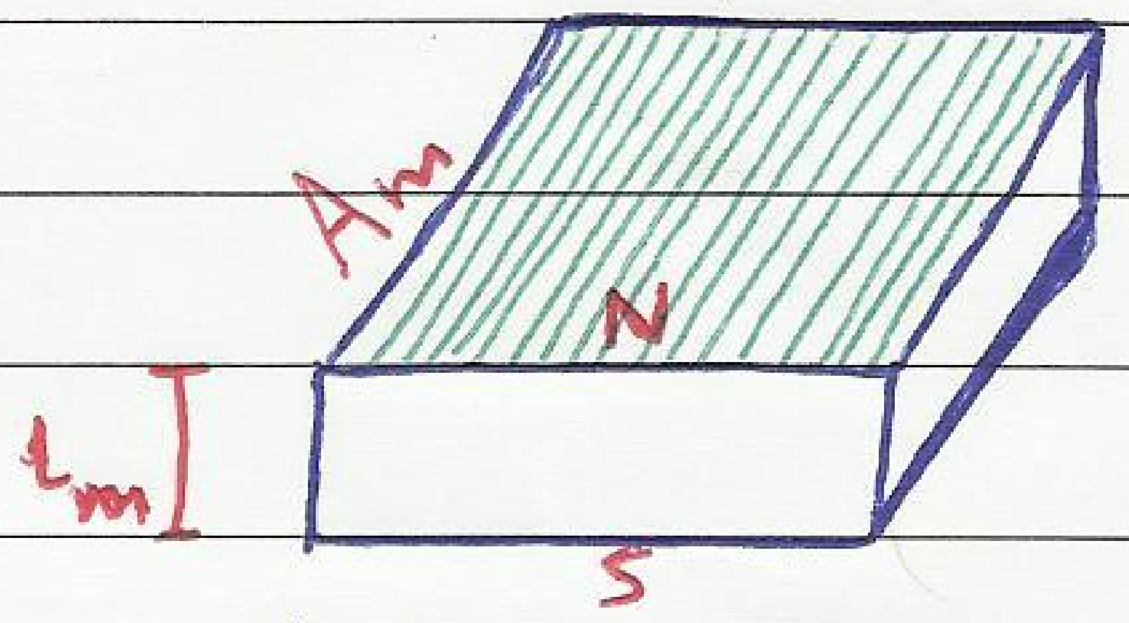
- leakage Flux coefficient Flux (f_{LKG}).

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

$f_{LKG} < 1$ ⇒ Typical "rule of thumb" values is 0.9
normally 0.7 → 0.9

* F_a is normally initially Zero (open electrical circuit).

$$R_p = \frac{l_m}{\mu_0 \mu_{rec} A_m} \qquad 1.0 \rightarrow 1.1$$



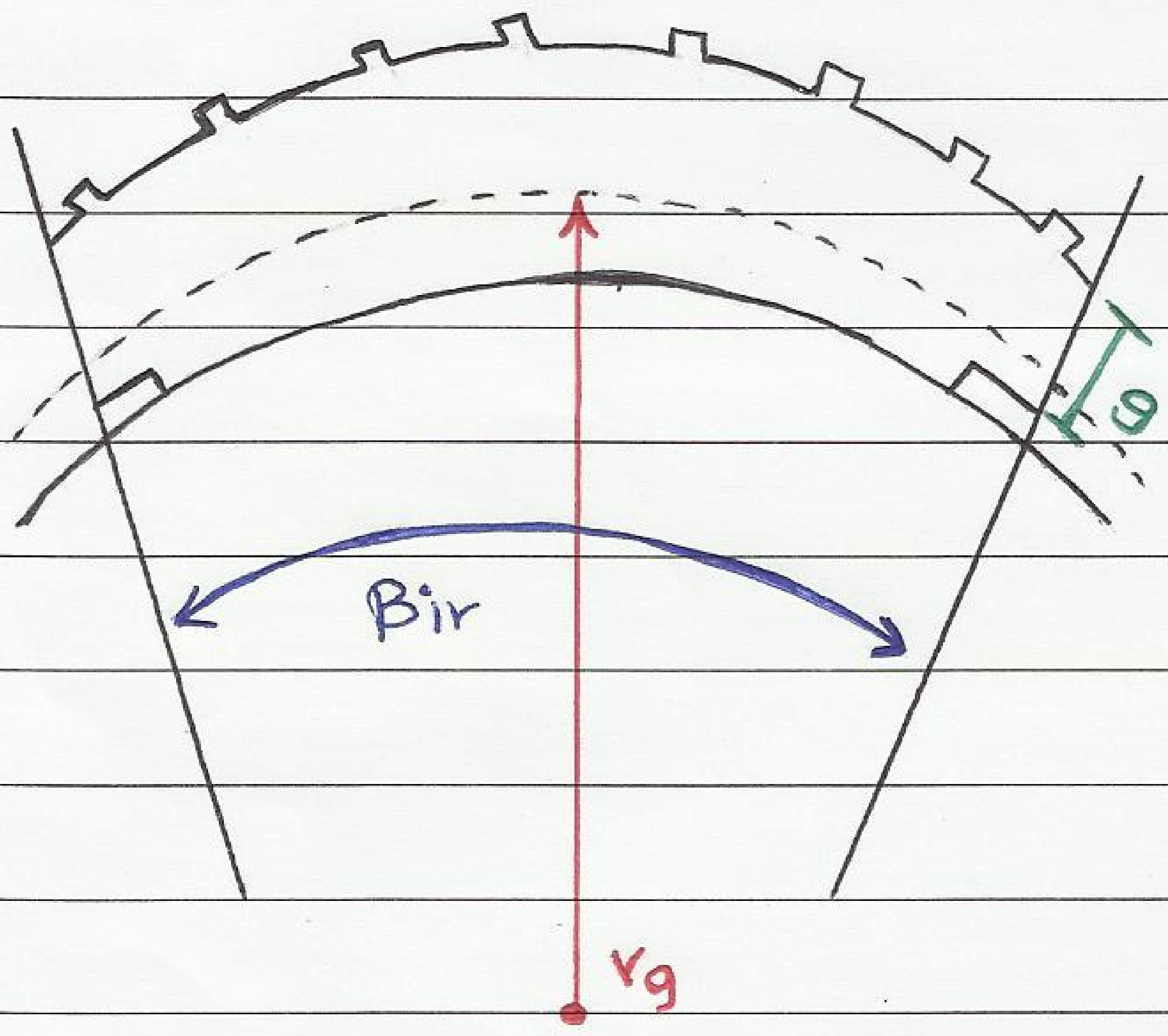
L_m : length of the magnet in the direction of magnetization.

Am :- magnet pole face area.

effective air gap

$$R_g = \frac{g'}{\mu_0 A_g} = \frac{K_c \, g}{\mu_0 \beta_{ir} r_g L_{stk}}$$

carter coefficients which accounts the irregulating of the air gap due to slots.



β_{ir} : pole pitch angle.

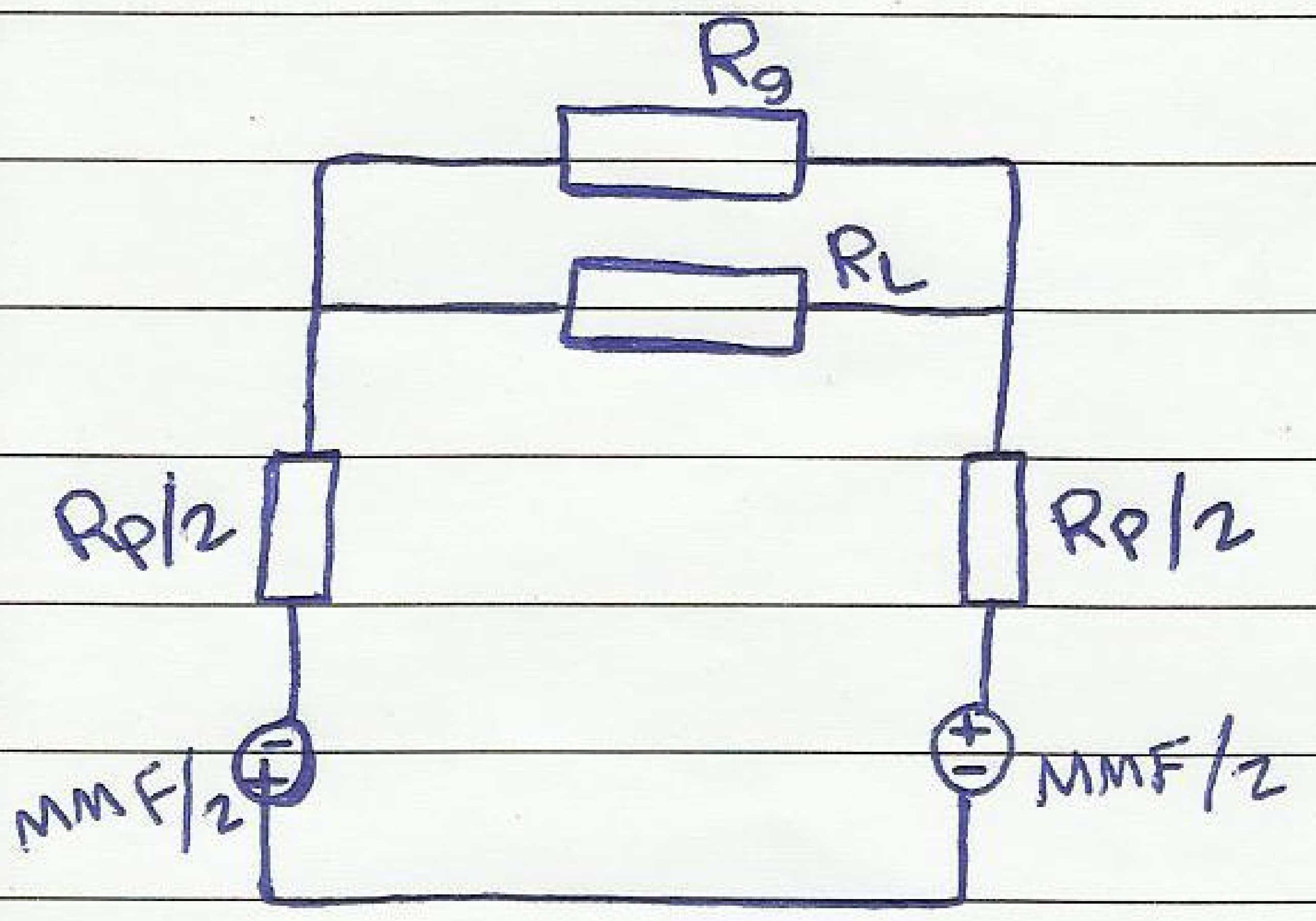
r_g : midway radius through the physical air gap.

L_{stk} :- active length of the machine.

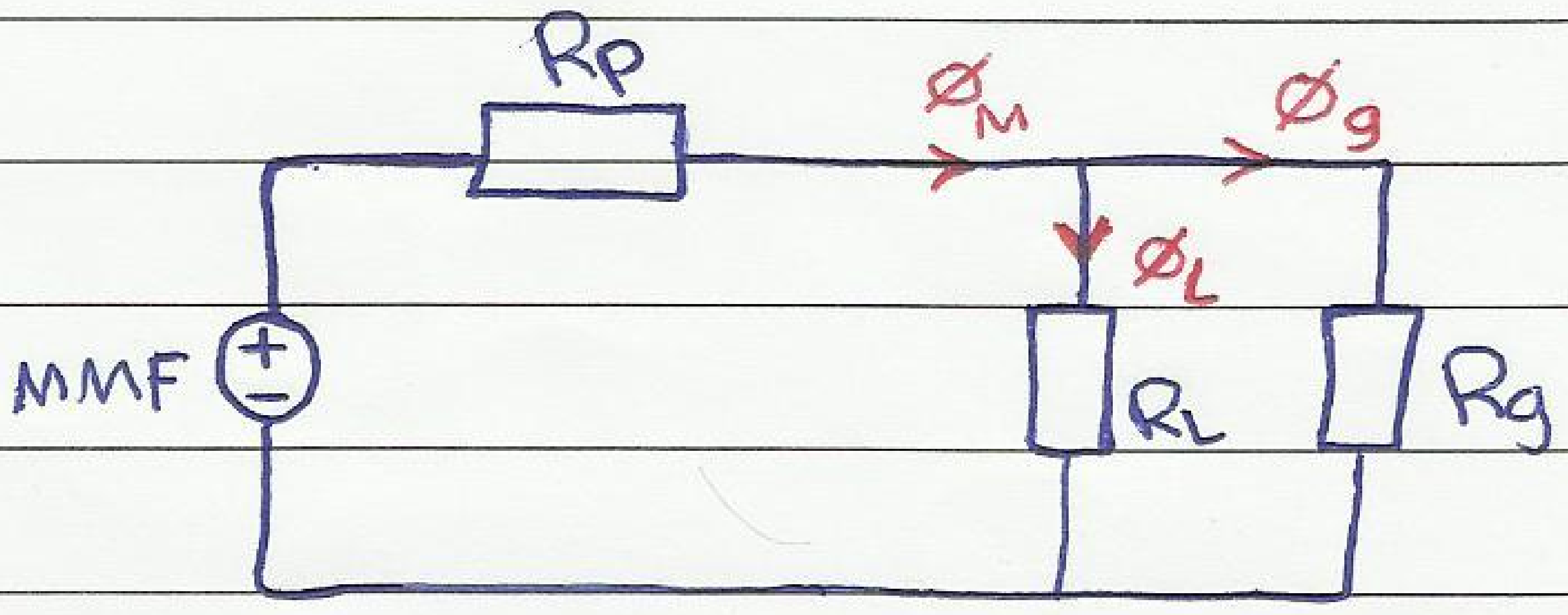
g :- physical air gap.

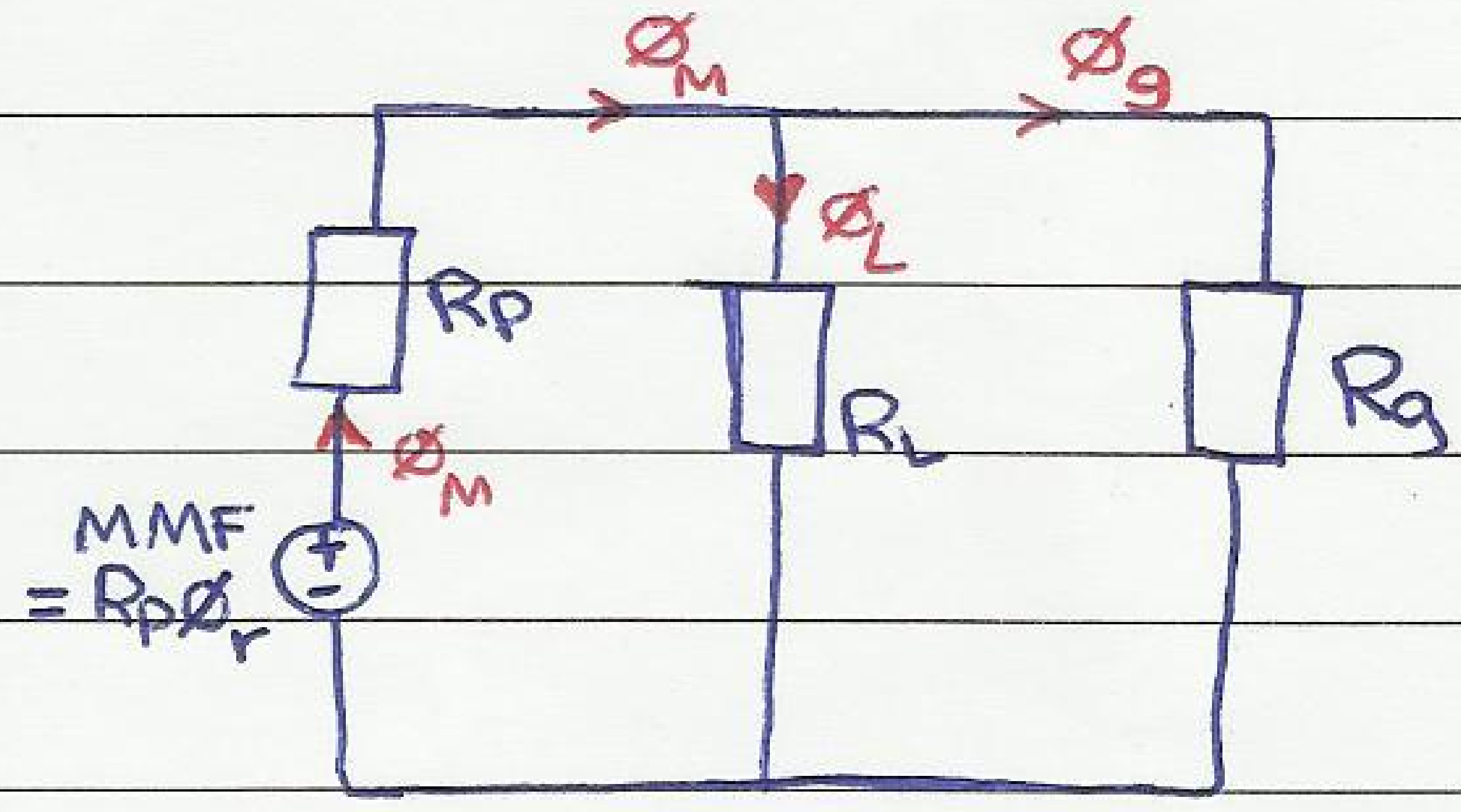
* Normally the stator and rotor are infinitely permeable

$\mu \rightarrow \infty$, i.e $R_s = R_r = 0$



$\Longrightarrow$





$$\Rightarrow \varnothing_g = \varnothing_M \frac{R_L}{R_L + R_g}$$

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

$$\varnothing_M = \frac{R_p \varnothing_r}{R_p + \frac{R_L R_g}{R_L + R_g}}$$

but , $\varnothing_M = \varnothing_g \dfrac{R_L + R_g}{R_L}$

$$\Rightarrow \varnothing_g = \varnothing_r \frac{R_p}{R_p + \frac{R_L R_g}{R_L + R_g}} \cdot \frac{R_L}{R_L + R_g}$$

$$F_{LKG} = \frac{\varnothing_g}{\varnothing_M} = \frac{R_L}{R_L + R_g}$$

$$\varnothing_g = \frac{F_{LKG}}{1 + F_{LKG}\left(\frac{R_g}{R_p}\right)} \cdot \varnothing_r$$

$\Longrightarrow$

$\Rightarrow \quad \varnothing_r = B_r A_M \qquad \qquad \varnothing_g = B_g A_g$

$$B_g = \frac{f_{LKG} \frac{A_M}{A_g}}{1 + \mu_{rec} f_{LKG} \frac{A_M}{A_g} \frac{g'}{l_M}} \cdot B_r$$

ALso :- $\varnothing_g = f_{LKG} \varnothing_M$

$$B_g A_g = f_{LKG} B_M A_M$$

$$B_M = B_g \frac{1}{f_{LKG}} \cdot \frac{A_g}{A_m} \quad \ldots\ldots (1)$$

* a convenient Formula is :-

$$P_C = \frac{1}{f_{LKG}} \cdot \frac{l_M}{g'} \cdot \frac{A_g}{A_m}$$

Permenance cofficient

- Another useful relation for PC is :-

$$B_M = \frac{P_C}{P_C + \mu_{rec}} \cdot B_r$$

. μ_{rec} is normally one for hard permenat magnet materials, Pc is around 5.

$$B_M = 0.83\, B_r \rightarrow \text{operating point} \ldots\ldots (2)$$

$$\boxed{B_M = \mu_{rec} \mu_0 H_M + B_r} \Rightarrow H_M$$

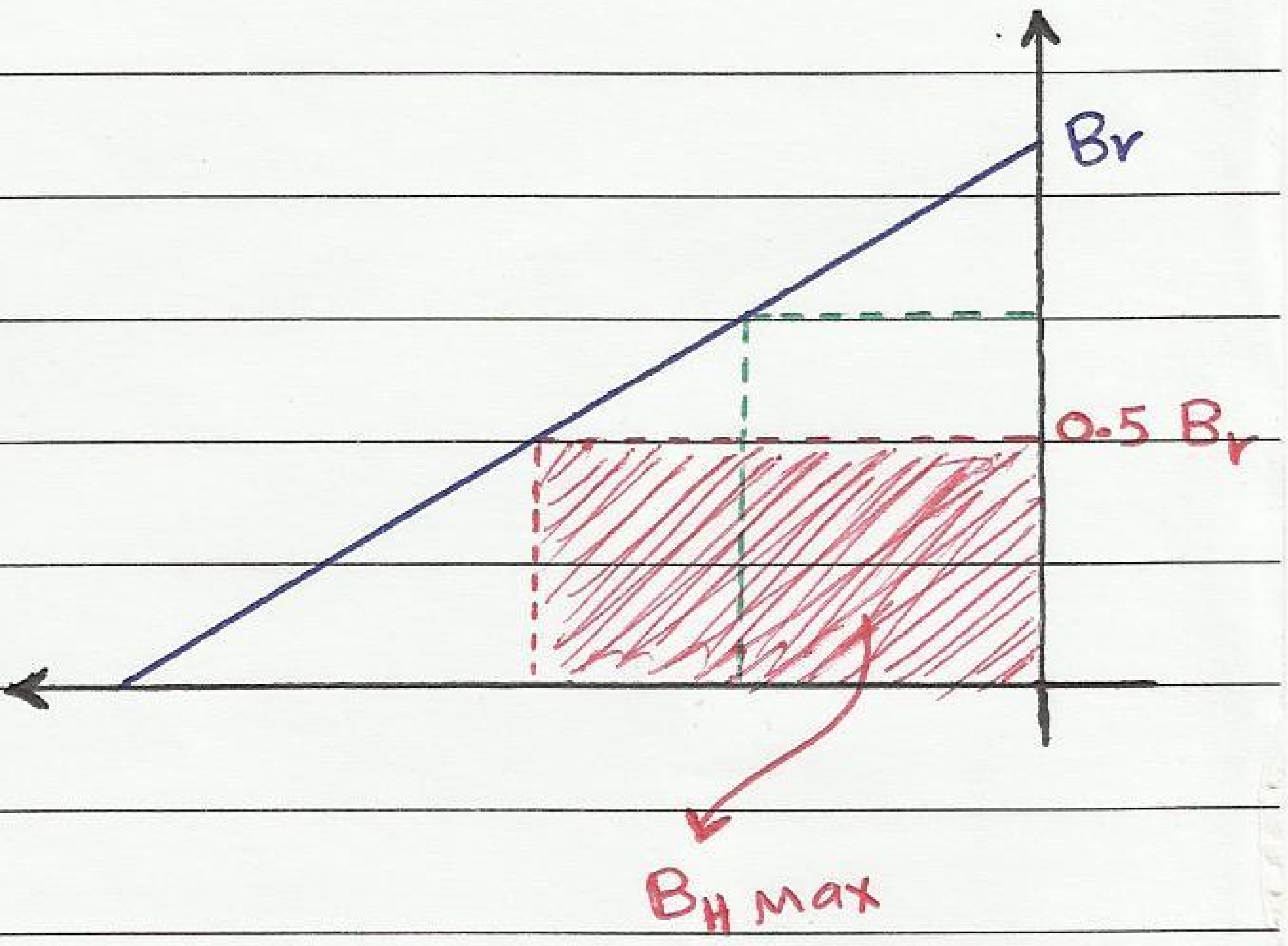
⇒ - OR H_M can be calculated graphically From the B/H curve of the magnet.

- B_r is given ⇒ B_M From equation 2
- From equation 1 ⇒ B_g ⇒ $\left\{ \begin{array}{l} A_g \\ A_m \end{array} \right.$ given

$F_{LKG} = 0.8$

- $\emptyset_g = B_g A_g$ ⇒ useful or linkage Flux

- If $PC = 1$ & $\mu_{rec} = 1$ ⇒ $B_M = 0.5\ B_r$



شكراً على ثقتكم .. لا تنسونا من صالح دعائكم

أخوكم علي كوفي محمود