Synchronous, Study

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CONTENTS

1 INTRODUCTION

Synchronous generators or alternators are very common in power generation in the world

In this Machine the stator is the Armature

And The Rotor is the Field coil

<u>NOTE</u>

-Power Production winding (Armature) on Stator so we <u>can't use Slip Rings</u> because of the large current flowing

-Easier to cool

-Protecting it's large coils from centrifugal forces if it was rotating

1.1 Principle of Operation

Due to the existence of a magnetic field on a rotating coil then it will produce an induced emf $e = -\frac{d\phi}{dt}$ due to the change of flux $d\phi$

- It's direction is that if current passes it will produce another flux that opposes that first flux That's what's called <u>Lenz's Law</u> and is represented by the negative sign "-" in the "e" relation

The rotating coil will undergo different flux values while rotating

Flux is <u>maximum</u> at some point of time (when it's <u>*perpendicular*</u> with field lines)

after it rotates 90° it will be <u>*aligned with*</u> field lines so it will have <u>zero</u> flux

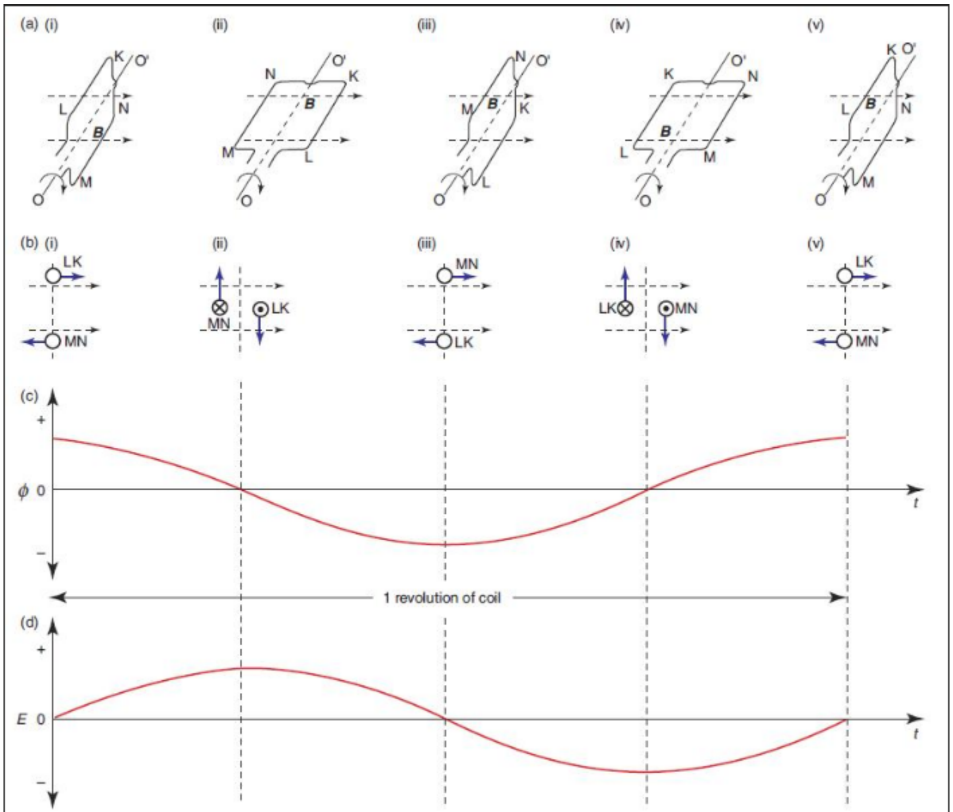


Figure 8.3 *The variation of flux and emf of a generator coil as it completes a single revolution*

For N coils it will be $e = -N\frac{d\phi}{dt}$,

$$\lambda = N\phi \,, \lambda = N\phi_{Max}\, cos\omega t = \lambda_{Max} \cos \omega t$$

$$e = -\frac{d\lambda}{dt} = \omega\lambda_{Max} \sin \omega t \;= E_{max} \sin \omega t$$

NOTE
Flux is a cos wave
E ind is a sin wave

To make sure that the voltage wave is sinusoidal we use slip rings to bring conductors together and using brushes to the terminals

For 3-ϕ we will need 3 coils with 120° shift and 6 slip rings with 6 brushes

Then we can connect output point either Y or Δ

NOTE in DC we used commutators here it's slip rings

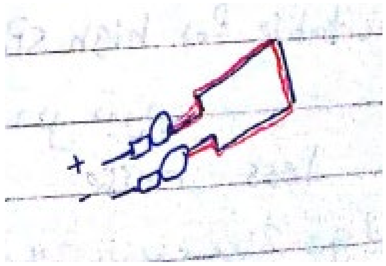
1.2 Motor or Generator

If Power input is mechanical rotational power (transformed to) electrical Power (it's G)

If Power input is electrical Power (transformed to) Mechanical Rotational Power (it's a M)

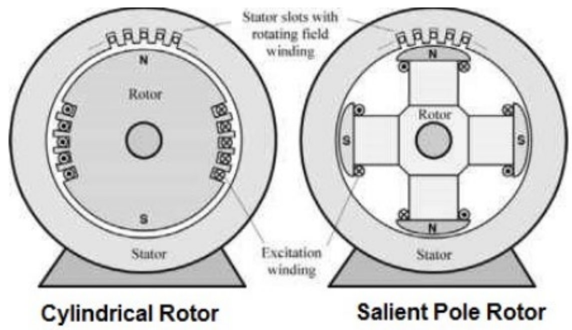
1.3 Rotor and Stator

Rotor will just have small dc excitation voltages and current so it will be used as field coils as we can use slip rings and brushes with it easily

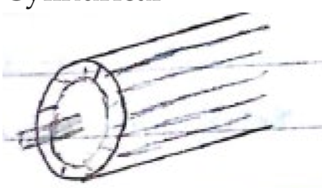


(smaller size , easier maintenance , less sparking)

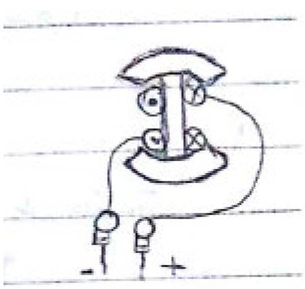
It can be



- Cylindrical



-
- Salient



Or we can use a PM rotor

Stator is the <u>armature</u> where power and high currents are produced

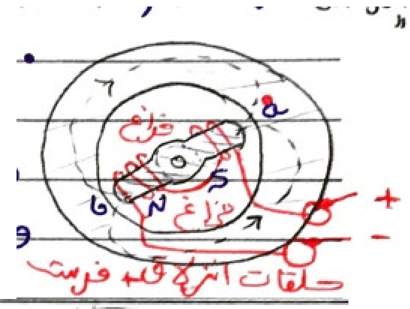
1.4 ROTOR

1.4.1 Salient Pole Rotor

It has a non-uniform airgap

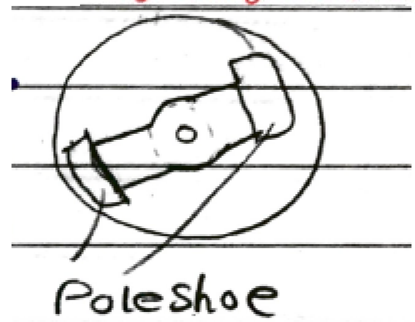
1.4.1.1 Pole Shoe

As we discussed the rotor is the field source but in the following schematic we notice that points a and b doesn't have any flux and it's **not symmetrically distributed (not sinusoidal)** which in turn will cause the existence of **harmonics**



Solution is by using **POLE SHOE**

So harmonic content will be reduced and flux wave will be more sinusoidal

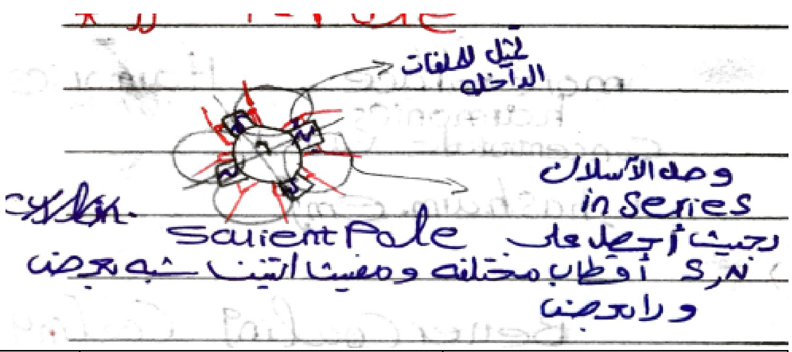


Salient Pole : has more mmf capability

But there exist space Harmonics

NOTE **Saliency causes Torque Ripple**

1.4.2 salient n-Pole



Poles	2-Pole	4-Pole	p-pole
Pole Pitch	180°	90°	360/p

But having uniform airgap and mmf path will make uniform emf

NOTE $MMF \rightarrow \phi \rightarrow emf$

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

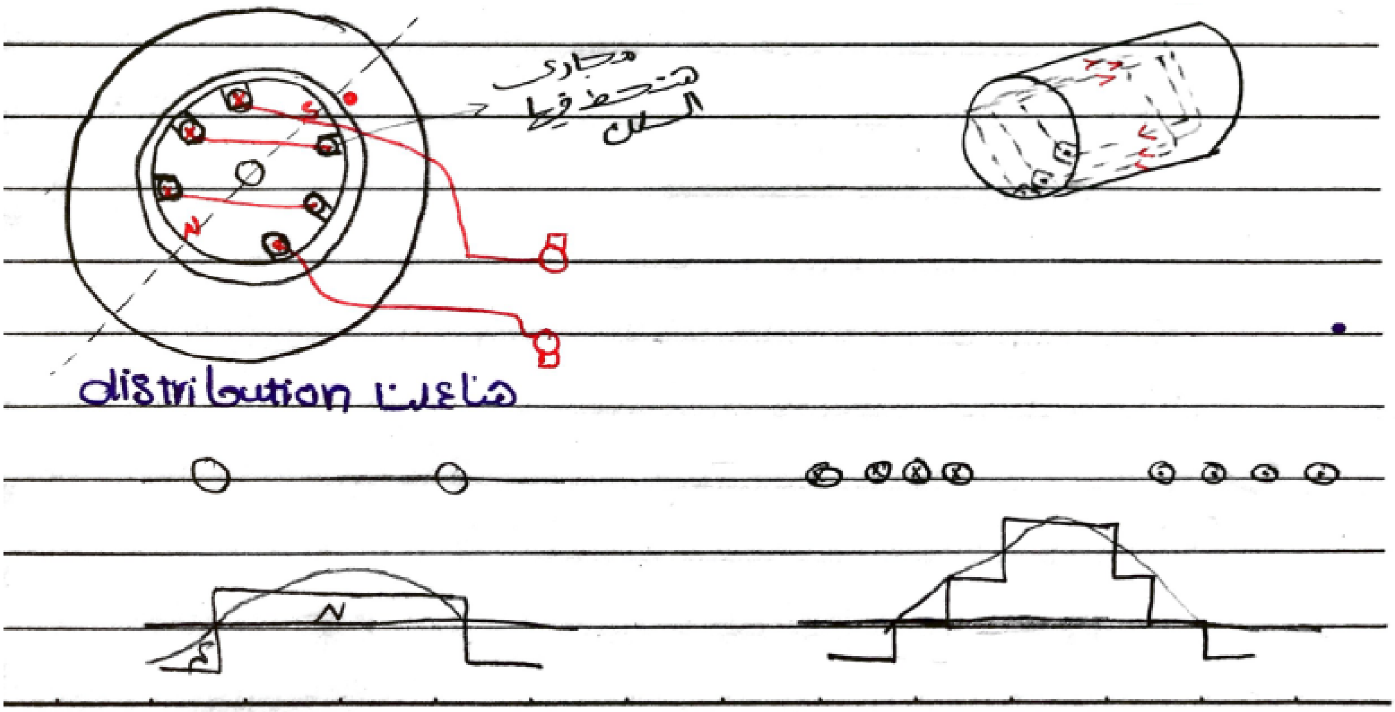
Which means for more Poles number we will have less speed

More number of poles will need bigger diameter

1.4.3 Cylindrical Pole Rotor

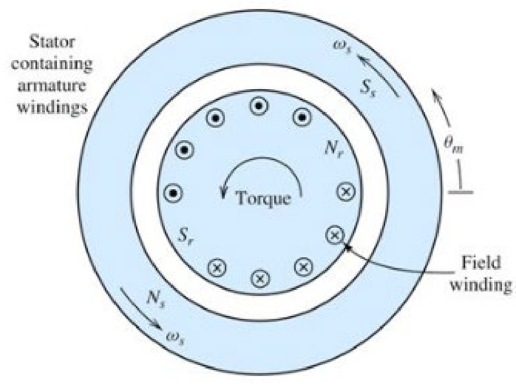
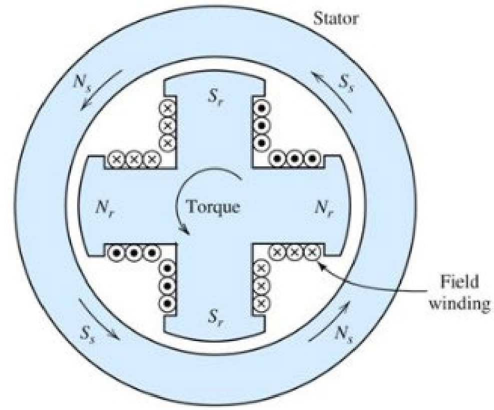
It has a uniform airgap

Less space Harmonics



> **<u>NOTE</u> Most Cylindrical Rotor are 2-pole as it's harder to make with more than 2 poles**

1.4.4 Salient Vs Cylindrical

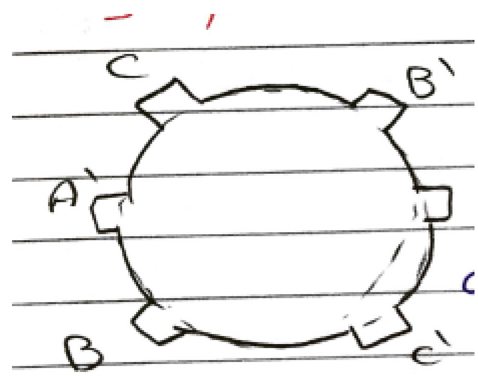
	Cylindrical	Salient
Construction	 (a) Two-pole cylindrical rotor machine	 (b) Four-pole salient rotor machine
Electromechanics energy conversion capability	Lower (Excitation)	Higher (Excitation + Saliency) T= —— + saliency term
Construction	Simple	Complicated
Harmonics	Less space harmonics More sinusoidal mmf and emf as coils are distributed	More Space Harmonics As coils are concentrated around poles Emf has harmonics
Cooling	Less Cooling	Better Cooling (can have higher rating)
Size	Bigger	Smaller
Noise	Less Noise	More Noise
Speed	More High speed applications	Suitable for Low speed applications
Application	Steam Turbine, Gas Turbine (HIGH SPEED)	Hydraulic Turbine,Wind Turbine ,Diesel (LOW SPEED)
No. of Poles	Low No. of Poles (2-pole)	Can have higher no. of poles
Diameter	**Small**	**Large**
Length	**Long**	**Short**
Torque Ripple	Lower	Higher

1.5 STATOR

Stator has to react to the changing rotor field (because its rotating) and then stator generates induced emf

To reduce <u>spaced harmonics</u> we distribute the stator windings

1.5.1 Distribution



A,B,C are coil start point and A′,B′,C′ are coil endings

Starts displaced on each other by 120°

1.5.2 No of Slots

For 2 Pole 3 phase is 6 and <u>above for distribution</u>

So most common

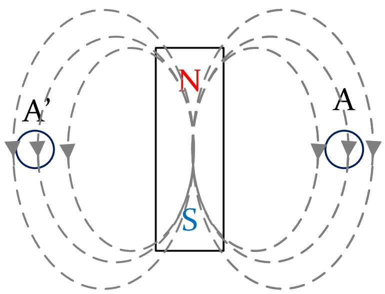
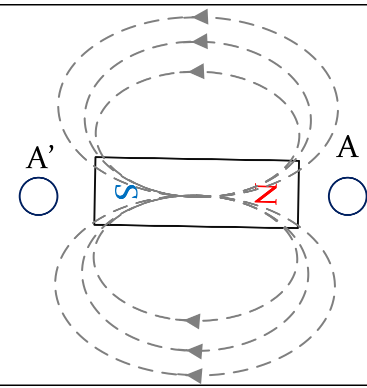
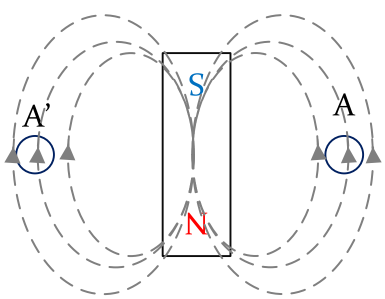
4Pole 3 phase = 12 slot and above

6Pole 3phase = 18 slots and above

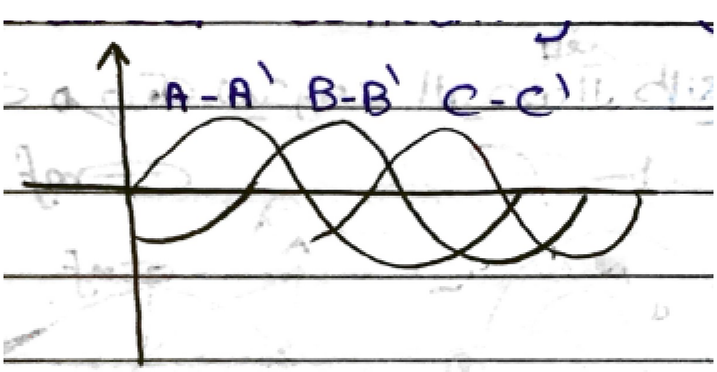
8Pole 3phase = 24 slots and above

1.5.3 2-pole and concentrated winding

Each phase on stator will have

Full Flux Linkage	
Zero Flux Linkage	
Full Flux Linkage (Negative)	

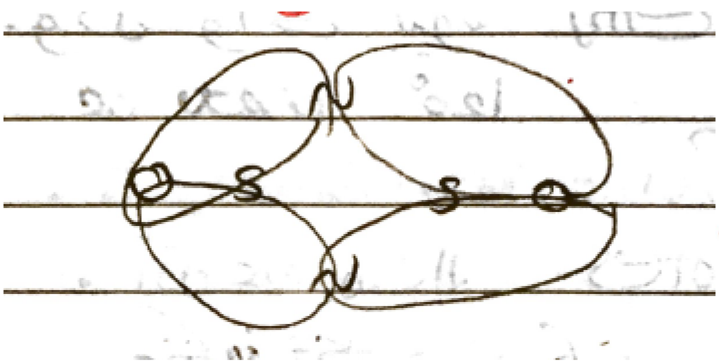
So each phase will have the following flux

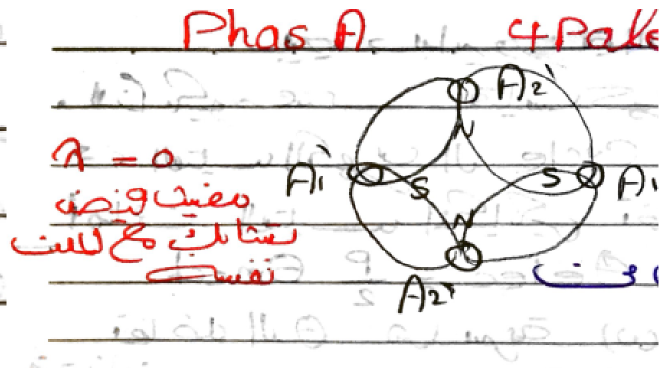


1.5.4 4-pole and concentrated winding

$$\theta_{NS} = 90\,^{\circ}$$

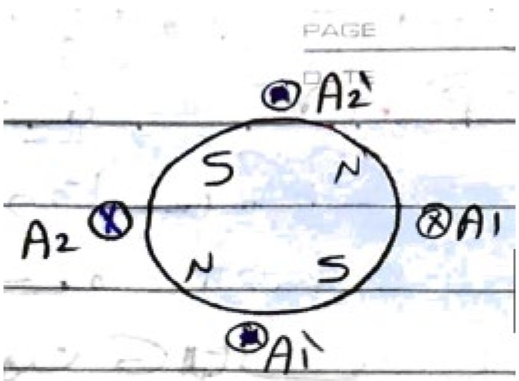
Flux Linkage for each phase will be zero when windings fall between field lines for a moment





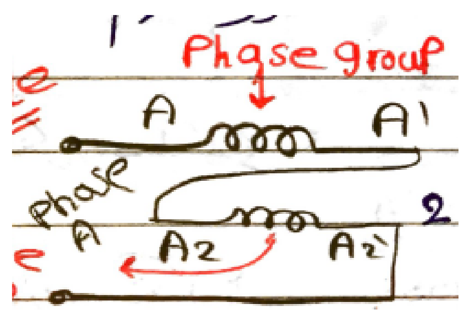
Otherwise there will be flux linkage

1.5.5 4-pole with 2 windings for phase A

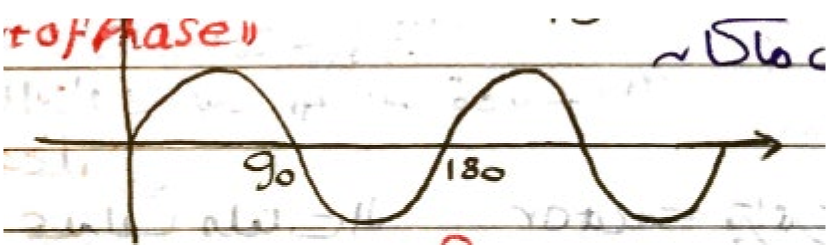


Each phase (i.e phase A) has 2 windings A1 and A2

I this case we connect the windings (phase groups) in <u>series</u> so that their voltages will add up



Here we notice that frequency doubles than in 2-pole as first peak is now at 45°



For One Revolution

We can make number of windings equal to the number of cycles separated by

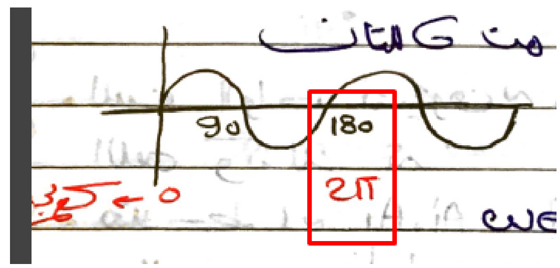
2 Pole	One cycle	180°
4 Pole	Two Cycle	90°
6 Pole	Three Cycle	60°

At 6 poles we can make a phase to 3 phase groups in series

1.5.6 Pole Pitch or Span

$$Span = \frac{360}{P}$$

It means pole pitch between a N and a S



$$\theta_{elec} = \frac{P}{2}\,\theta_{mech}$$

$$\because \omega = \frac{d\theta}{dt}$$

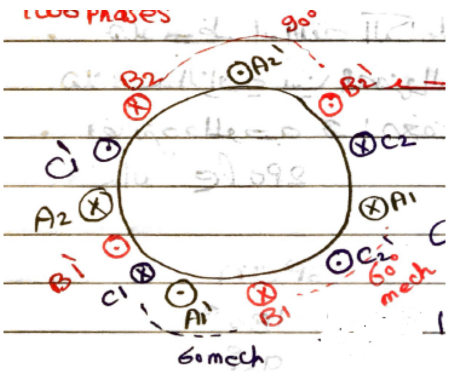
$$\omega_{elec} = \frac{P}{2}\,\omega_{mech} = \frac{P}{2}\frac{2\pi N_s}{60} = 2\pi\left(\frac{P}{2}\frac{N_S}{60}\right) = 2\pi f$$

1.5.7 3phase with 2 and 4 poles

We know that

$$\begin{array}{lll} Poles & 2pole \rightarrow & 4pole \\ Span & 180 \rightarrow & 90 \\ 3\phi\ shift & 120 \rightarrow & x = 60 \end{array}$$

<u>Note</u> in 4 pole rotor the phase shift between phases is 60° mechanically and 120 electrically also between each phase start and end A1 and A1' seperated by 90 degree , each phase group separated α



Graph Notes :

$$S = m * p * q$$

$$\theta_{coil\ span} = \frac{180}{\frac{P}{2}}$$

$$\theta_{phases} = \frac{120}{\frac{P}{2}}$$

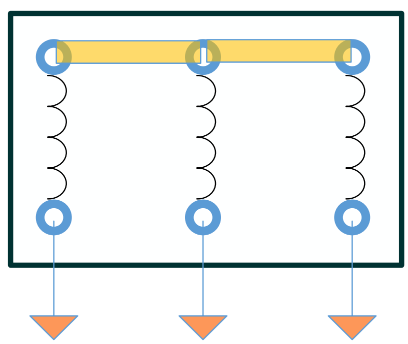
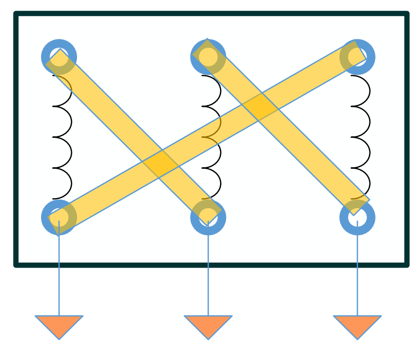
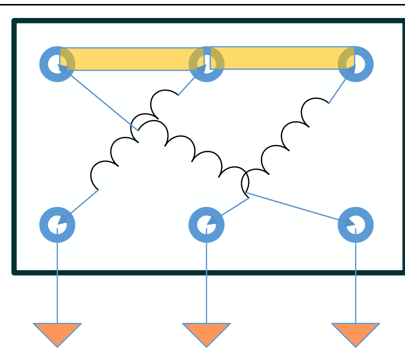
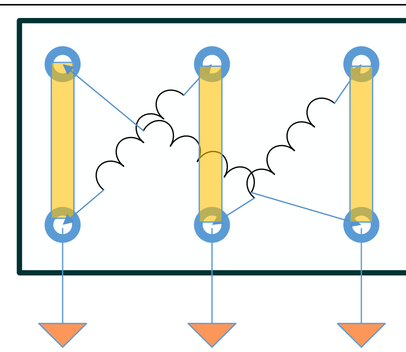
$$slot\ angle\alpha = \frac{180P}{S} = \frac{180P}{m * p * q}$$

We Notice it's important to know Rotor's Number of Poles before making stator windings

1.5.8 Calculate number of slot

$$No\ of\ slots\ = m * P * q$$

1.5.9 Junction Box

	star	Delta
Config. 1	 	
Config. 2	 	

1.5.10 Another method to show winding

1.5.10.1 (2Pole - 3ϕ) [concentrated]

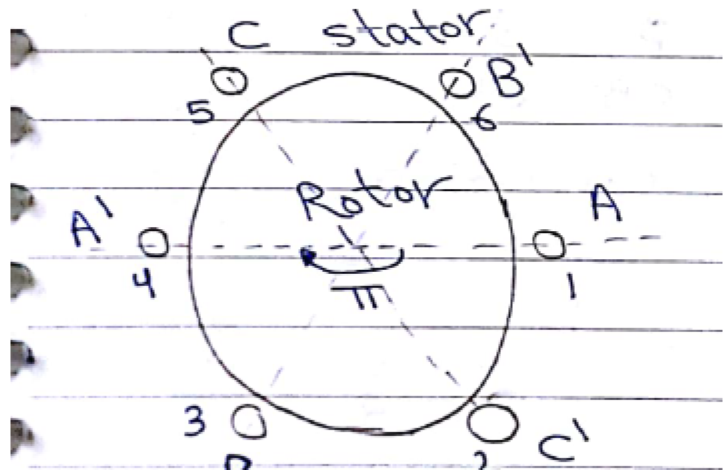
No of slots = m*p= 6 slots

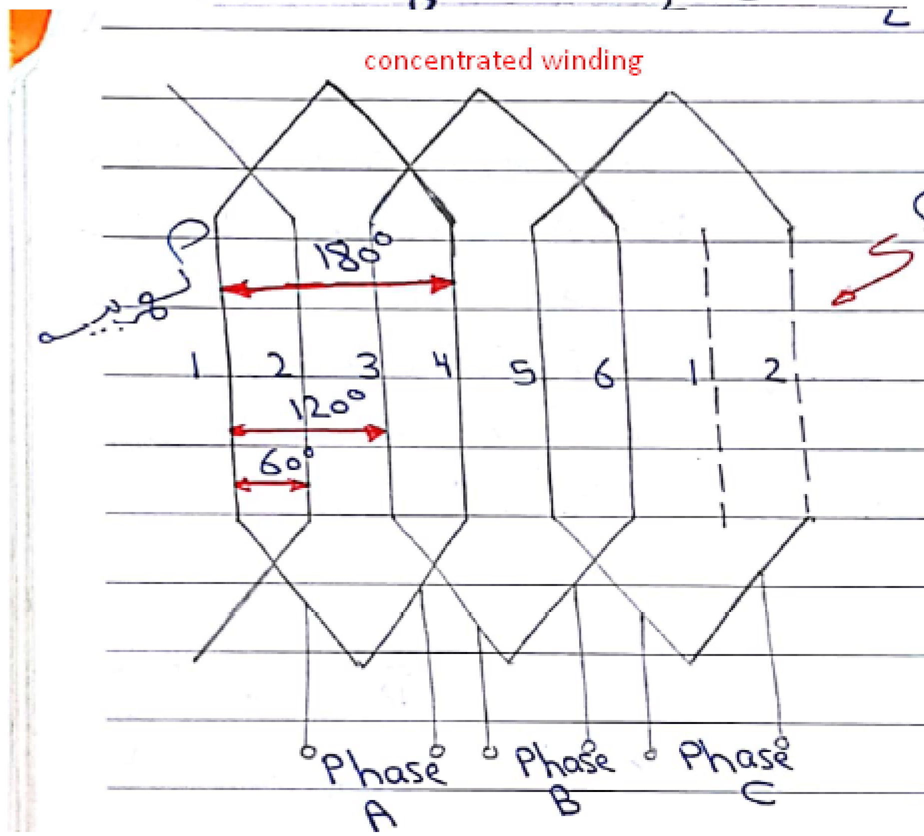
$$slot\ angle = \frac{360}{m * p}$$

$$\theta_{phase} = 180 = \ 3\ slots$$

$$\theta_{3phase} = 120 = 2\ slots$$

نجمع عدد ال slots على الslot اللي انا عندها وارجع السلك





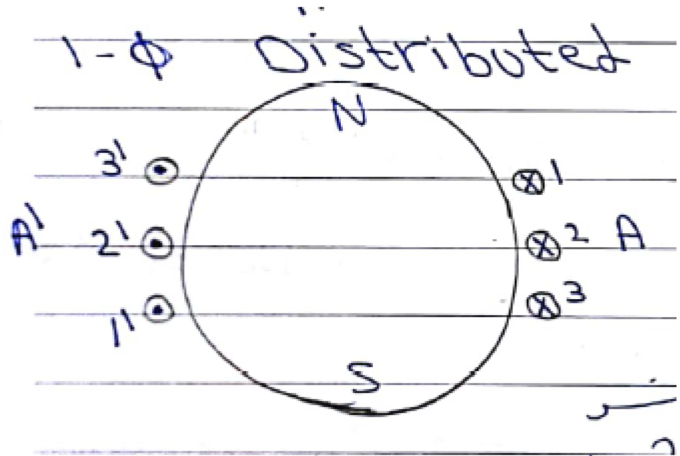
1.5.10.2 2 pole 3ph (3 phase groups) [distributed]

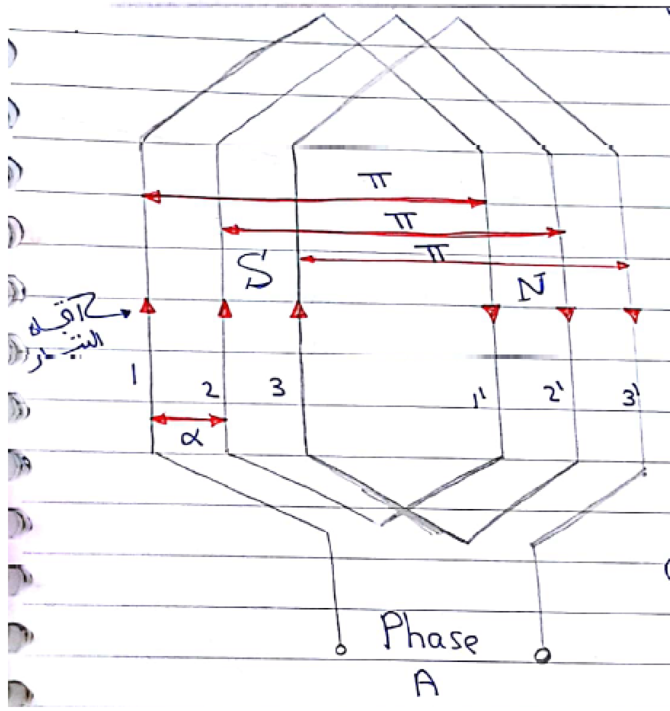
Slots = m*p*q = 3*2*3 = 18 slot

$$slot\ angle\text{"}\alpha\text{"} = \frac{360}{m*p*q} = 20$$

$$\theta_{phase} = 180 = \ \ 9\ slots$$

$$\theta_{3phase} = 120 = 6\ slots$$





1.5.11 No of slots per pole per phase "q"

When we distribute winding more and more sinsuidal the output is

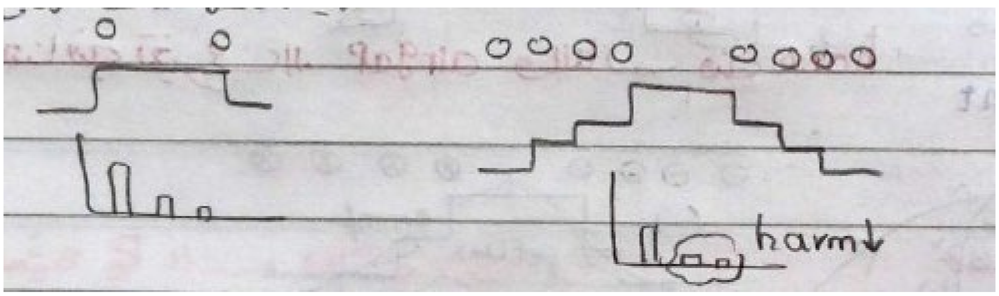
And less harmonics

We can represent distribution by "q"

$$q \uparrow \Rightarrow \ Harmonics \downarrow$$

$$q = \frac{S}{mp}$$

If $q = 1 \ \ it's\ a\ concentrated\ winding$



But increasing slots is the solution but when we increase no. of slot we need more Diameter and volume and cost

Increasing number of slots decreases space between each 2 slots which makes a <u>small path for magnetic field</u>

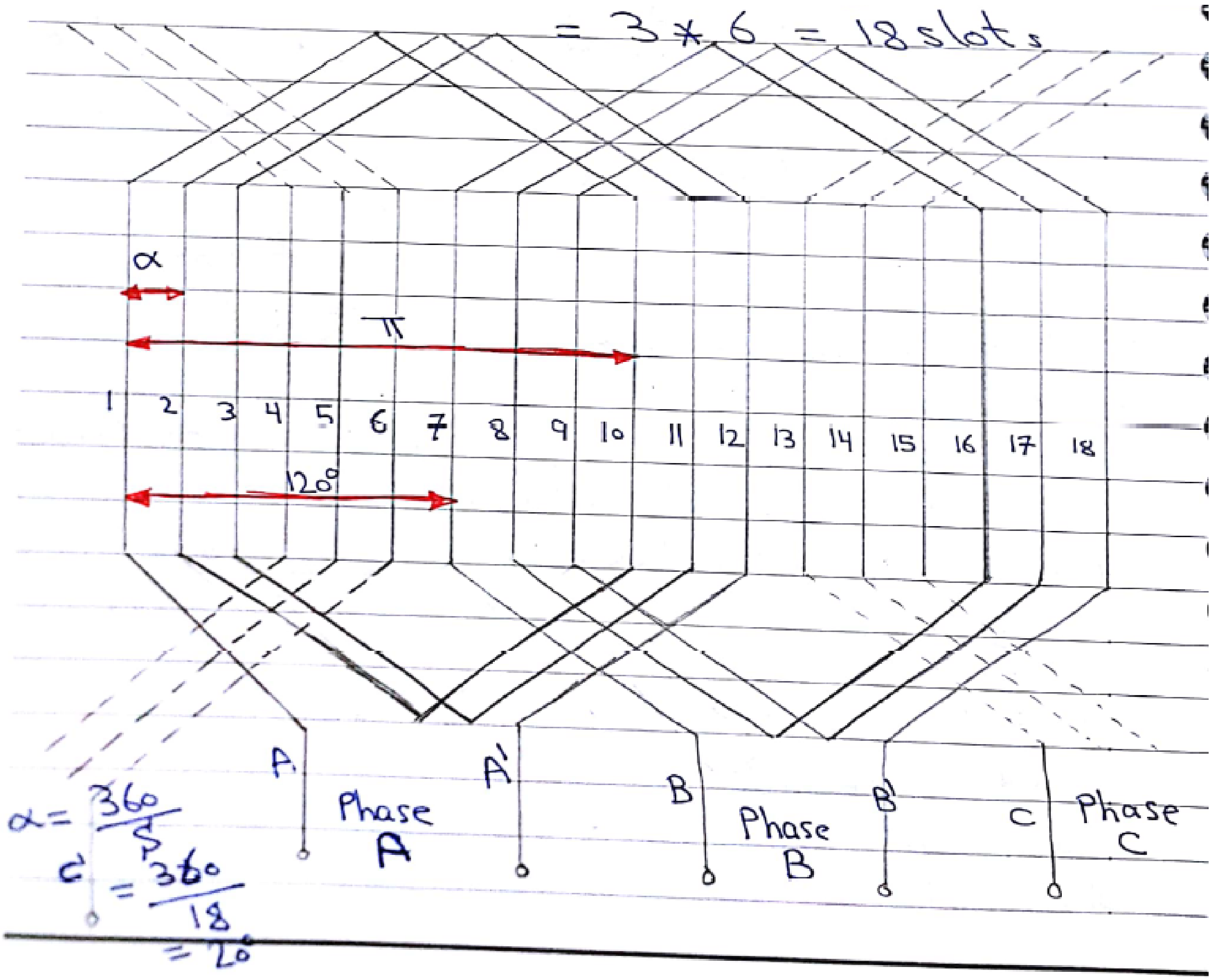
1.5.11.1 2 pole 3ph (3 phase groups) [distributed [same but explained more]

Slots = m*p*q = 3*2*3 = 18 slot

$$slot\ angle = \frac{360}{m * p * q} = 20$$

$$\theta_{phase} = 180 = \ \ 9\ slots$$

$$\theta_{3phase} = 120 = 6\ slots$$

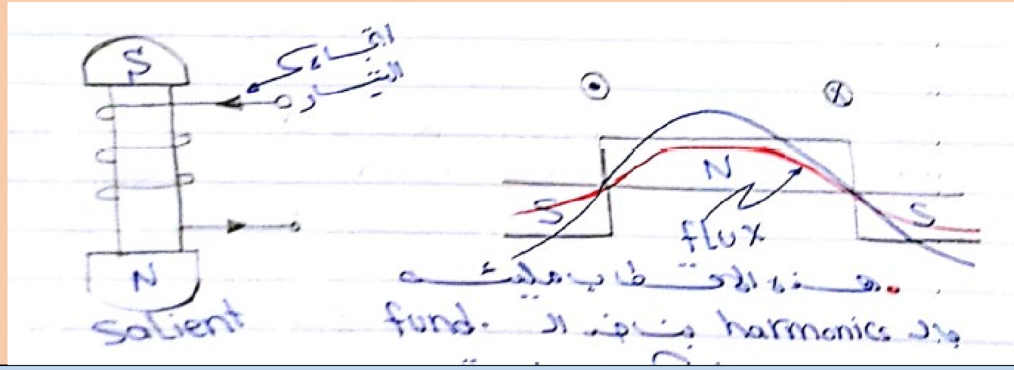
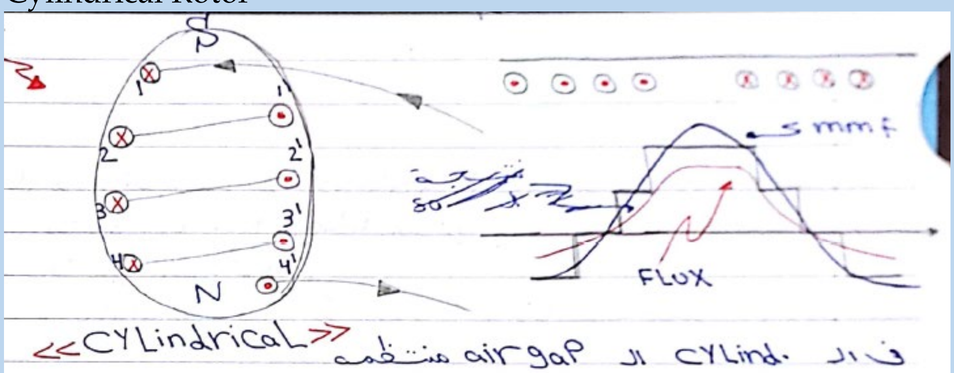


1.6 MMF Distribution in synchronous machines

1.6.1 ROTOR

$$Stator \rightarrow 3\phi AC\ Excited$$
$$Rotor \rightarrow DC\ Excited$$

Rotor can be

<table>
<tr>
<td>Concentrated</td>
<td>Salient Pole Rotor

</td>
</tr>
<tr>
<td>Distributed</td>
<td>Cylindrical Rotor


Airgap is uniform
MMF is near sinusoidal
Flux is same form of MMF (sin – sin)
$$\phi = \frac{NI}{R}$$</td>
</tr>
</table>

NOTES

-in both salient or Cylindrical the Rotor sees a uniform gap and stationary flux

-for stator the MMF rotates by the speed of rotation of prime mover

-for the rotor MMF is stationary

1.6.2 Stator

<u>Supplied with</u>

1- AC balanced 3ϕ with same magnitude and displaced by $120°$ electrically
2- Pass in 3 windings has same N and displaced by $120°$ mechanically

<u>Produces</u>

Rotating MMF which rotates with speed determined by 1- frequency 2- no of poles

(this rotating component consist of 3 pulsating and it's mag is 3/2 from each one)

<u>At speed</u>

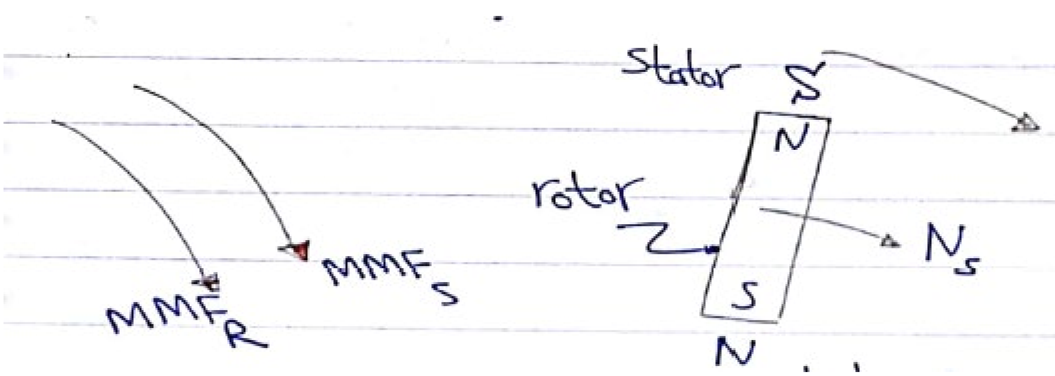
Synchronous speed

$$\omega = 2\pi f$$
$$\omega = 2\pi \frac{P}{2} \frac{N_s}{60}$$
$$\therefore \omega_{elec} = \frac{P}{2} \omega_m$$

$$also, \theta_{elec} = \frac{P}{2} * \theta_{mech}$$

1.6.3 Synchronization

MMF of Rotor and MMF of stator are rotating at the same speed



As they are at the same speed, then their poles attach to each other , **<u>Synchronize</u>**

Rotor and stator poles may have difference in angle δ but still rotating at the same speed

1.6.4 Out of synchronism

The machine can get out of synchronism when due to loading or Excitation condition δ gets too large which causes poles to lose each other and voltage pulsates

<u>NOTE</u> all loading cases must have current I_a, I_f

1.6.5 Armature reaction

Which means that the armature (stator) reacts to the main cause

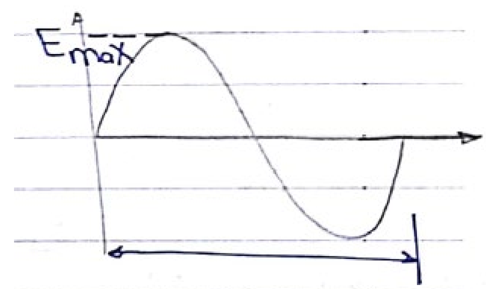
Motor	It's used to make the stator's field react to the mechanical loading condition of the rotor **(Back EMF)**
Generator	Due to electric load there will be a reaction that creates a **(Back Torque)** against the prime mover torque

NOTE

AR is not a bad thing in DC machine for examples it limits the starting current

And in Synchronous the existence of a back torque helps to stabilize the machine with Tnet =0
if Tnet $\neq$ 0 then there will be acceleration (Driving +Ve or Braking -ve) either way it won't stabilize

1.7 Induced EMF in Generator



$$e = E_{Max}\sin(\omega t)$$

$$E_{rms} = \frac{E_{Max}}{\sqrt{2}}$$

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

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

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

	Cause	Reslut
Generator	Ns	f
Motor	f	Ns

So induced EMF (assume concentrated winding)

$$E = 4.44\, f\, \phi T_{ph}$$

$$E = 4.44\frac{PN_s}{120} * \phi T_{phi}$$

$$so,$$

$$E \propto N_s\phi$$

Q: if I have a synchronous machine and required certain Voltage and Frequency which first ?

Frequency First , fix it through fixing the speed Ns

Then V , can be fixed because it changes ϕ not the speed

That's because

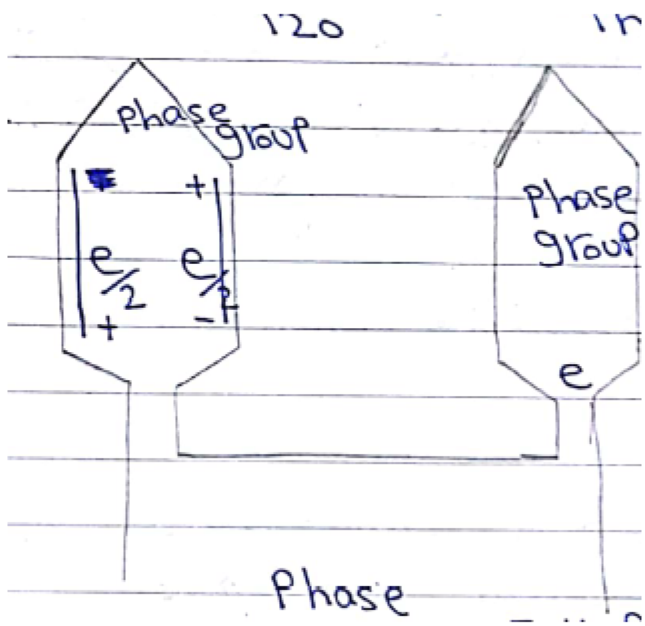
Frequency doesn't change if we change ϕ in the machine

But E changes if we change the machine speed

	N	ϕ
F	$\propto$	NO
E	$\propto$	$\propto$

1.8 Winding Methods

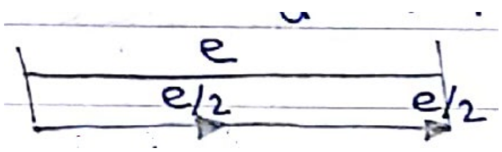
There are two methods to do the winding of the different phase groups



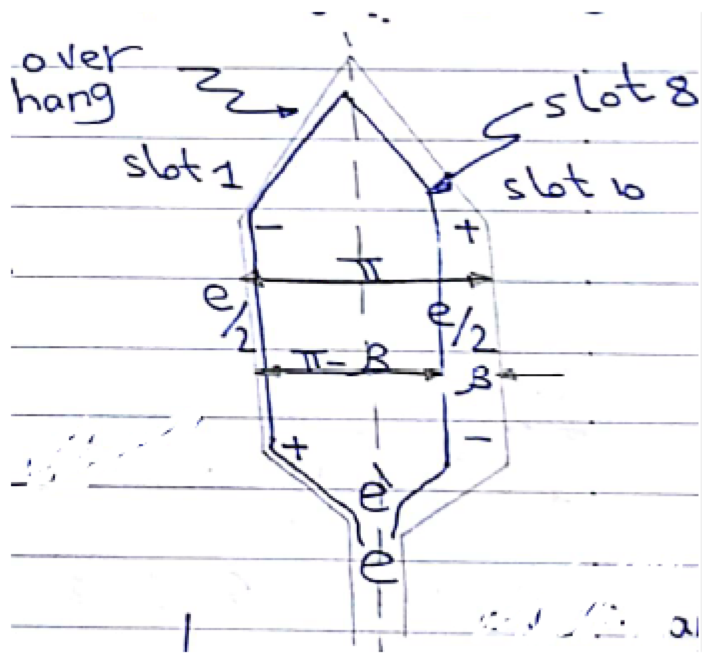
1.8.1 Method 1 : Full Pitch

Coil starts in slot1 and ends at slot10 : exactly 180 °

Sum of emf = e (each phase group e/2)



1.8.2 Method 2 : Chording



Starts at slot1 ends at slot8

angle= 180 ° $-\beta$

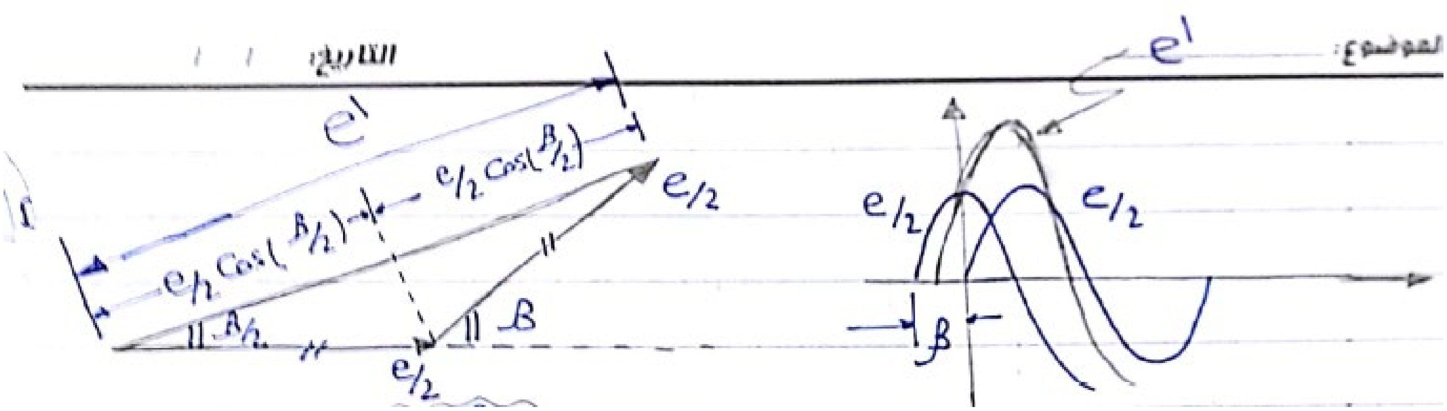
this is called chording

<u>Advantages</u>

1- Saving copper (less resistance)
2- Decreasing copper losses (saving money – less heat)
3- Easy handling
4- decreasing effect of space harmonic

Do chording to eliminate the effect of one of the harmonics (3rd mostly)

1.8.2.1 EMF sum & Chording Pitch Factor (Kp)

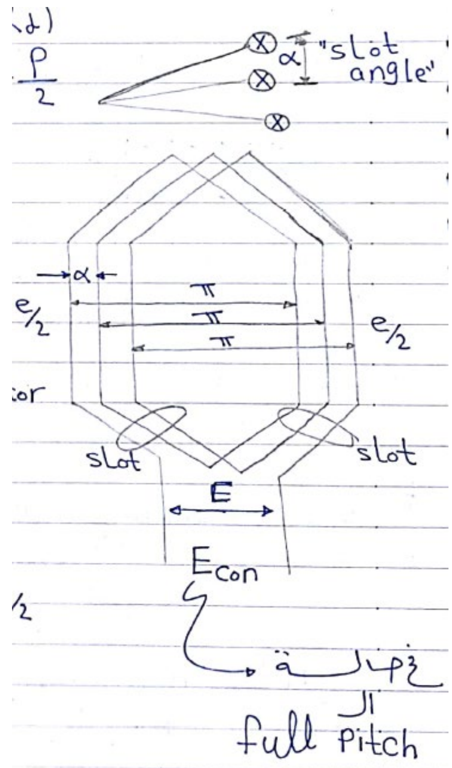


$$e' = e\cos\left(\frac{\beta}{2}\right) = e\,K_p$$

$$k_p : chording\ pitch\ factor$$

1.8.2.2 Distributed factor (Kd)

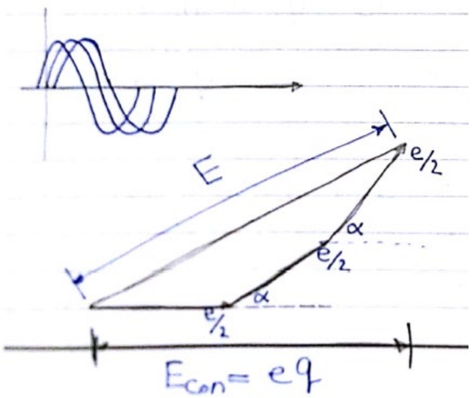
Due to number of winding for same phase



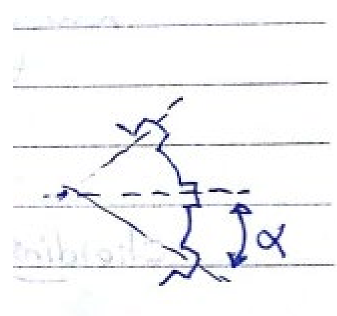
$$\alpha_{mech} = \frac{360}{S}$$

$$q = \frac{S}{mp}$$

$$E_{conductor} = eq$$



$$E = E_{cond} * \frac{\sin\left(\frac{q\alpha}{2}\right)}{q\sin\left(\frac{\alpha}{2}\right)} = E_{cond} * K_d$$



$$K_d = \frac{\sin\left(\frac{q\alpha}{2}\right)}{q\sin\left(\frac{\alpha}{2}\right)}$$

$$No\ Ditribution\ K_d = 1$$
$$No\ Chording\quad K_p = 1$$

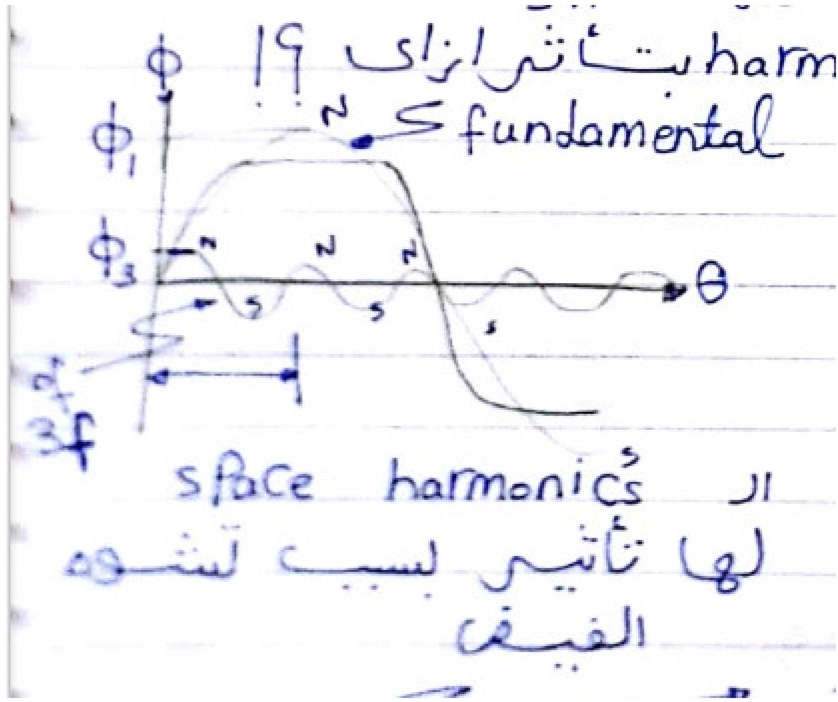
$$\therefore E_{ph} = 4.44\,f\phi T_{ph}K_pK_d$$

$$K_w = K_pK_d\ \ (winding\ factor)$$

1.9 Harmonics Calculations

1.9.1 Space Harmonics

Space harmonics cause distortion in the field distribution



$$\phi = \phi_1 \sin\theta + \phi_3 \sin 3\theta + \phi_5 \sin 5\theta + \cdots$$

Fir nth Harmonic

$$E_n = 4.44\, f_n \phi_n T_{ph} K_{p_n} K_{d_n}$$
$$f_n = nf$$

$$K_{p_n} = \cos\left(\frac{n\beta}{2}\right)$$

$$K_{d_n} = \frac{\sin\left(\frac{qn\alpha}{2}\right)}{q \sin\left(\frac{n\alpha}{2}\right)}$$

$$E_{ph} = \sqrt{E_1^2 + E_3^2 + E_5^2 + \cdots}$$

Only E_1 Participates in Energy Conversion

E_3,E_5,... only losses and heat

1.9.1.1 *To remove 3rd Harmonic*

1.9.1.1.1 To remove nth harmonic

Put $n\beta = \pi$

1.9.1.1.2 to remove 3rd harmonic

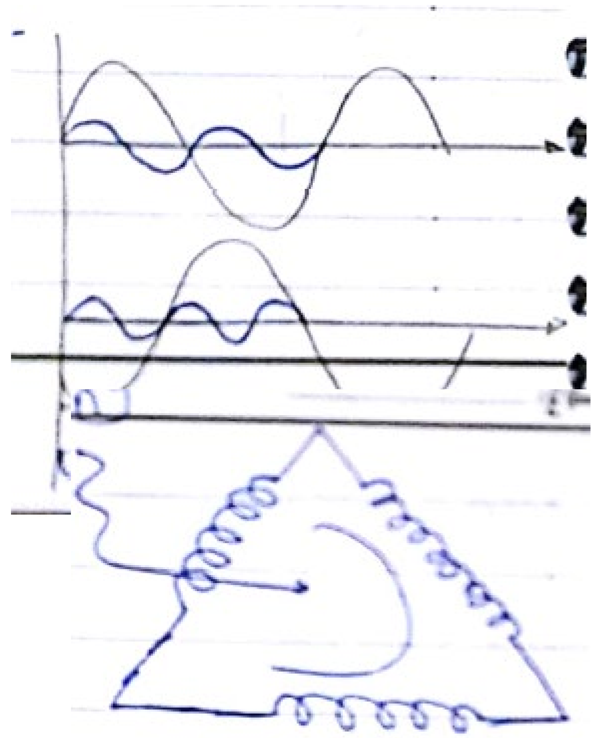
Tripling harmonics 3, 9, ... are only in phase not in line has (1,5,7,..)

$$3\beta = \pi$$

$$\beta = \frac{\pi}{3} = 60\,^{\circ}$$

So we removed 3rd harmonic only from E not the ϕ $(still\ has\ 3rd\ harmonics\ )$

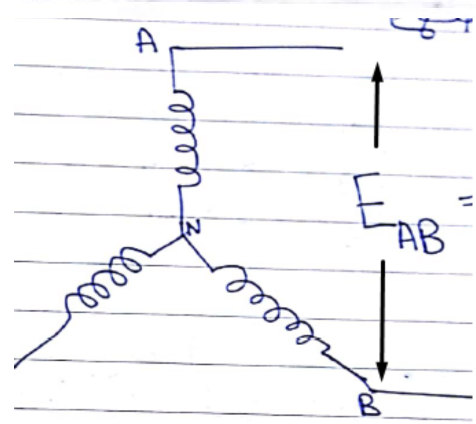
In Delta tripling harmonics are trapped inside circulating (but it causes heat losses)



In star $E_{AB} = E_A - E_B$

So after removing triplin relation becomes

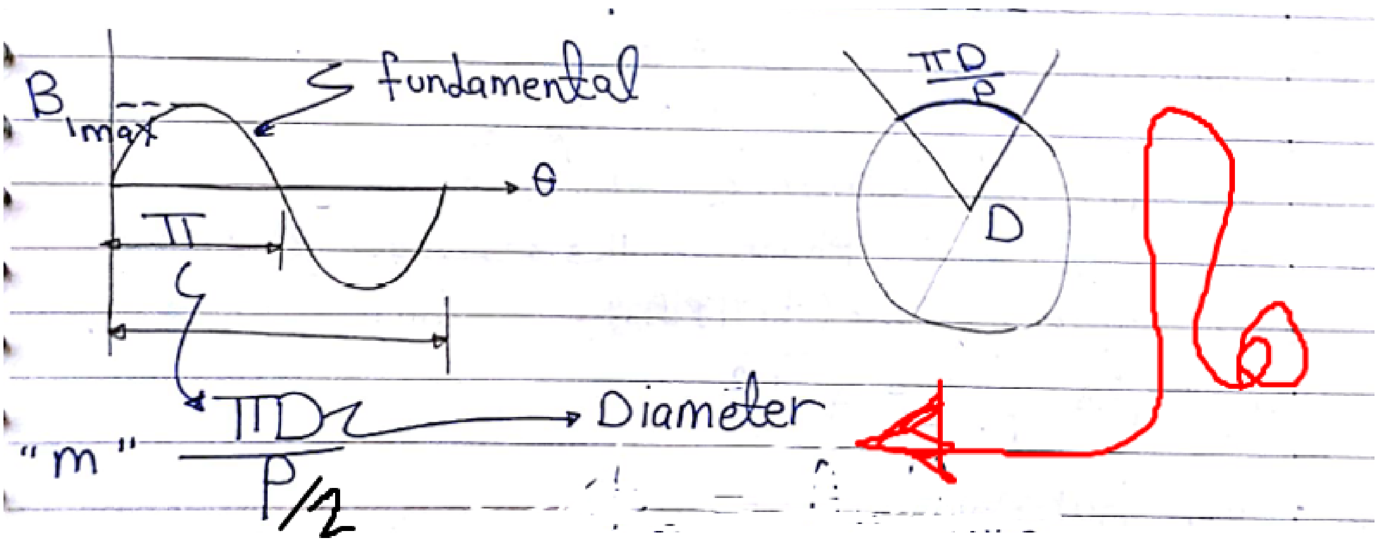
$$E_{LL} = \sqrt{3} * 0.9963\ E_{ph}$$



$$B(\theta) = B_{1_{Max}} \cos\theta + B_{3_{Max}} \cos 3\theta + B_{5_{Max}} \cos 5\theta + \cdots$$

$$\boldsymbol{\phi_n = A_n B_{av_n} = \frac{\pi DL}{nP} \ * \ \frac{2}{\pi} B_{n_{Max}} = \ \frac{L}{n}\tau_p \ * \ \frac{2}{\pi} B_{n_{Max}}}$$

1.9.2 Relation Between electrical and Mechanical Angle



Harmonics increase rms

But cause a lot of iron losses (1st is effective , other are losses)

Causes voltage drop

Causes harmonic pollution

For Sheet

$$T_{ph} = \frac{Z_s S}{2m}$$

$$q = \frac{S}{mp}$$

$$\alpha = \frac{180P}{S}$$

$$\boldsymbol{q\alpha = "phase\ spread"}$$

$$f_n = nf$$

$$K_{p_n} = \ cos\left(\frac{n\beta}{2}\right)$$

$$K_{d_n} = \frac{sin\left(\frac{qn\alpha}{2}\right)}{q\ sin\left(\frac{n\alpha}{2}\right)}$$

$$K_w = K_p K_d$$

$$E_n = 4.44\ f_n \phi_n T_{ph} K_{p_n} K_{d_n}$$

$$\boldsymbol{E_{ph} = \sqrt{E_1^2 + E_3^2 + E_5^2 + \cdots}}$$

$$\boldsymbol{E_L = \sqrt{3}\ E_{ph}}$$

$$\phi_n = \frac{1}{n}\ \phi_1 * \frac{B_n}{B_1}$$

$$B(\theta) = B_{1_{Max}}\, cos\,\theta + B_{3_{Max}}\, cos\,3\theta + B_{5_{Max}}\, cos\,5\theta + \cdots$$

$$\boldsymbol{\phi_n = A_n B_{av_n} = \frac{\pi DL}{nP}\ \ *\ \ \frac{2}{\pi}\ B_{n_{Max}} = \ \ \frac{L}{n}\tau_p\ \ *\ \ \frac{2}{\pi}\ B_{n_{Max}}}$$

2 SYNCHRONOUS GENERATOR

2.1 THE SPEED OF ROTATION OF A SYNCHRONOUS GENERATOR

$$f_{se} = \frac{NP}{120}$$

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

2.2 THE INTERNAL GENERATED VOLTAGE OF A SYNCHRONOUS GENERATOR

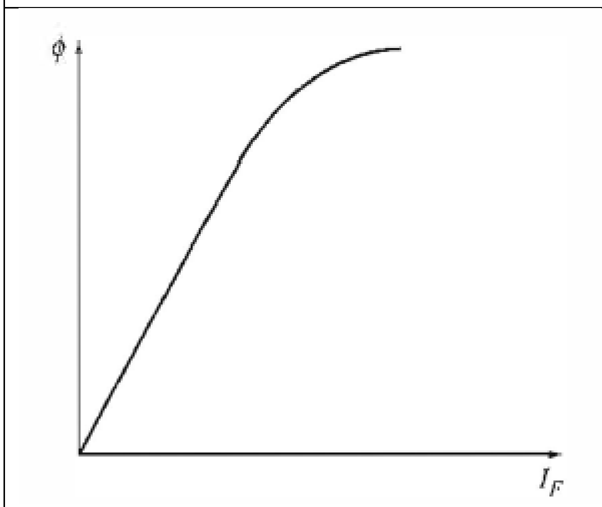
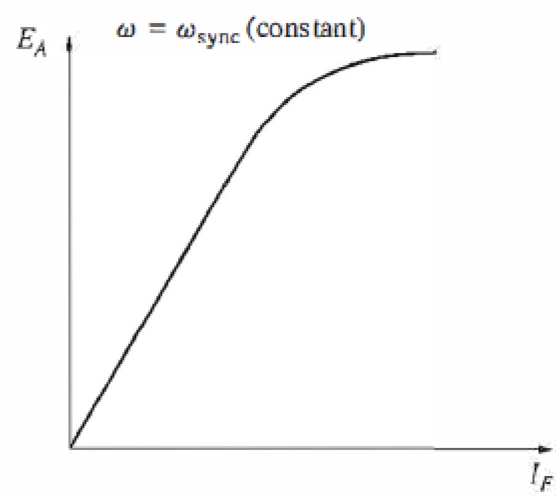
$$E_A = \sqrt{2}\,\pi N_C \phi f$$

$$E = K\phi\omega$$

$$K = \frac{N_c}{\sqrt{2}} \rightarrow \omega_e$$

$$K = \frac{N_c P}{\sqrt{2}} \rightarrow \omega_m$$

The internal generated voltage E_A is directly proportional to the flux and to the speed, but the flux itself depends on the current flowing in the rotor field circuit.

The field circuit I_F is related to the flux ϕ	E_A is directly proportional to the flux. *magnetization curve* *open-circuit characteristic*
	

2.3 THE PRODUCTION OF EQUIVALENT CIRCUIT OF A SYNCHRONOUS GENERATOR

V_ϕTerminal Voltage is less than E_A "Induced Voltage"

V_ϕ= E_A only if $I_a = 0$

2.3.1 factors that cause the difference between E_A and V_ϕ :

1. The distortion of the air-gap magnetic field by the current flowing in the stator, called **armature reaction.**

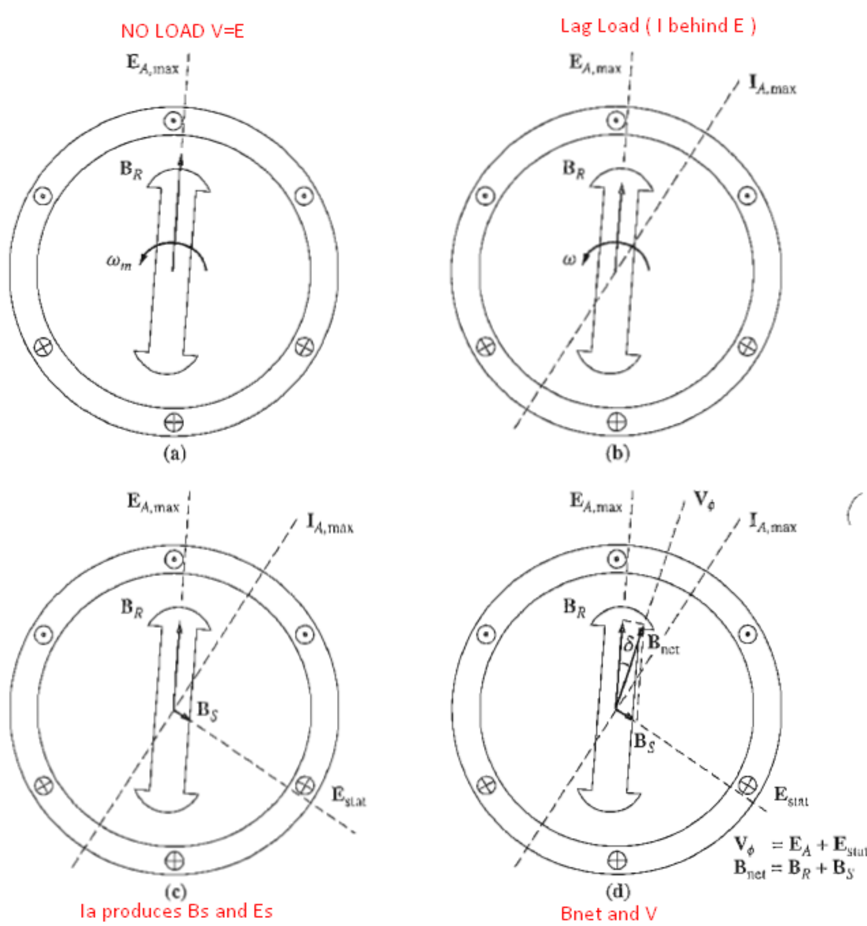
2. The **self-inductance** of the armature coils.

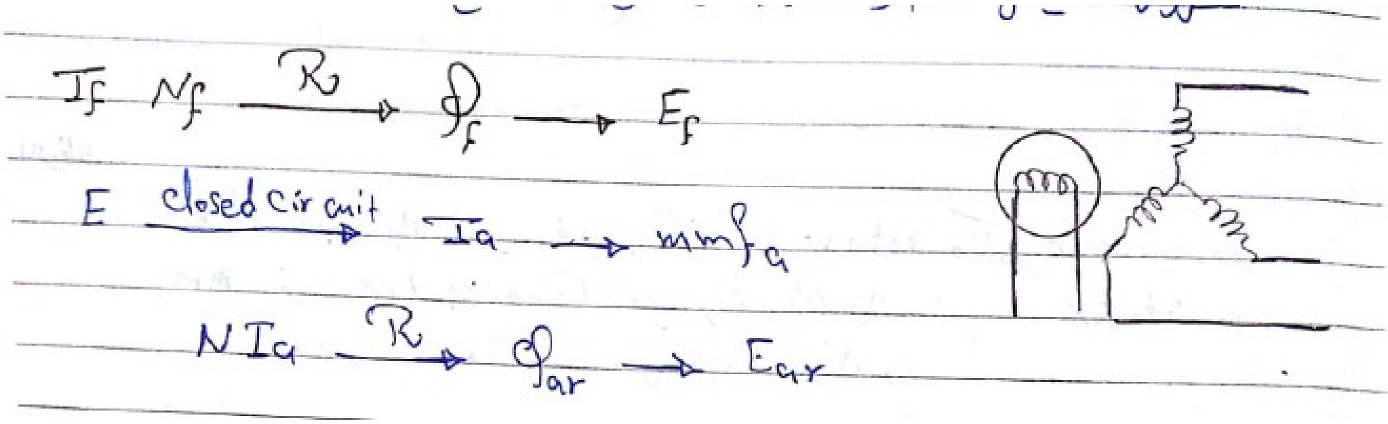
3. The **resistance** of the armature coils.

4. The effect of **salient-pole rotor shapes**. (ignored)

2.3.1.1 Armature Reaction

If a load is attached to the terminals of the generator, current flows. But a three-phase stator current flow will produce a **magnetic field of its own in the machine**. This stator magnetic field **distorts the original** rotor magnetic field, changing the resulting phase voltage. **This effect is called armature reaction because the armature (stator) current affects the magnetic field which produced it in the first place.**





$$so,$$

$$V_\phi = E_A + E_{stat}$$
$$B_{net} = B_R + B_s$$

Both B_{net} and V_ϕ are in the same direction

<u>NOTE</u> The angle between B_R and B_{net} is known as the <u>internal angle</u> or <u>torque angle δ</u> for the machine. This angle is proportional to the amount of power being supplied by the generator,

2.3.1.1.1 To Model AR

- Voltage E_{stator} lies at an angle of 90° behind the plane of maximum current I_A (-j)

-the voltage E_{stator} is directly proportional to the current I_A (Let by const called X)

So it's represented

$$E_{stat} = -jXI_A$$

$$\therefore V_\phi = E_A - jXI_A$$

2.3.1.2 Coil Inductance and Resistance Effect

$$V_\phi = E_A - jXI_A - jX_AI_A - R_AI_A$$

Let's lump up X's into one X called the **<u>synchronous Reactance</u>**

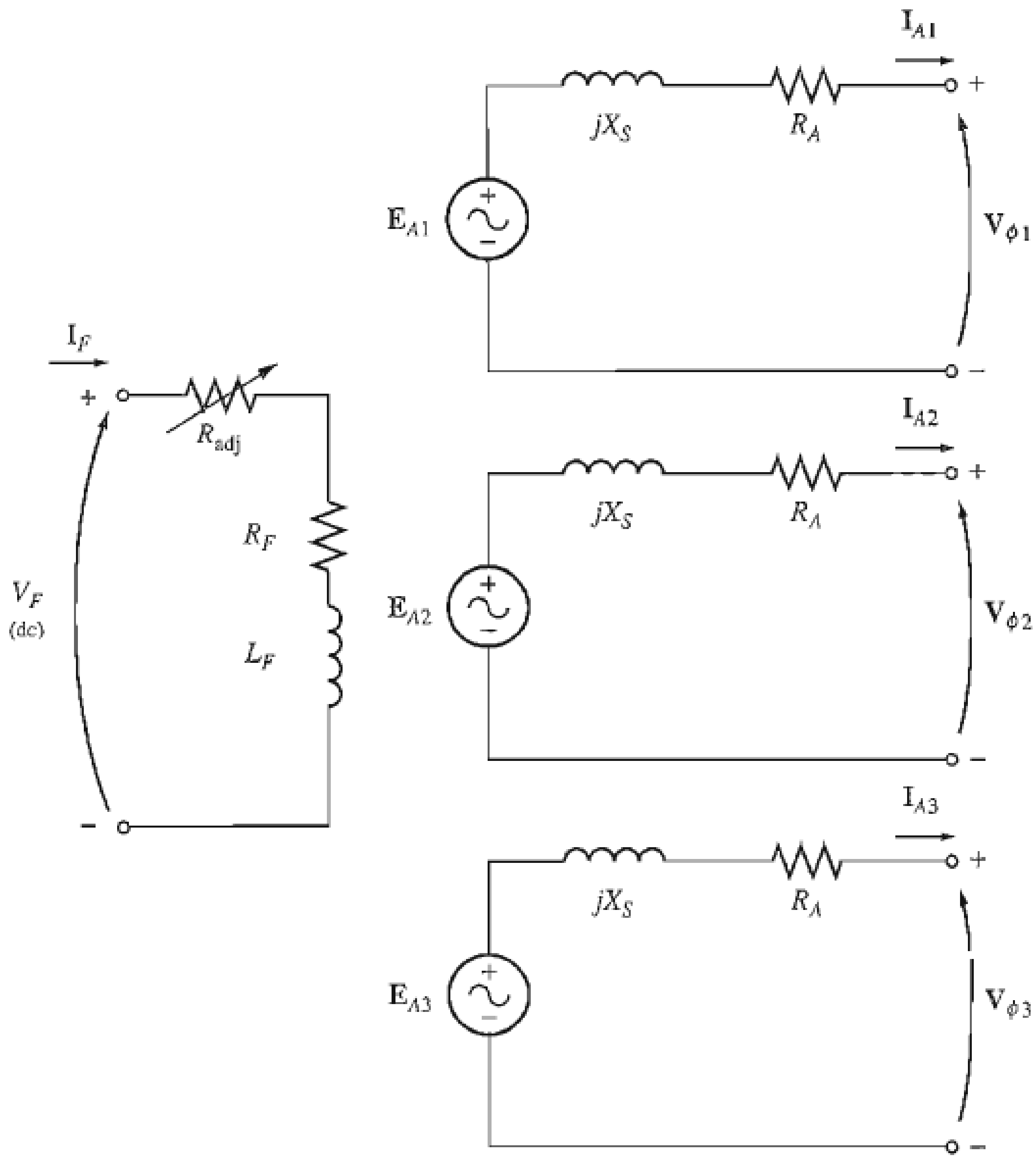
$$X_S = X + X_A$$

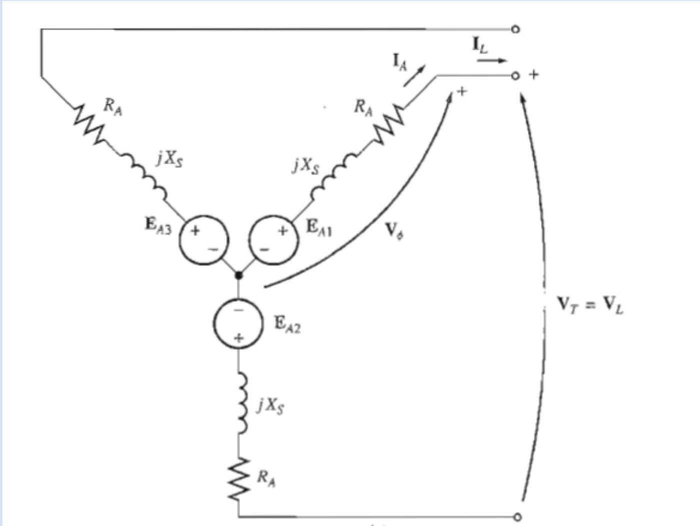
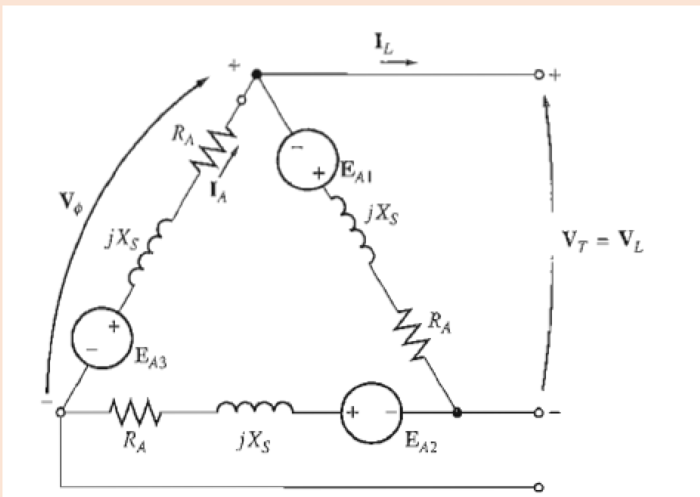
2.3.2 Final V terminal Equation

$$V_\phi = E_A - jX_SI_A - R_AI_A$$

2.4 Final Equivalent Circuit

2.4.1 Three phase full equivalent circuit

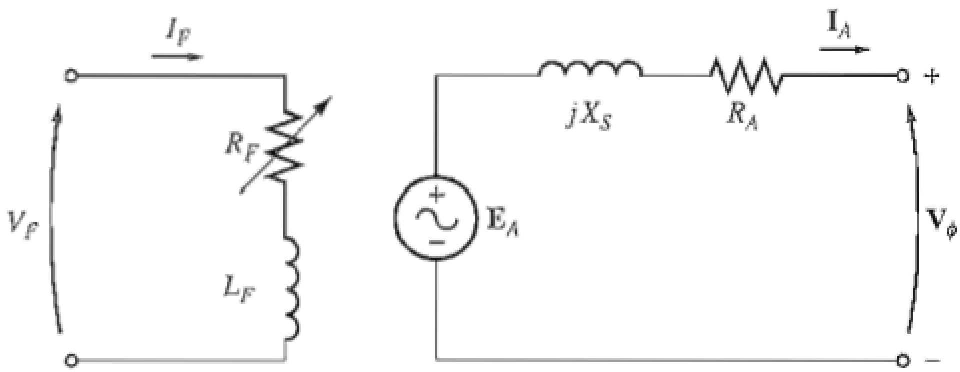


Y	Y  (a)	$V_\phi = \dfrac{V_T}{\sqrt{3}}$
Δ	Δ  (b)	$V_\phi = V_T$

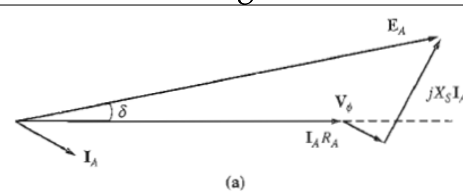
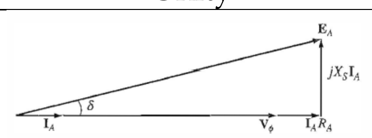
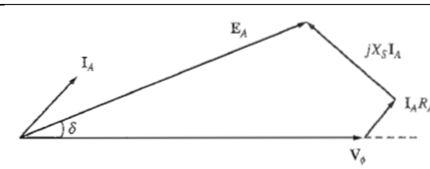
2.4.2 The per-phase equivalent circuit

The fact that the three phases of a synchronous generator are identical in all respects except for phase angle normally leads to the use of a per-phase equivalent circuit.

NOTE The three phases have the same voltages and currents only when the loads attached to them are balanced.



2.5 THE PHASOR DIAGRAM OF A SYNCHRONOUS GENERATOR

Lag	Unity	Lead
		

Notice that, for a given phase voltage and armature current, a larger internal generated voltage EA is needed for lagging loads than for leading loads. Therefore, a larger field current is needed with lagging loads to get the same terminal voltage, because $E_a = k\phi\omega$

Alternatively ,

For a given field current and magnitude of load current, the terminal voltage is lower. for lagging loads and higher for leading loads. (for given E and Ia then V_t higher for lead)

2.6 POWER AND TORQUE IN SYNCHRONOUS GENERATORS

- SG converts mechanical power to three-phase electrical power.
- Prime mover must have the basic property that its speed is almost constant regardless of the power demand , if that were not so, then the *resulting power system's frequency would wander.*

2.6.1 Power Flow Diagram

Power Flow determines mechanical input, converted and electrical output Power

$$P_{in} = T_{app}\omega_m$$

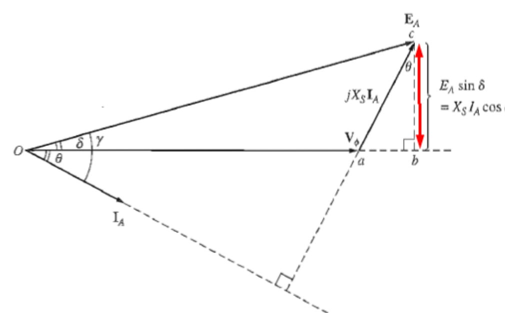
$$P_{conv} = T_{ind}\,\omega_m = 3E_AI_A\cos\gamma$$

Losses : Mechanical, Core, Stray

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

$$Q_{out} = \sqrt{3}\,V_LI_L\sin\theta \;=\; 3\,V_\phi I_A\sin\theta$$

2.6.2 Power Equation



Since $X_s \gg R_A$ let's ignore R_A

Then we can derive a good equation from phasor

$$X_sI_A\cos\theta = E_A\sin\delta$$

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

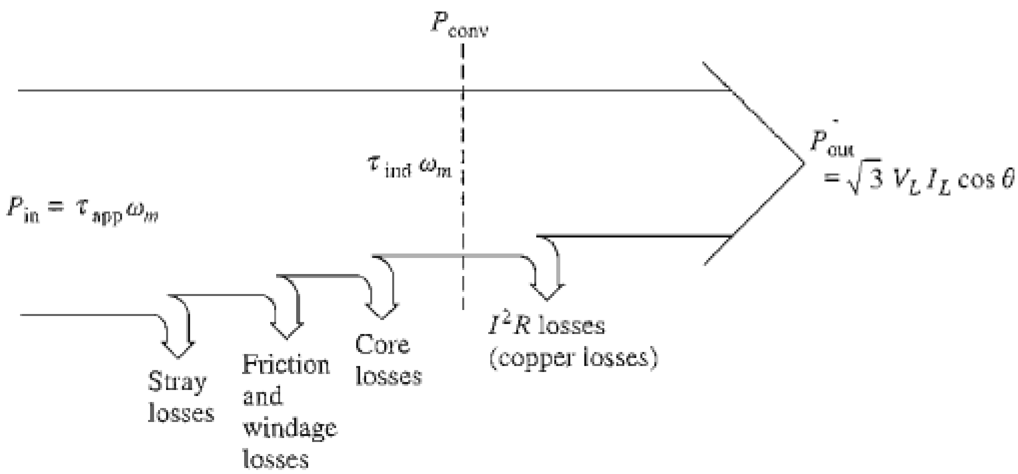
$$\boldsymbol{P_{conv} = P_{out} = \frac{3V_\phi E_A}{X_s}\sin\delta}$$

as there's no resistance $P_{conv} = P_{out}$

P_{out} depends on δ $(internal\ angle - torque\ angle\ )$

At $\delta = 90\,°\ \rightarrow P_{max}$

$$P_{Max} = \frac{3V_\phi E_A}{X_S}$$



$$P_{cu_{Field}} = V_f I_f = I_f^2 R_f$$

$$P_{cu_A} = 3 I_a^2 R_a$$

$$\therefore P_{in} = P_{out} + P_{cu_f} + P_{cu_A} + P_{rot}$$

$$\boxed{[P_{cu_{field}} + P_{rot}] = P_{constant}}$$

due to a constant speed and constant voltage level.

- Constant speed → friction. const
- Costant voltage → Core losses const

$$\therefore P_{in} = P_{out} + P_{cu_A} + P_{const}.$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - (P_{const} + P_{cu_A})}{P_{in}}$$

$$\eta = \frac{3 V_t I_a \cos\phi}{3 V_t I_a \cos\phi + P_{cu_A} + P_{const}}$$

NOTES

1- This P_{Max} is called ***the static stability limit of the generator***
2- *assume* $V_{\phi} const$

$$\boldsymbol{P_{out} \propto I_A \cos\theta \;\propto\; E_A \sin\delta}$$
$$\boldsymbol{Q_{out} \propto I_A \sin\theta}$$

2.6.3 Induced Torque

<u>magnetic</u>

$$T_{ind} = k\, B_R \times B_S$$

$$T_{ind} = k\, B_R \times B_{net}$$

$$T_{ind} = k\, B_R B_{net} \sin\delta$$

OR <u>electrical</u>

$$P_{conv} = T_{ind}\,\omega$$

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

For *stability* reasons Full Load (P and T)($\boldsymbol{\delta = 20 : 30}$) doesn't exceed $\boldsymbol{\frac{1}{3}}$ (P, T MAX $\boldsymbol{\delta = 90}$)

2.7 MEASURING SYNCHRONOUS GENERATOR MODEL PARAMETERS

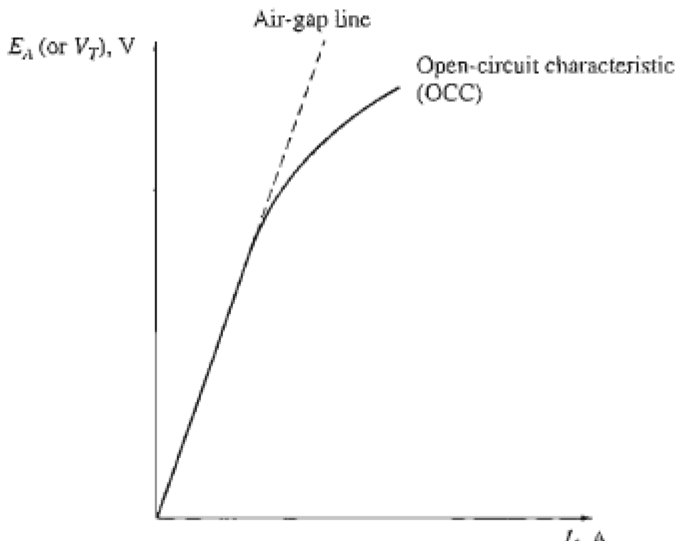
to completely describe the behavior of a real synchronous generator we need 3 quantities

1. The **relationship** between field current and flux
 (and therefore between the field current and E_A)
2. The synchronous **reactance**
3. The armature **resistance**

2.7.1 Open circuit test

- Turned at rated speed
- disconnected from all loads (no load)
- Field current is set to zero
- Then the field current is gradually increased in steps
- Terminal voltage is measured at each step

We measure E_A *vs* I_f ***open-circuil characteristic (OCC)***



(a)

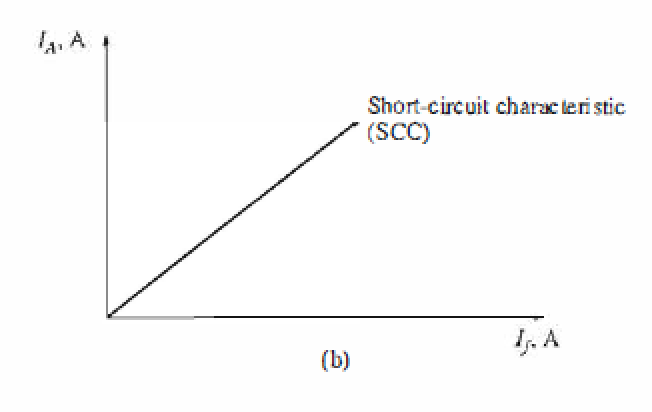
Notice linear region is called <u>air gap line</u>

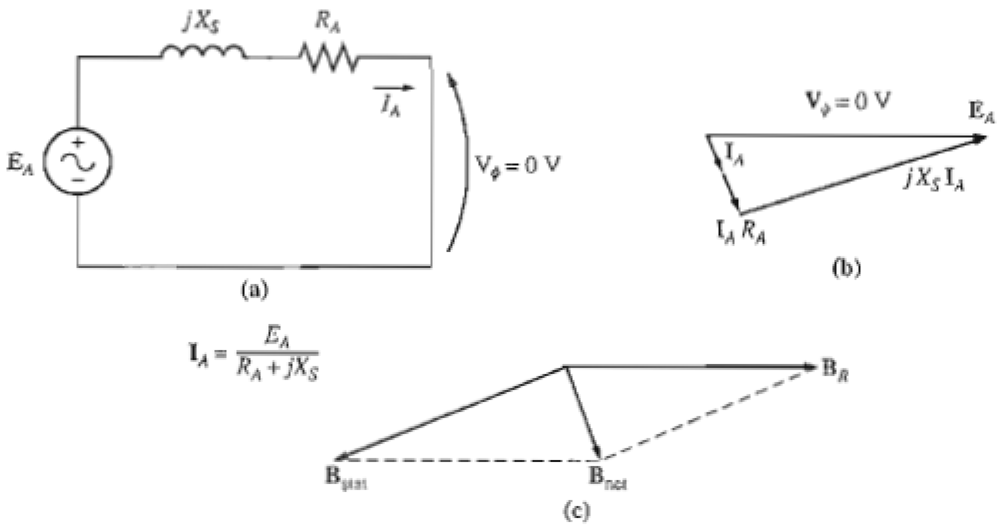
<u>At knee region</u> saturation factor = If2/If1 = 1.2

2.7.2 short-circuit test

- adjust the field current to zero
- short-circuit the terminals
- I_A measured while increasing the field current

$$I_A = \frac{E_A}{R_A + jX_s}$$





Since Bs (AR) almost cancels B_R, the net magnetic field **B_{net} is very small** *(corresponding to internal resistive and inductive drops only).* Since the net magnetic field in the machine is so small (V small too), the machine is **unsaturated** and the SCC is **linear**

2.7.3 To calculate Xs

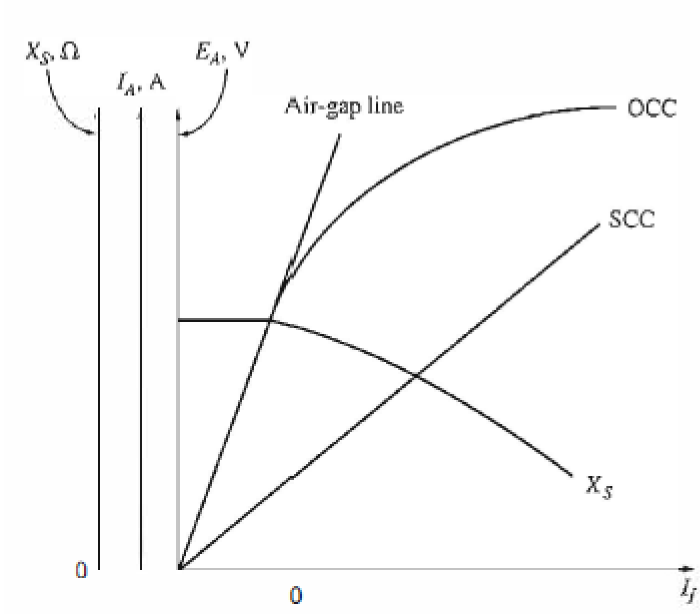
approximate method for determining the synchronous reactance Xs at a given field current is

1. Get the internal generated voltage E_A from the OCC at that field current.
2. Get the short-circuit current flow $I_{A,sc}$ at that field current from the SCC.
3. Find Xs by applying

$$Z_s = \sqrt{R_A^2 + X_S^2} = \frac{E_{A,OCC}}{I_{A.SCC}}$$

$$\text{Or if } X_S \gg R_A \rightarrow X_S \cong \frac{E_A}{I_A} = \frac{V_{\phi,oc}}{I_A}$$

approximate method for determining the synchronous reactance Xs at a given field current is



The **constant value of reactance** found at low values of field current *is the* ***unsaturated*** *synchronous reactance of the machine.*

Approximation : at high field current , we obtain E_A from OCC (saturated) and divide it by I_A obraoined from SCC (not saturated) , so they are <u>not the same</u> so <u>Xs is only approximate at high field currents</u>

2.7.4 DC test

To obtain winding resistance

- applying a dc voltage to the windings while the machine is stationary
- Measuring the resulting current flow.
- Make for skin effect (1.15)

Note : This Resistance can be ignored it's error effect <u>is much less</u> than saturation error

STAR	$R_{DC} = \frac{1}{2} R_{mDC_{LL}}$
DELTA	$R_{DC} = \frac{3}{2} R_{mDC}$

2.7.5 The Short-Circuit Ratio

$$SC\ ratio = \frac{field\ current\ required\ for\ the\ rated\ voltage\ at\ open\ circuit}{field\ current\ required\ for\ the\ rated\ armature\ current\ at\ short\ circuit.}$$

$$SC\ ratio = \frac{I_f(V_{rated.OCC})}{I_f(I_{rated,SCC})}$$

*It's just reciprocal of the per-unit value of the approximate **saturated synchronous reactance***

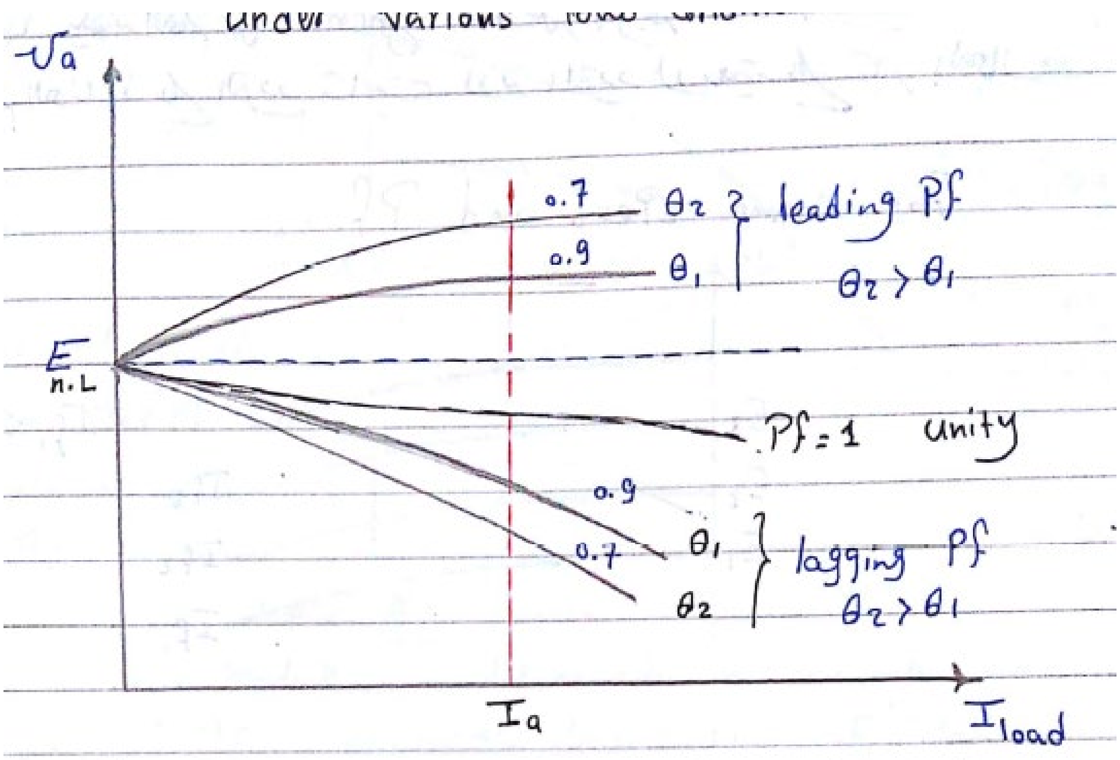
Adds no new information, but you must know it

2.8 Generator External Characteristics:

1- Field Current
2- Speed
3- Load Condition (Magn., Power flow)

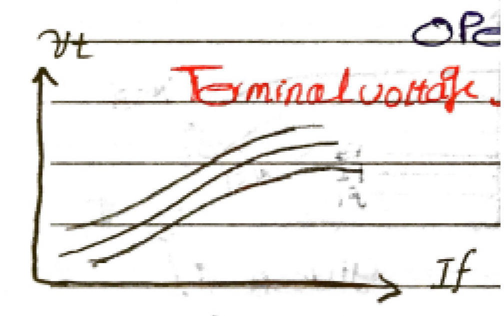
2.8.1 Under various load conditions ($Vt\ vs\ I_L$)

For same <u>Excitation , Speed (E, N)</u>



- We make prime mover speed N=const
- Then we change I_f until we get to the required V_T
- Here at no load $V_t > E$ as it has condenser (Lead) Effect
- $V_T = E - IZ$
- I changes with load condition (if it's lag then E will decrease sharply)

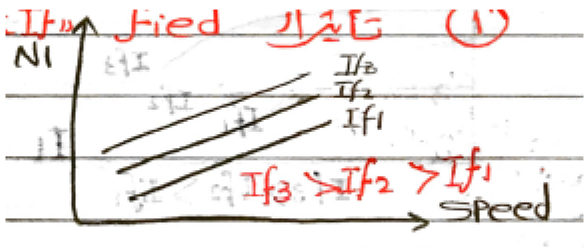
2.8.2 V_T vs I_f



Given (N at no load)

Linear at first then saturation

2.8.3 V_T vs N

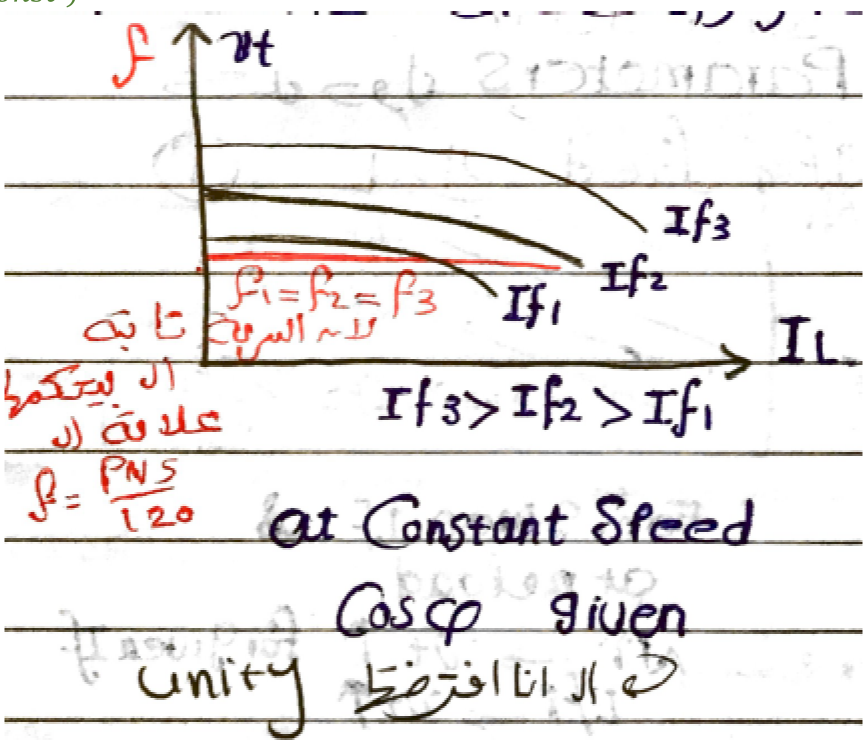


Given (If at no load)

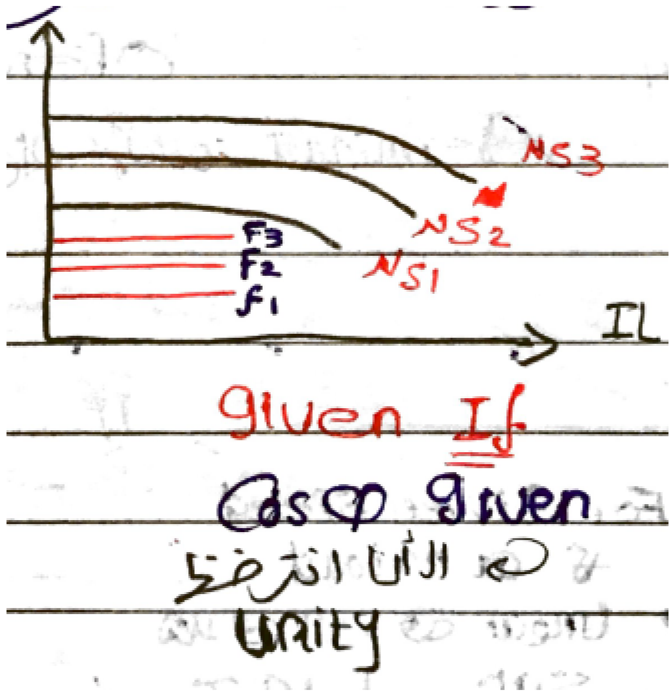
$$N \uparrow \Rightarrow V_t \uparrow$$

$$I_f \uparrow \Rightarrow V_t \uparrow$$

2.8.4 V_T vs I_L (N $const$)



2.8.5 V_T vs I_L (I_f or E $const$)



NOTE

$$PF \rightarrow f \rightarrow Load\ Impedance \rightarrow ch/c$$

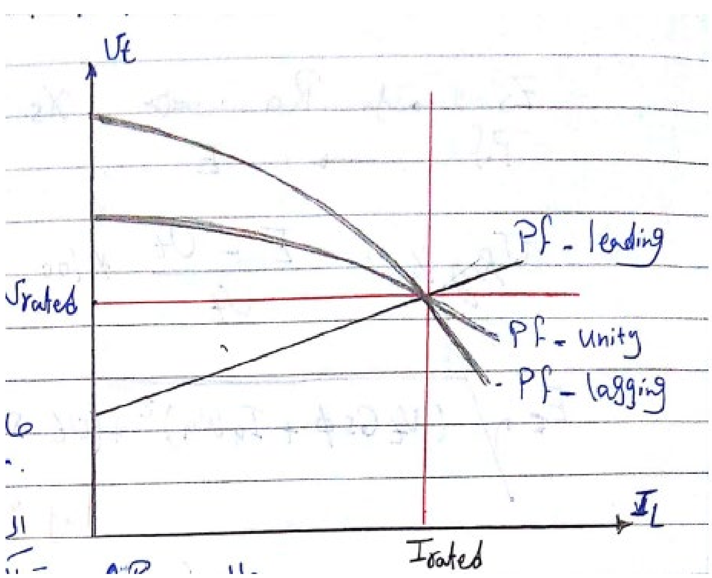
When impedance changes drop changes ($f \uparrow \rightarrow X \uparrow \rightarrow drop \uparrow$)

2.8.6 To get Vrated and Irated

High E >Vr lag (so when it drops it get Vr at Ir)

Unity maybe not very high

Lead Low Excitation E < Vr so when it increases gets Vr at Ir



2.9 THE SYNCHRONOUS GENERATOR OPERATING ALONE

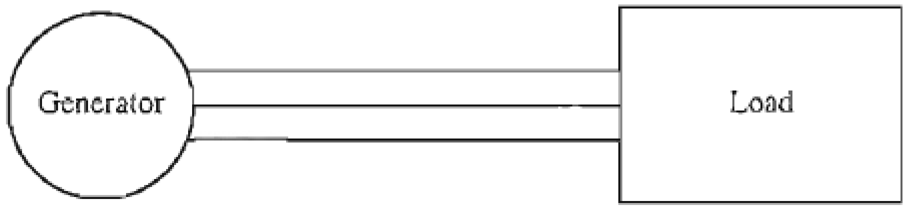
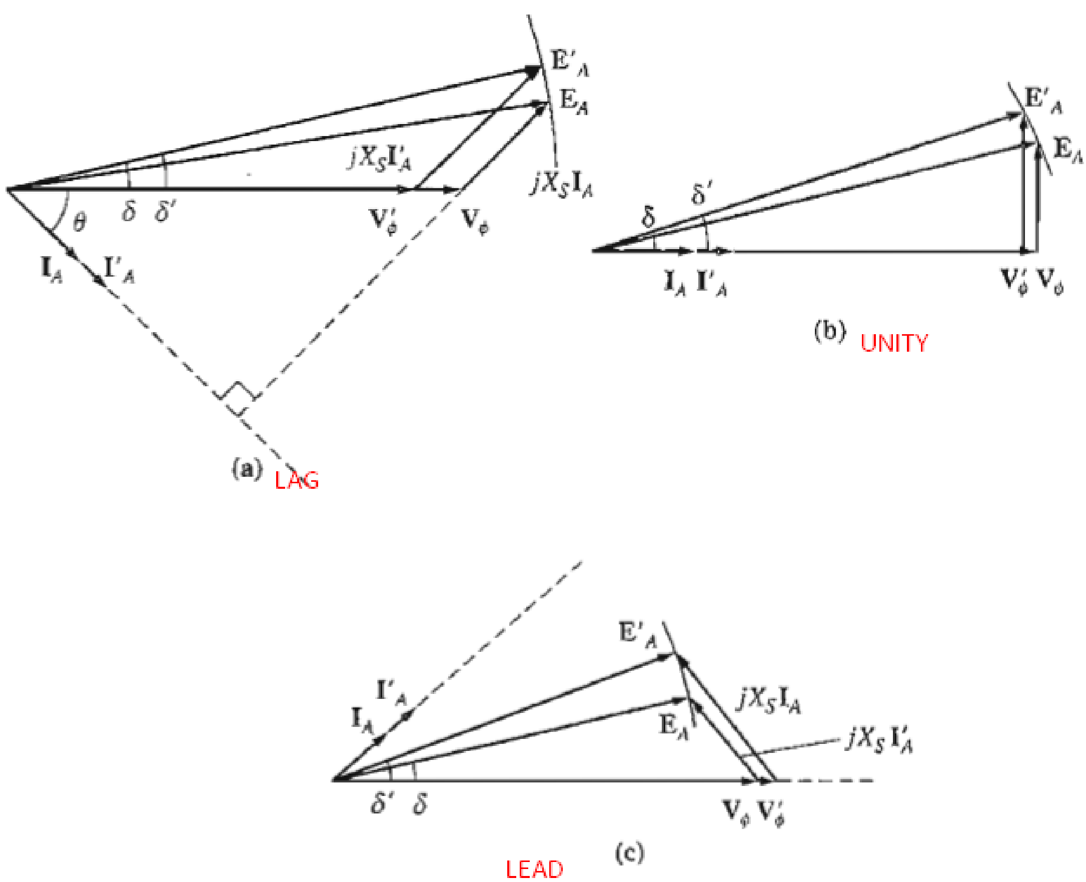


FIGURE 4–21
A single generator supplying a load.

2.9.1 What happens when we increase the load on this generator?

1- Increasing load, increase in the real and/or reactive power drawn from the generator.
2- increases the load current drawn from the generator.
3- Field resistor has not been changed, the field current is constant,<u>ϕ is constant</u>
4- Since the prime mover also keeps a constant speed ω, the magnitude of the interal generated voltage $\boldsymbol{E_A = k\phi\omega}$ **is constant.**
5- To find what changes we have to draw phasor diagram for different loading conditions
6- We find that the V_ϕ (<u>Lag : decreases sharply</u> , <u>Unity : decrease</u> , <u>Lead : increases</u>)



General conclusions

1. If lagging loads (+ Q or inductive reactive power loads) are added to a generator, V_ϕ and the terminal voltage V_T decrease significantly.

2. If unity-power-factor loads (no reactive power) are added to a generator, there is a slight decrease in V_ϕ, and the terminal voltage.

3. If leading loads (-Q or capacitive reactive power loads) are added to a generator, V_ϕ and the terminal voltage will rise.

2.9.2 Voltage Regulation

to compare the voltage behavior of two generators is by their voltage regulation

$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}} \times 100\%$$

Lag	Large +ve
Unity	Small +ve
Lead	-ve

2.9.2.1 How can terminal voltage variations be corrected for?

If V_T decrease, we want to increase $E_A = k\phi\omega$ since we have no control over frequency, then we must increase ϕ through I_f

1. Decreasing the field resistance in the generator increases its field current.
2. An increase in the field current increases the flux in the machine.
3. An increase in the flux increases the internal generated voltage $E_A = k\phi\omega$
4. An increase in EA increases v4, and the terminal voltage of the generator.

Or The Reverse

3 SYNCHRONOUS MOTOR

3.1 Principle of Operation

a three-phase set of currents in an armature winding produces a uniform rotating magnetic field Bs. Therefore, there are two magnetic fields present in the machine, and the rotor field will tend to line up with the stator field.

the stator magnetic field is rotating, the rotor magnetic field (and the rotor itself) will constantly try to catch up.

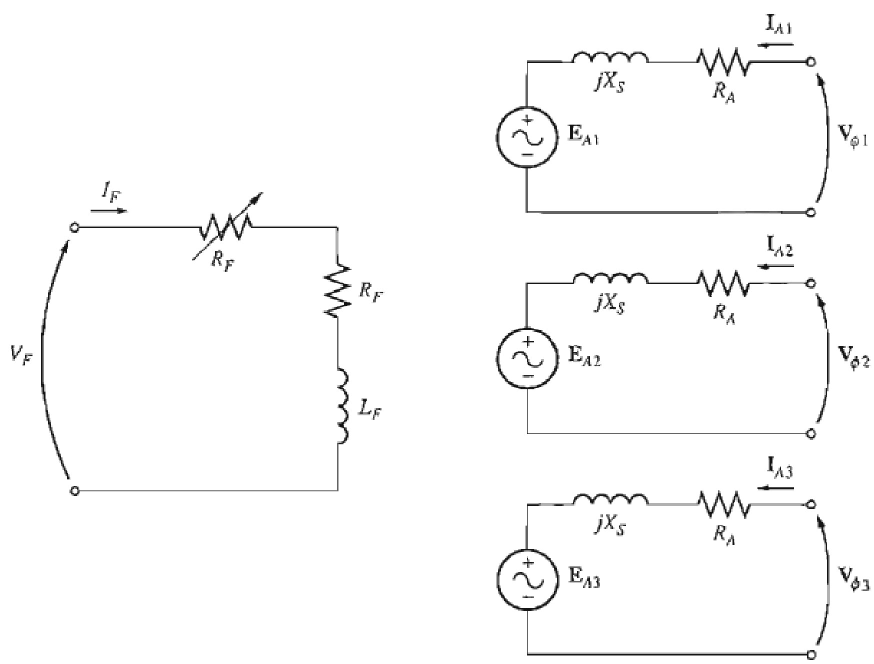
The larger the angle between the two magnetic fields (up to a certain maximum),the higher the Torq.

The basic principle of synchronous motor operation is that

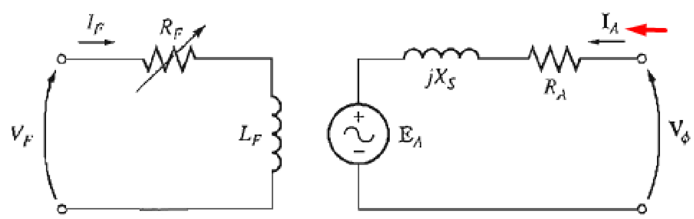
the rotor "chases" the rotating stator magnetic field around in a circle, never quite catching up with it.

3.2 The Equivalent Circuit of a Synchronous Motor

Direction of I_a is reversed



(a)



(b)

$$V_\phi = E_A + jX_sI_A + R_AI_A$$

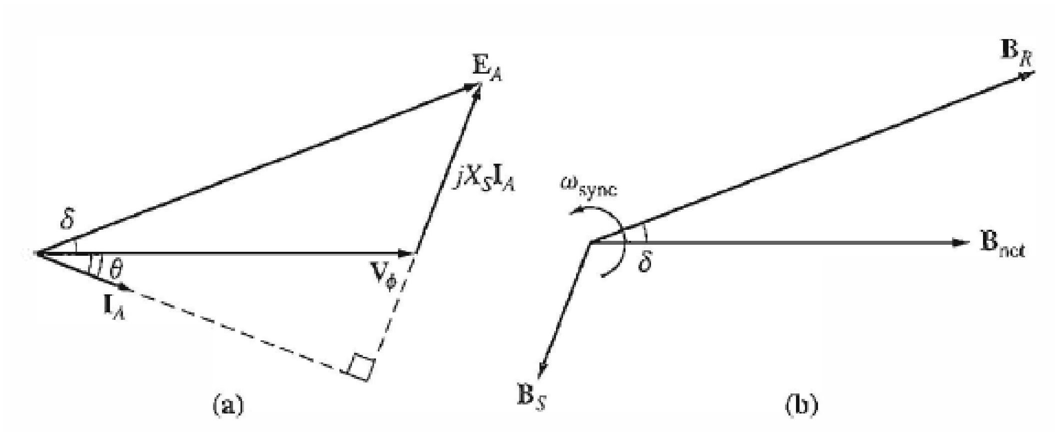
$$E_A = V_\phi - jX_sI_A - R_AI_A$$

3.3 The Synchronous Motor from a Magnetic Field Perspective

Remember Generator

$$B_R \rightarrow E_A$$
$$B_{net} \rightarrow V_\phi$$
$$B_{stat} \rightarrow E_{stat} = -jX_sI_A$$

The phasor and magnetic field diagram rotate at synchronous speed counterclockwise



In generator, torque in this machine is clockwise, <u>opposing the direction of rotation</u>. In other words, the induced torque in the generator is a <u>countertorque,</u> opposing the rotation caused by the external applied torque '**Tapp** · ($\boldsymbol{T_{ind}}$ ***opposes*** $\boldsymbol{T_{App}}$)

If applied torque in negative now ,

- B_R, slows down and <u>falls behind Bnet</u> the operation of the machine suddenly changes.
- the induced <u>torque's direction reverses and</u> becomes counterclockwise.
- the machine's torque is now <u>in the direction of motion</u>, and the machine is acting as a motor.
- The increasing torque angle δ results in a larger and larger torque in the direction of rotation,
- until eventually the motor's induced torque equals the load

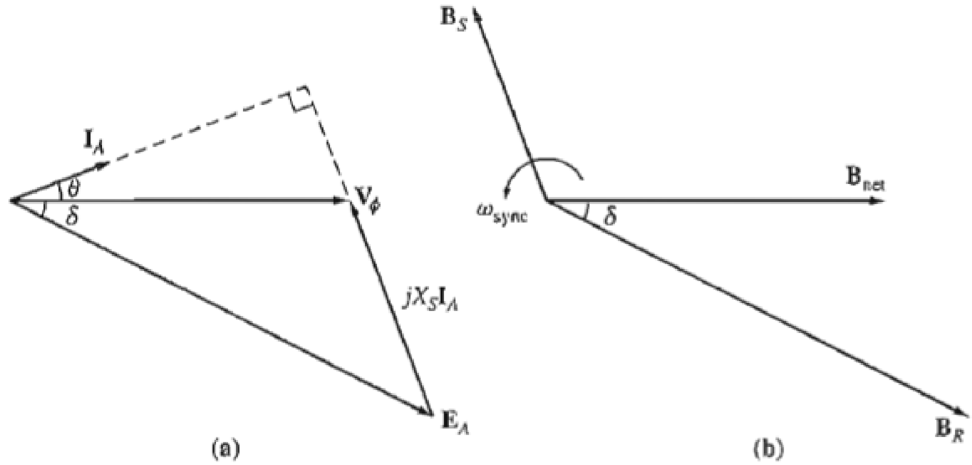
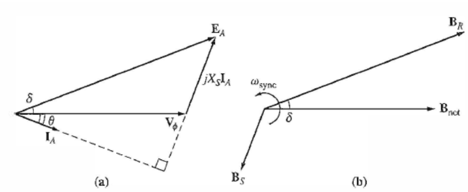
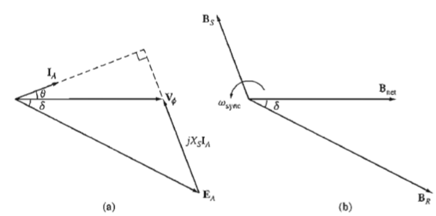


FIGURE 5–4
(a) Phasor diagram of a synchronous motor. (b) The corresponding magnetic field diagram.

Arrow $E_A - V_\phi$ reversed direction <u>because of</u> the reference direction of I_A reversed

	Generator	Motor
phasor diagram	E_A lies ahead of V_ϕ,, and B_R lies ahead of B_{net}	E_A lies behind V_ϕ , and B_R lies behind B_{net} .
Torque direction	induced torque is a countertorq ue **opposing** the direction of **motion**. 	induced torque is in the **direction** of **motion**,  FIGURE 5–4 (a) Phasor diagram of a synchronous motor. (b) The corresponding magnetic field diagram.

3.4 STEADY-STATE SYNCHRONOUS MOTOR OPERATION

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 rate of **rotation of the magnetic fields**,

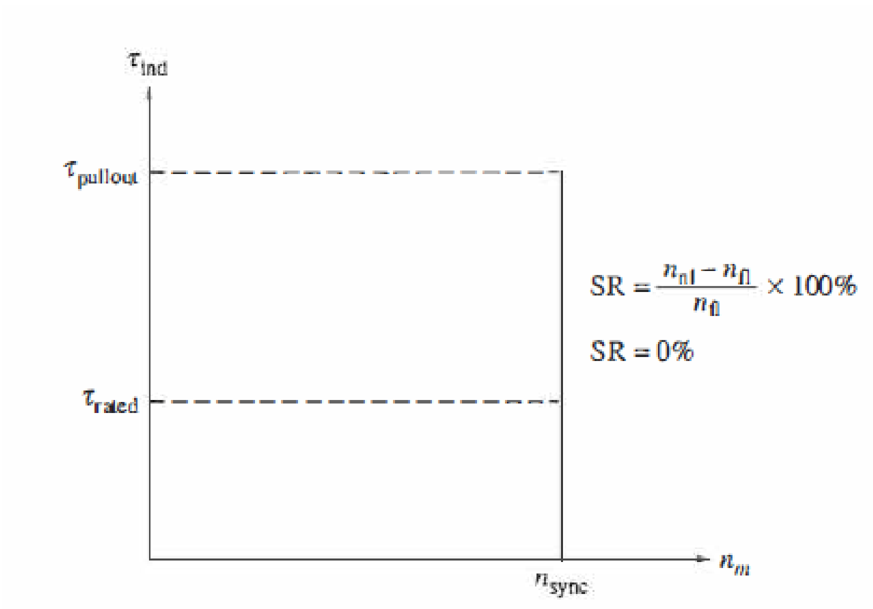
and the rate **of rotation of the applied mechanical** fields is locked to **the applied electrical frequency**,

so the speed of the synchronous motor will be constant regardless of the load.

This fixed rate of rotation is given

$$n_m = \frac{120 f_{se}}{P}$$

3.4.1 Speed Regulation



speed of the motor is constant from no load all the way up to the maximum torque that the motor can supply (called the pullout torque),

SR= 0 %

$$T_{ind} = k\, B_R B_{net} \sin \delta$$

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

$$T_{pullout} = \frac{3 V_\phi E_A}{\omega_m X_s} = 3\, T_{FL}$$

So for more stability we operate at large field current meaning large E_A

3.4.2 If Torque is more than Pullout

the rotor can no longer remain locked to the stator and net magnetic fields. Instead, the rotor starts to slip behind them

magnetic field "laps" it repeatedly, and the direction of the induced torque in the rotor reverses with each pass. The resulting huge torque surges, first one way and then the other way, cause the whole motor to vibrate severely. The loss of synchronization after the pullout torque is exceeded is known as **slipping poles.**

3.5 The Effect of Load Changes on a Synchronous Motor

3.5.1 What happens when load increases on motor

Load $\uparrow \longrightarrow \omega_m \downarrow \longrightarrow \delta \uparrow \longrightarrow T \uparrow \longrightarrow$

$\omega_m' \uparrow \simeq \omega_m$

$\rightarrow$ at $\delta' > \delta$

هنحمل أكتر لإن تحمل لـ $T_L = T_{max}$

"أقصى حمل يقدر يشيله الموتور"

the **load** on the shaft of the motor is **increased**,

the rotor will initially **slow down**.

As it does, the torque angle $\boldsymbol{\delta}$ **becomes larger**, and the **induced torque increases.**

The increase in induced torque eventually speeds the rotor back up, and the motor again turns at synchronous speed but with a larger torque angle δ.

3.5.2 How does phasor diagram change?

- E_A must be constant as the load changes.
- The distances proportional to power ($E_A \sin\delta$ *and* $I_A \cos\theta$) **will increase,**
- So E_A swings down
- jX_sI_A has to increase to reach from E_A to V_ϕ
- I_A increases
- PF (θ) changes becoming more and more lag

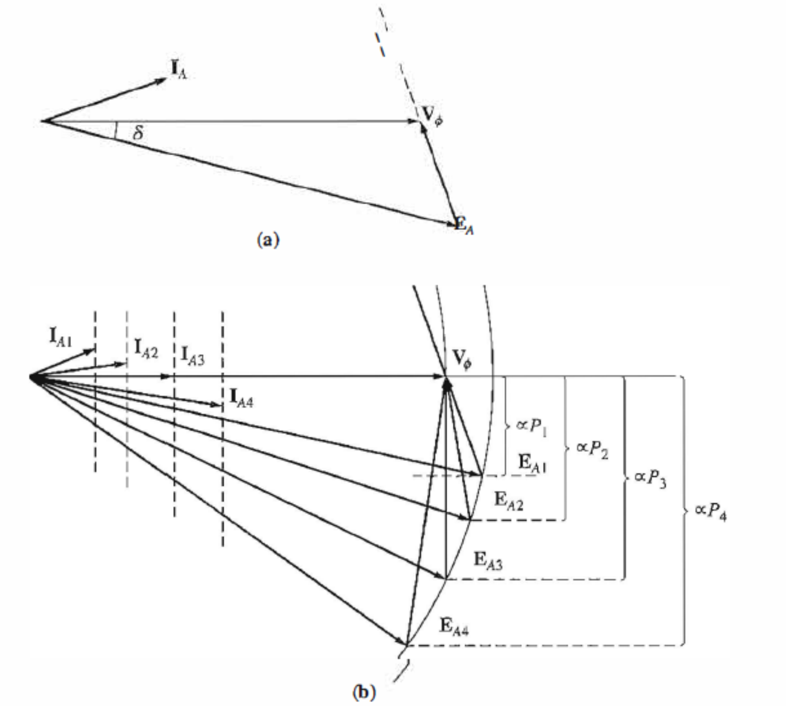


FIGURE 5–6
(a) Phasor diagram of a motor operating at a leading power factor. (b) The effect of an increase in load on the operation of a synchronous motor.

3.6 The Effect of Field Current Changes on a Synchronous Motor

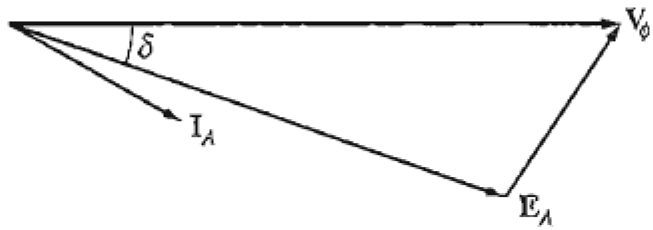
<u>Note</u> that an increase in field current increases the magnitude of E_A but <u>does not affect the real power</u> supplied to the motor. The power supplied to the motor changes only when the shaft load torque changes

So here

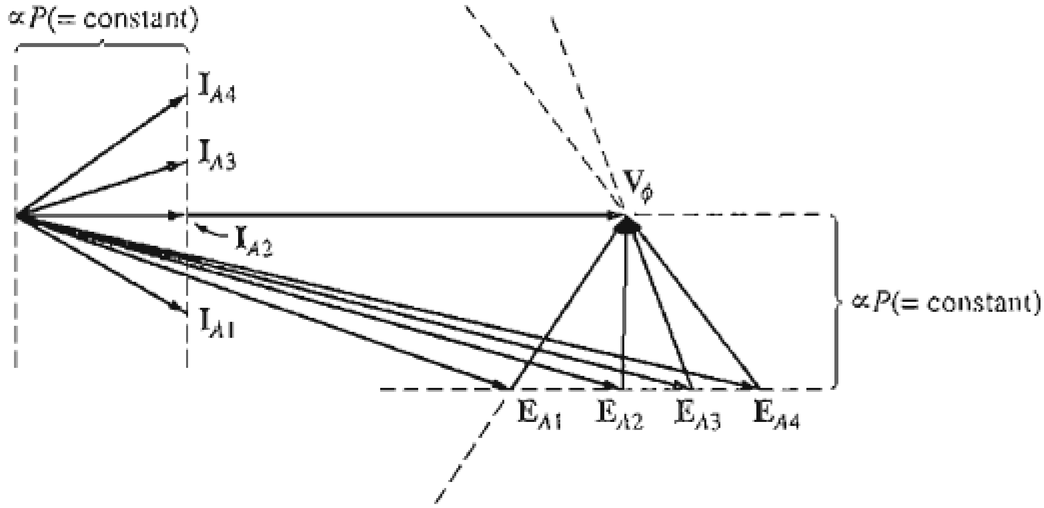
$$P\ is\ const\ (E_A \sin\delta\ \ and I_A \cos\theta)\ are\ constant$$

$$V_T\ is\ const$$

So $when\ I_f \uparrow\ \ only\ E_A\ uparrow$ as following



(a)



(b)

FIGURE 5–8
(a) A synchronous motor operating at a lagging power factor. (b) The effect of an increase in field current on the operation of this motor.

- as the value of E_A increases, I_A first decreases and then increases again

Low E : lag (Consuming reactive power Q)($E_A \cos\delta < V_\phi$) (UNDEREXCITED)
Middle : unity (Resistive)
High E : Lead (producing reactive power Q))($E_A \cos\delta > V_\phi$) (OVEREXCITED)

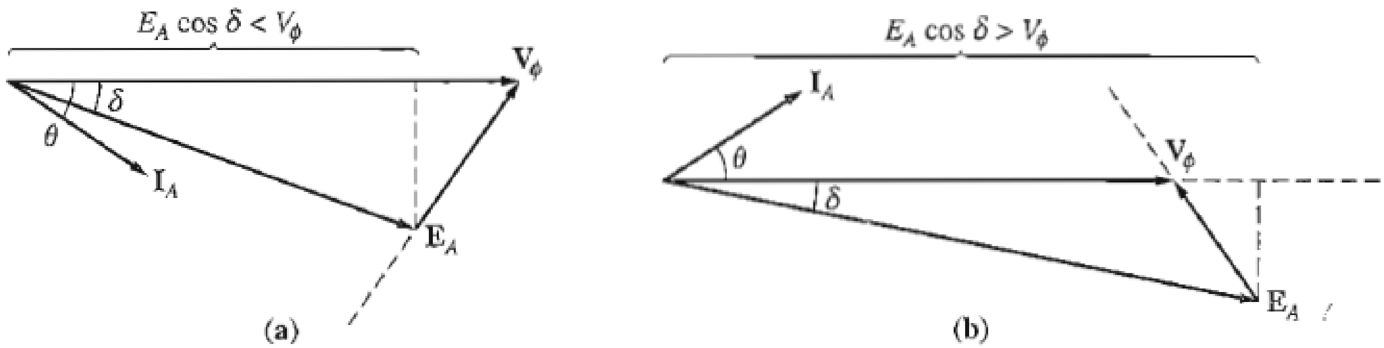
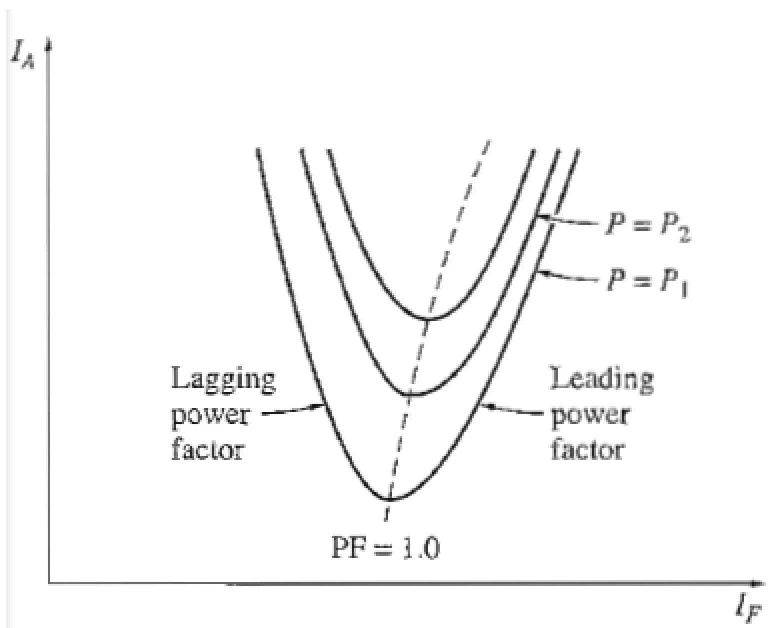


FIGURE 5–10
(a) The phasor diagram of an *underexcited* synchronous motor. (b) The phasor diagram of an *overexcited* synchronous motor.

So we can draw the v-curve



4 ELECTRICAL LOAD DIAGRAM

It's a general representation for the phasor diagram

As,

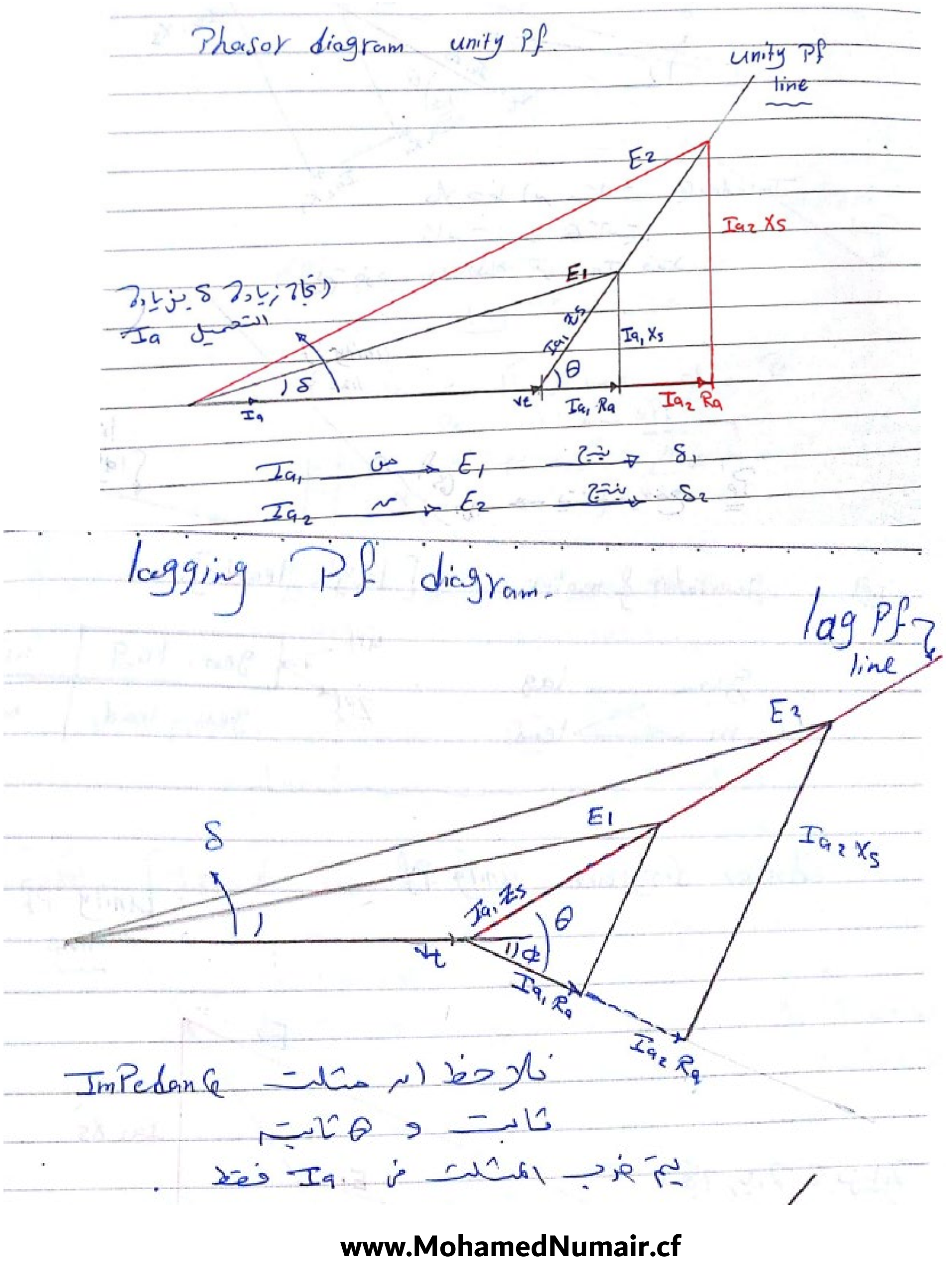
$$P_e = 3\, V_t I_A \cos\phi$$
$$= 3\frac{V_t}{Z_s}\, I_a\, Z_s \cos\phi$$

Machine Zs and Vt are constants so

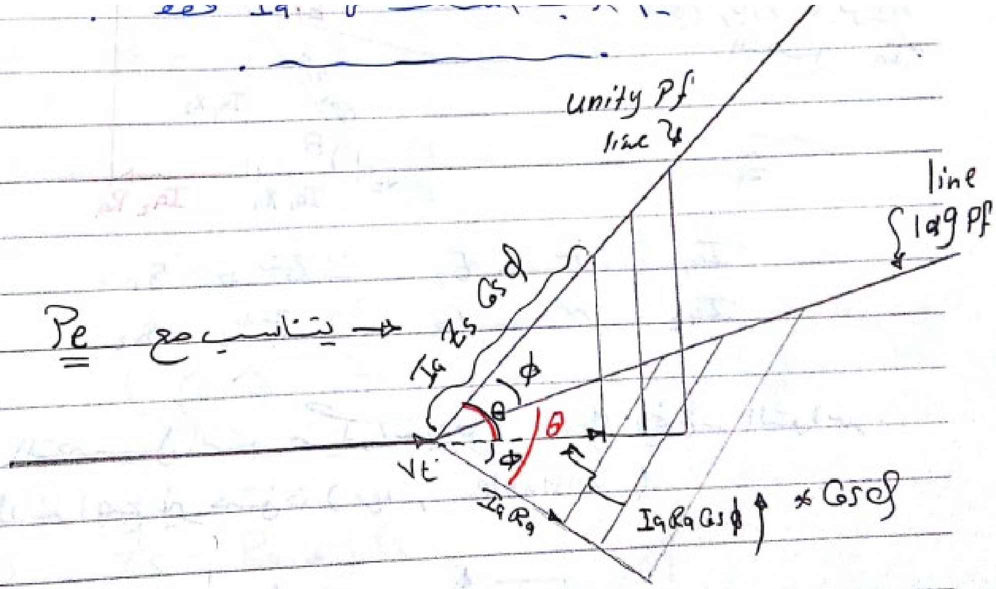
$$P_e \propto I_a Z_s \cos\phi$$

To draw it let's study the machine's phasor diagram at

Unity – Lag – Zero Lag



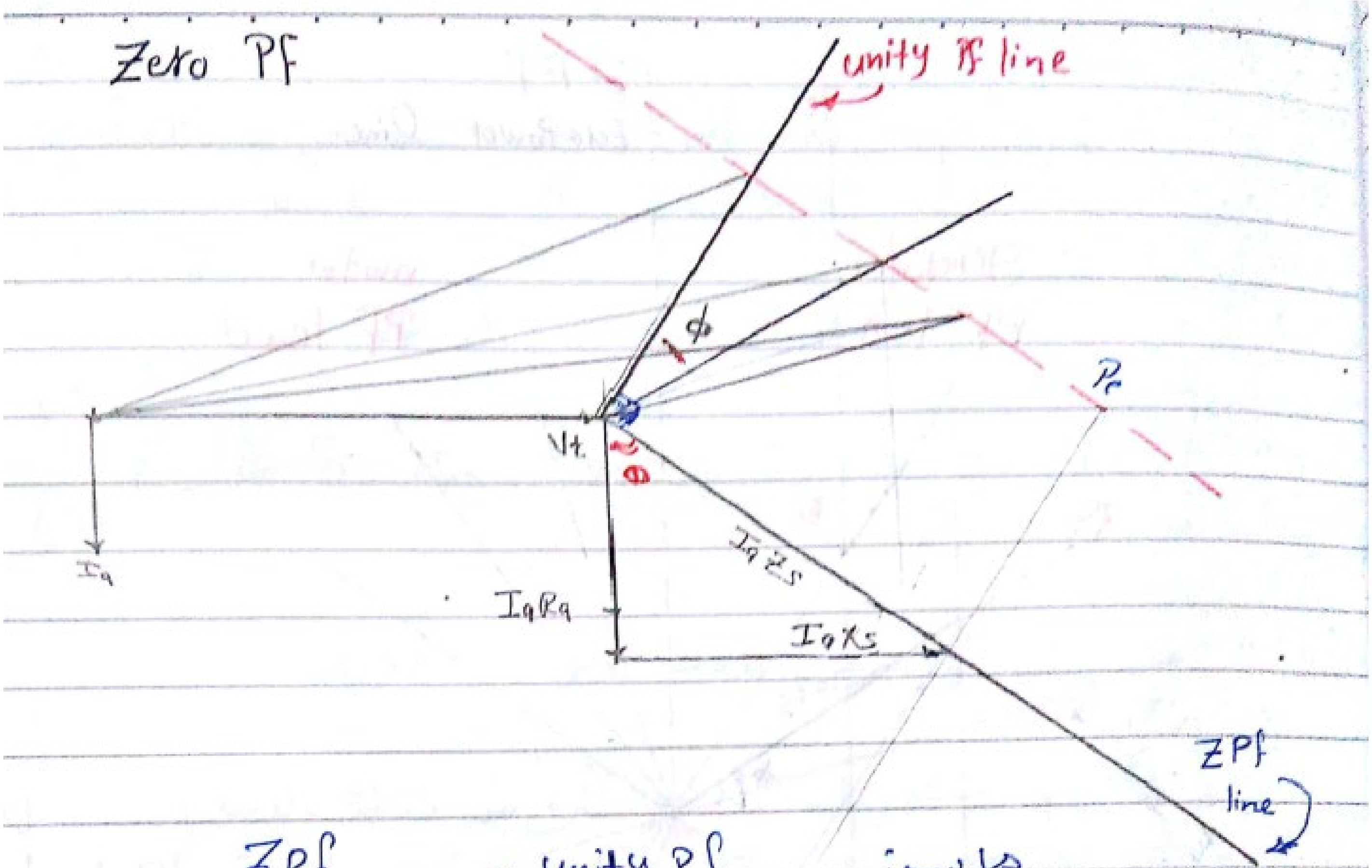
Pe يتناسب مع →



كلما زاد $I_a \cos\phi \, Z_s$ تزيد P_e

اسقاط $I_a Z_s$ على خط unity Pf يعطي تناسب

مع القدرة المسحوبة Synch



ما بين unity Pf و ZPf

منطقة lag Pf

Pe له limit من أكتر من pf وذلك بداية

من UPf ← اقصى Pe

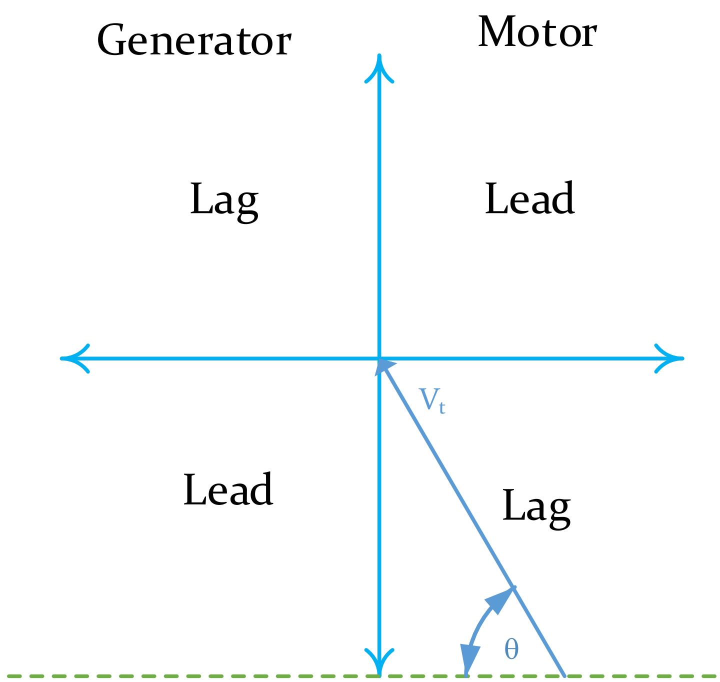
ثم يقل الى ان يكون بصفر عند ZPf

$Pe = 0 \leftarrow \phi = 90$

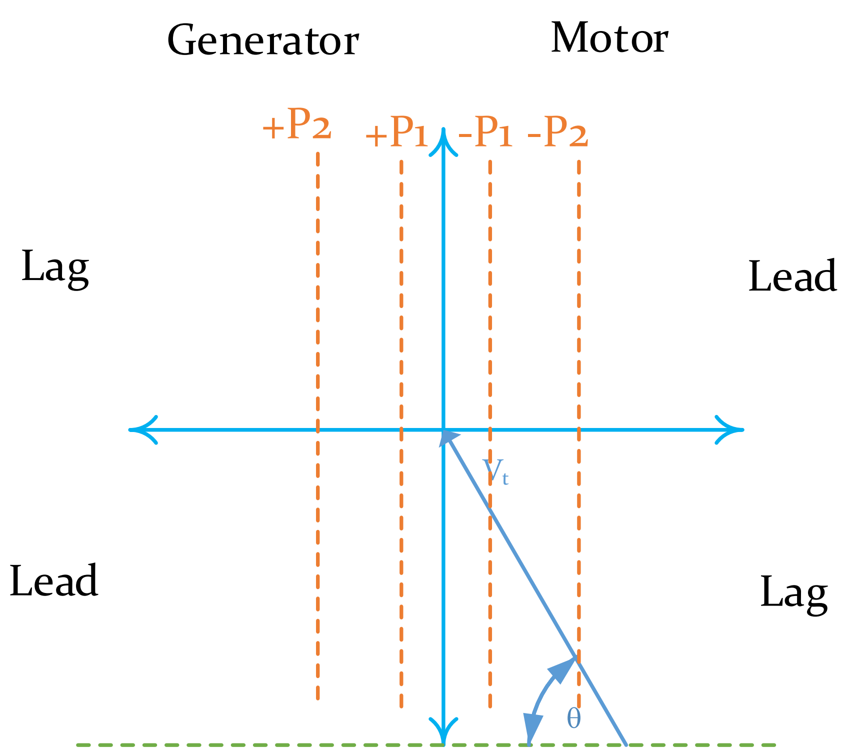
We note as ϕ increase PF worsens until $\phi = 90° \; at \; ZPF$

So to represent different cases of machine operation (M, G) and (Lead , Lag)

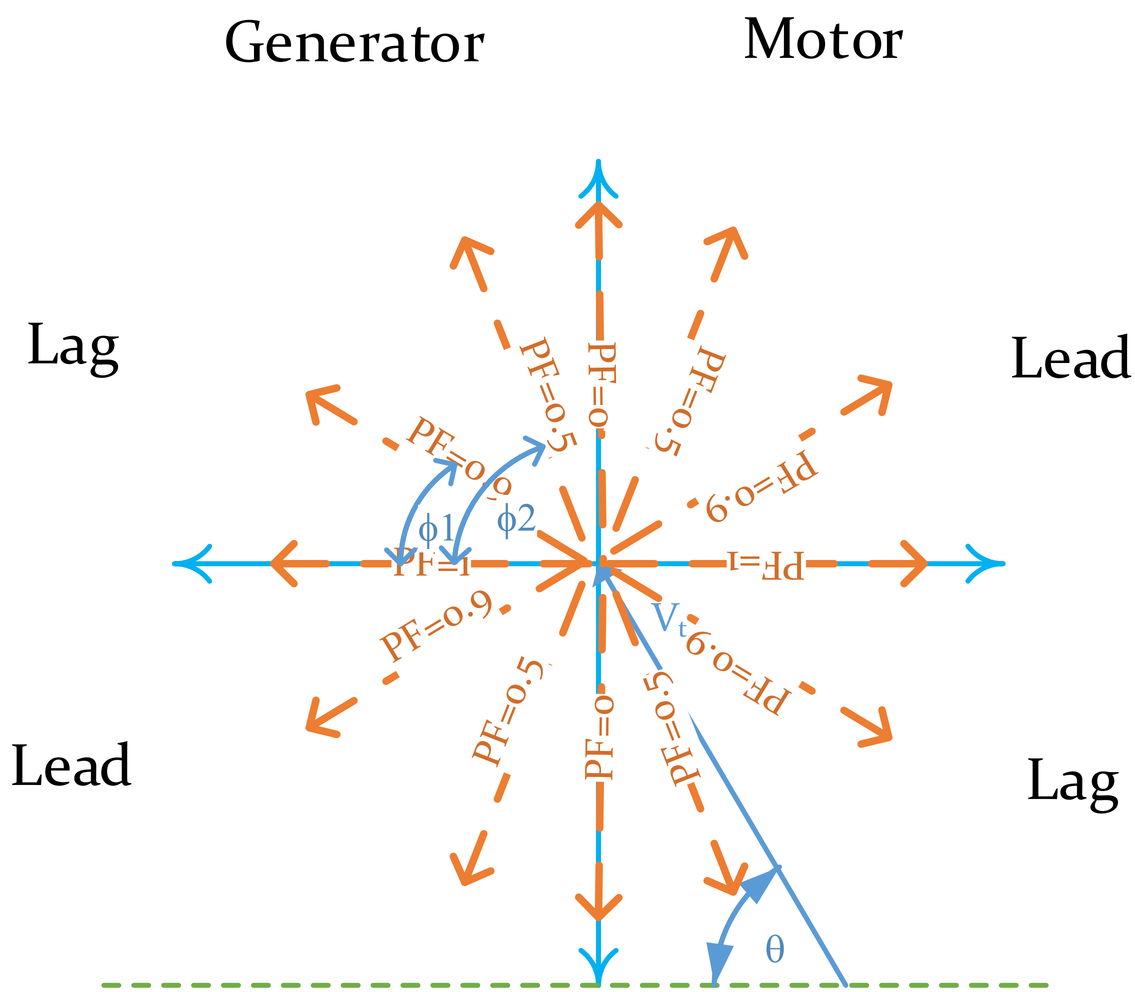
We can conclude the Electrical Load Diagram



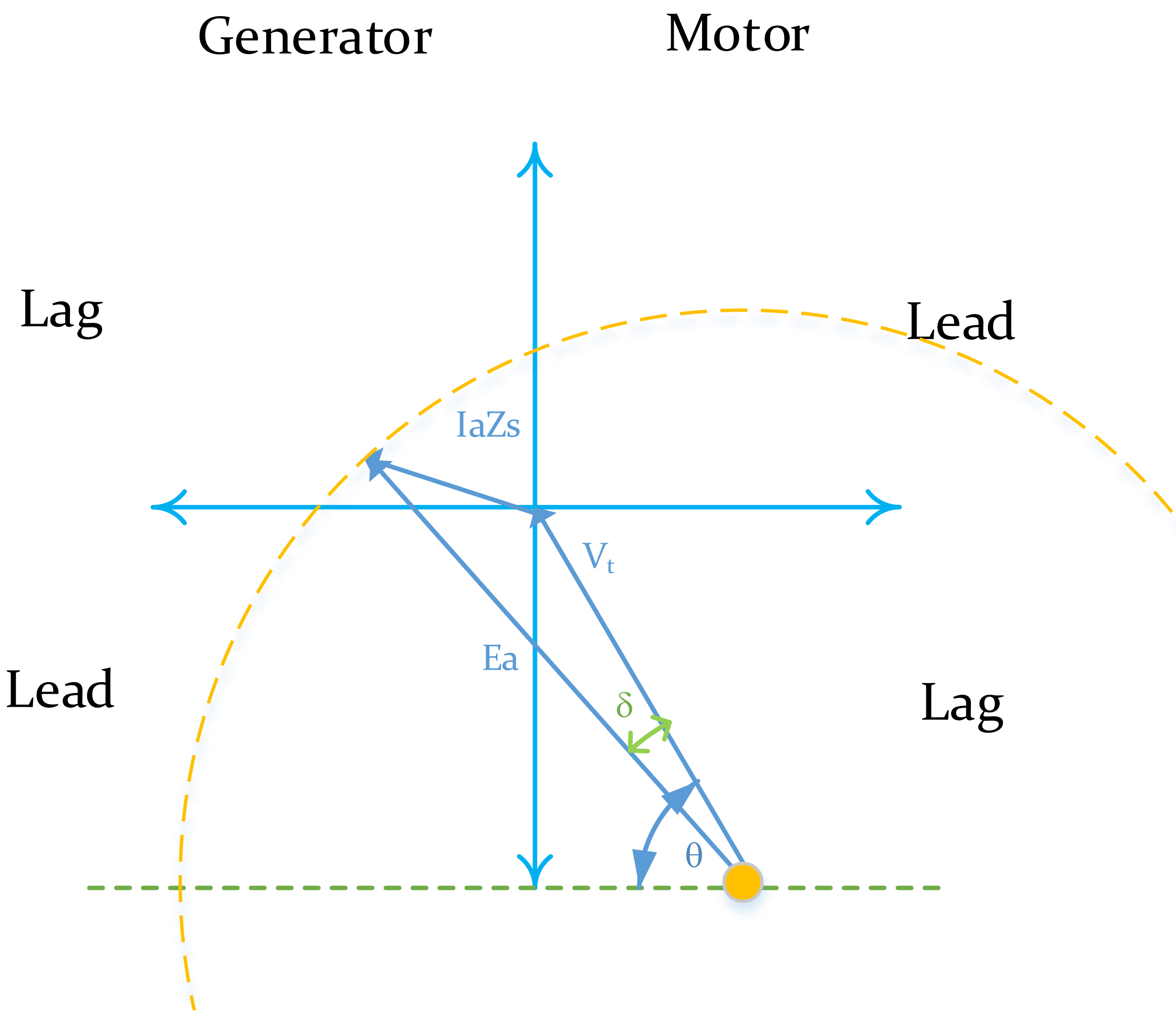
4.1 Locus for constant Power



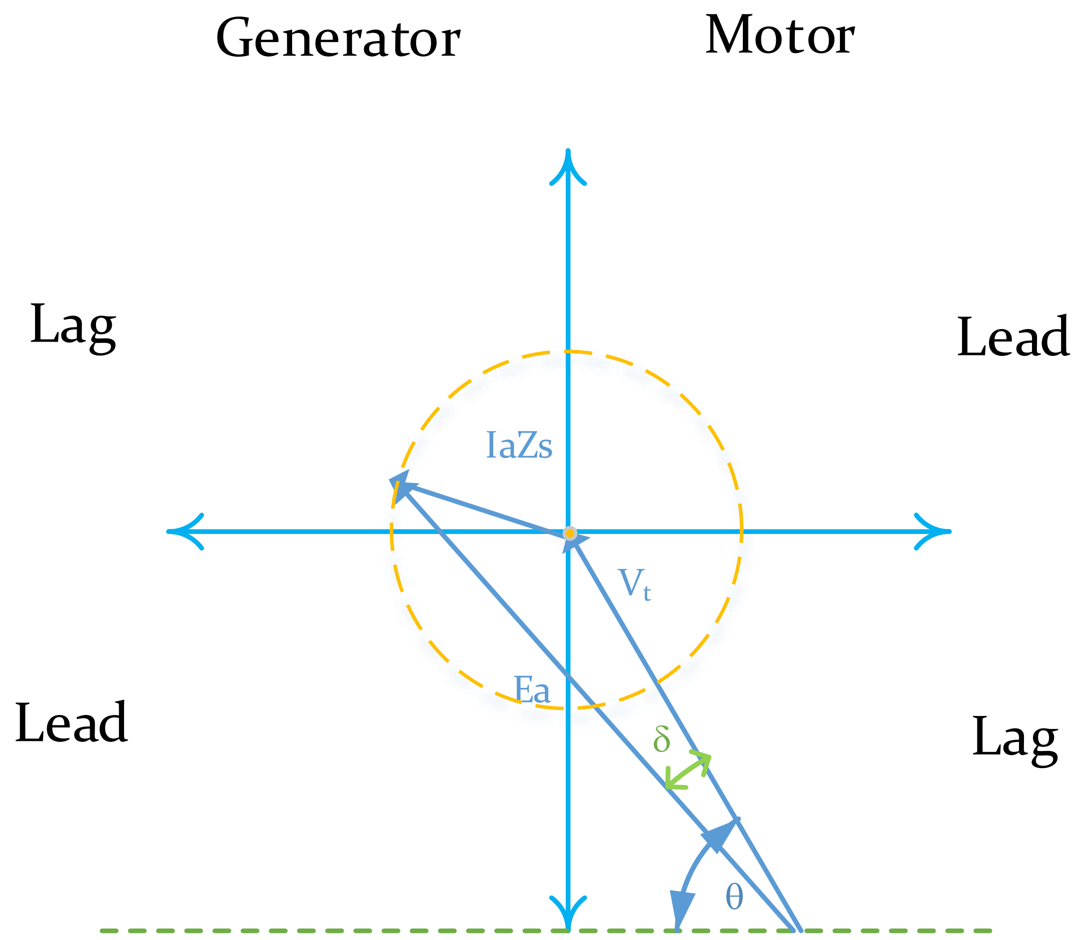
4.2 Locus for constant PF ($PF = \cos\phi \rightarrow const\ \phi$)



4.3 Locus for const Excitation E



4.4 Locus for constant load current Ia



4.5 Power Angle changes too

Power angle can be positive (G) or negative (M)

And it's value determines machine's stability and indication of Power and Torque output

<u>NOTE</u> The above Examples are made for generating mode for motoring the I_aZ_a will be in the other direction

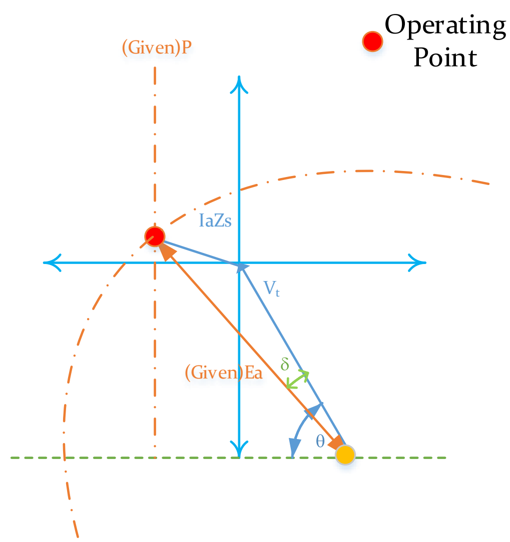
4.6 Electrical Load Diagram Problem

1- From Problem get $V_\phi = \frac{V_t}{\sqrt{3}}$
2- Get the angle $\theta = \tan^{-1}\left(\frac{X_s}{R}\right)$
3- Assume a scale m_v
4- Deduce power scale $m_p = \frac{3V_\phi}{Z_S} m_v$
5- Get the inputs and draw them to get operating point

Inputs are (Power (M , G) and PF (Lag , Lead) and E and δ and I_a

For 3 inputs we can get the rest

4.6.1 Given P and E



Easy then

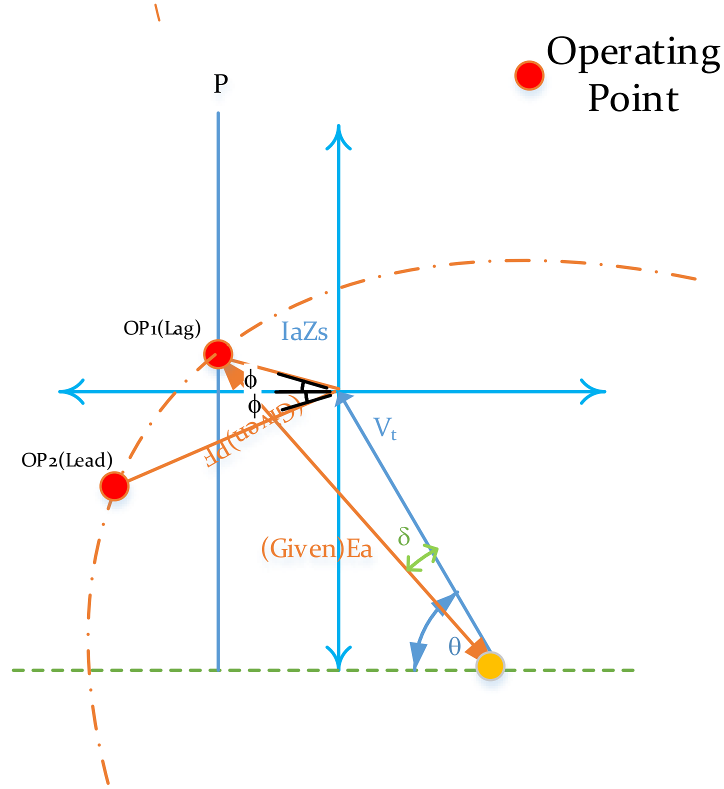
$$measure\ \delta$$

$$Get\ \phi \rightarrow PF = cos\ \phi$$

$$Get\ I_a Z_s\ then\ I_a = \frac{I_a Z_s}{Z_S}$$

4.6.2 Given PF and E

Same



4.6.3 Given P and Ia

Problem 1 : They may not intersect (Then machine can't deliver this power at this current !)

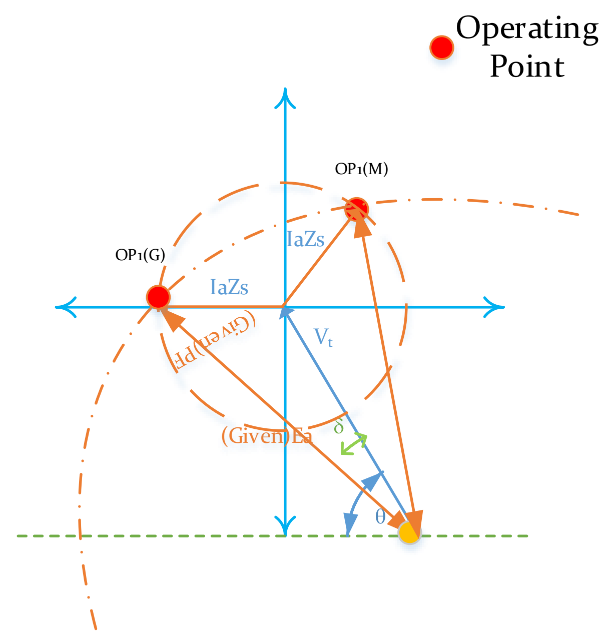
Problem 2 : 2 Value for E (High Excitation and Low Excitation) (Lead , Lag) both satisfy

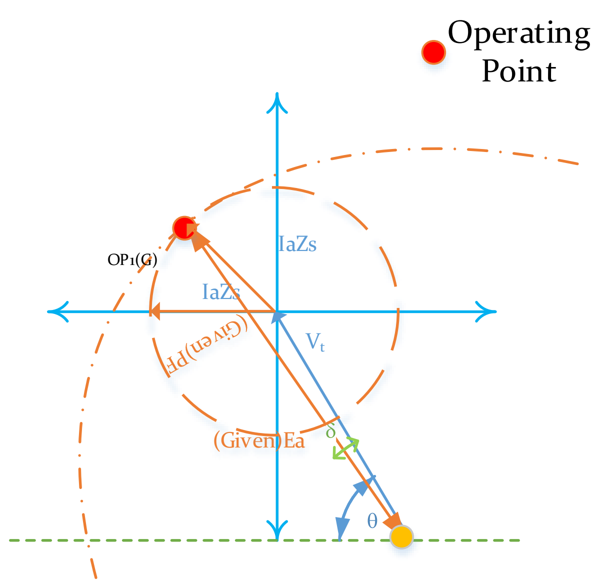
Then we study if the high is above rated value or needed specific PF

4.6.4 Given E and Ia

They are 2 circles so

Problem 1 : They may intersect at 2 points (M and Generator) (Lag, Lead) so we must determine at which case we want to operate





Problem 2 : They May just Touch at one point

This is THE MINIMUM (CRITICAL) CURRENT that must be in the load that we can't go less than

4.7 Neglecting Ra

If we neglect the effect of resistance Ra, then the Vt will be Vertical

If $\delta > 90$ then the operation point is **unstable**

NOTE if we consider Ra op point may not be stable for $\delta < 90$ **exactly at $\delta = \theta$**

As poles won't be moving together instead they will lap each other ad voltage will be oscillating increasing and decreasing

4.8 Relation between If or E (Excitation) and Ia (Armature Current)
AKA. V CURVE

Assuming Ra neglected

$$P_e = P_g = \frac{3V_tE}{X_s}\sin\delta$$

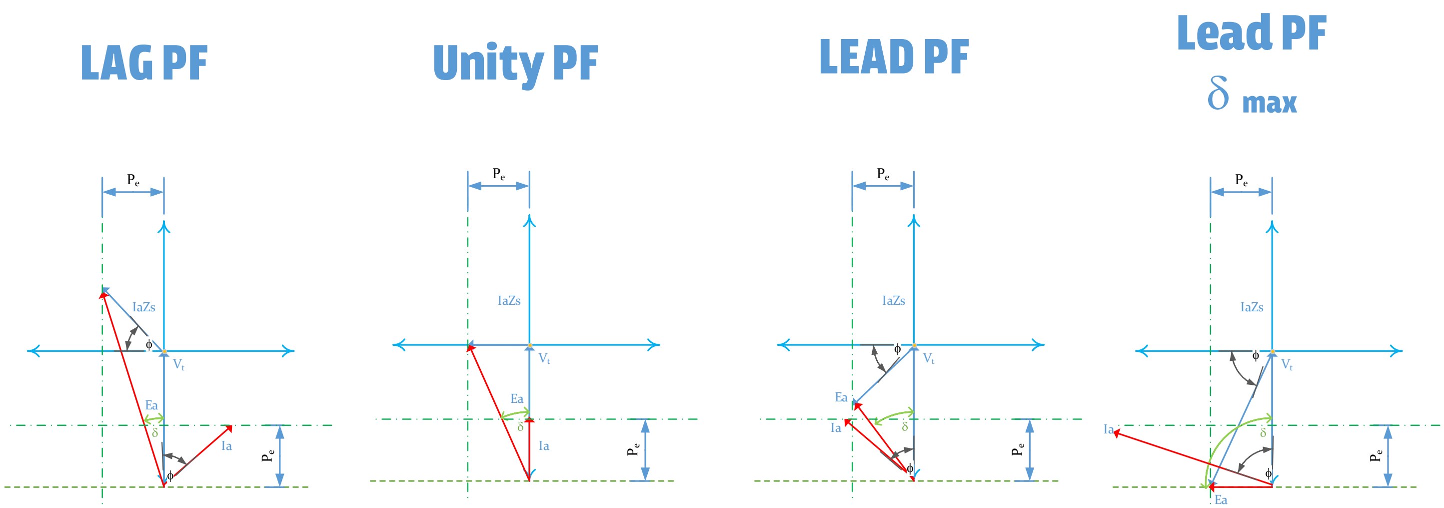
$$\therefore P_e \propto E\sin\delta$$

$$P_e = 3\,V_tI_a\cos\phi$$

$$\therefore P_e \propto I_a\cos\phi$$

To study the relation from <u>Electrical Loading Diagram</u>

We will draw different E to give different Ia at (lead , unity , lag and ZPF) (P const)



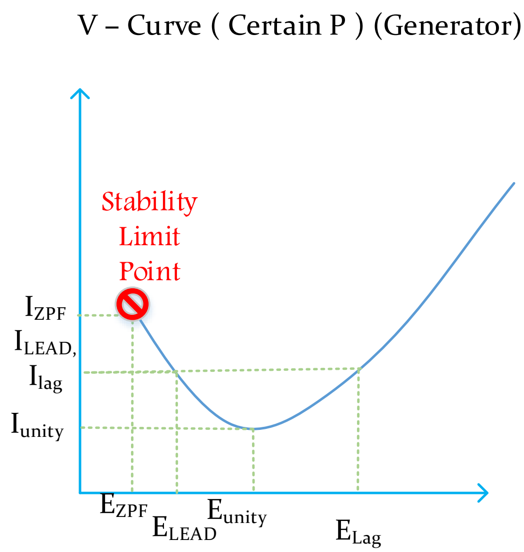
We notice as we decrease excitation ($I_f \downarrow$)

1- $I_a \downarrow$ decrease at <u>lag PF</u>
2- I_a is minimum at <u>unity PF</u>
3- $I_a \uparrow$ increases again at <u>Load PF</u>

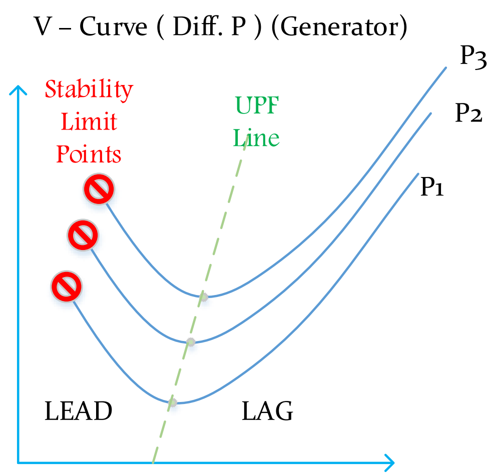
And

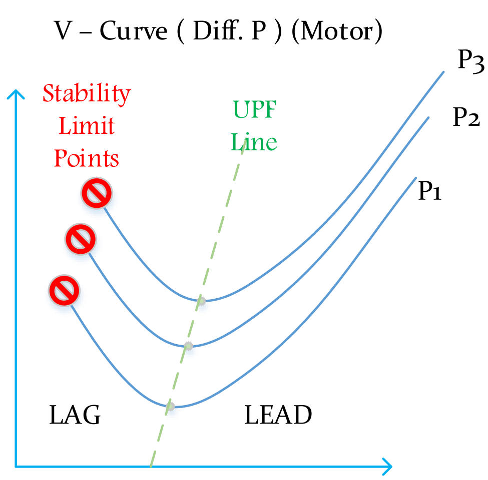
$$\delta \uparrow \textit{always at different PFs}$$

4.8.1 V curve for certain P



4.8.2 V curve for different Ps

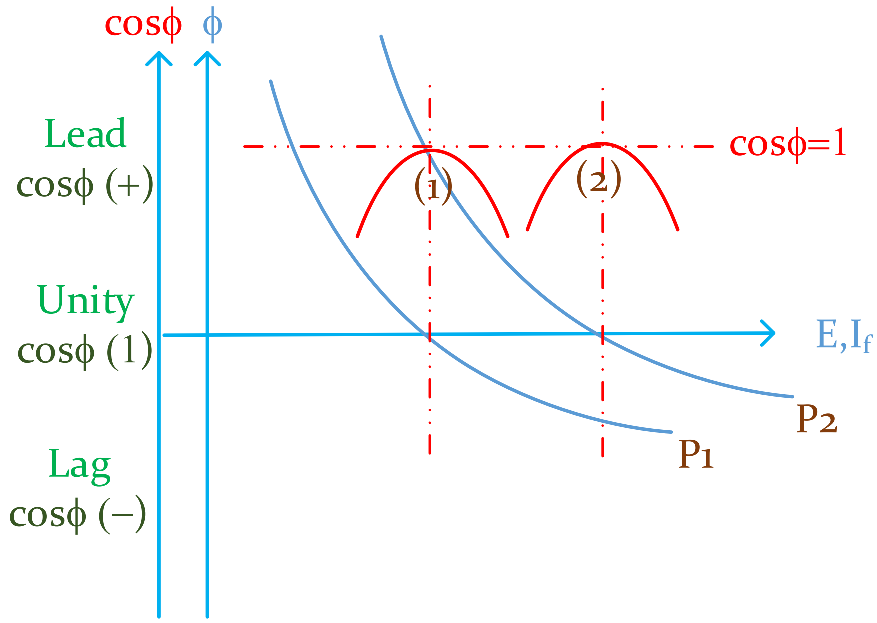


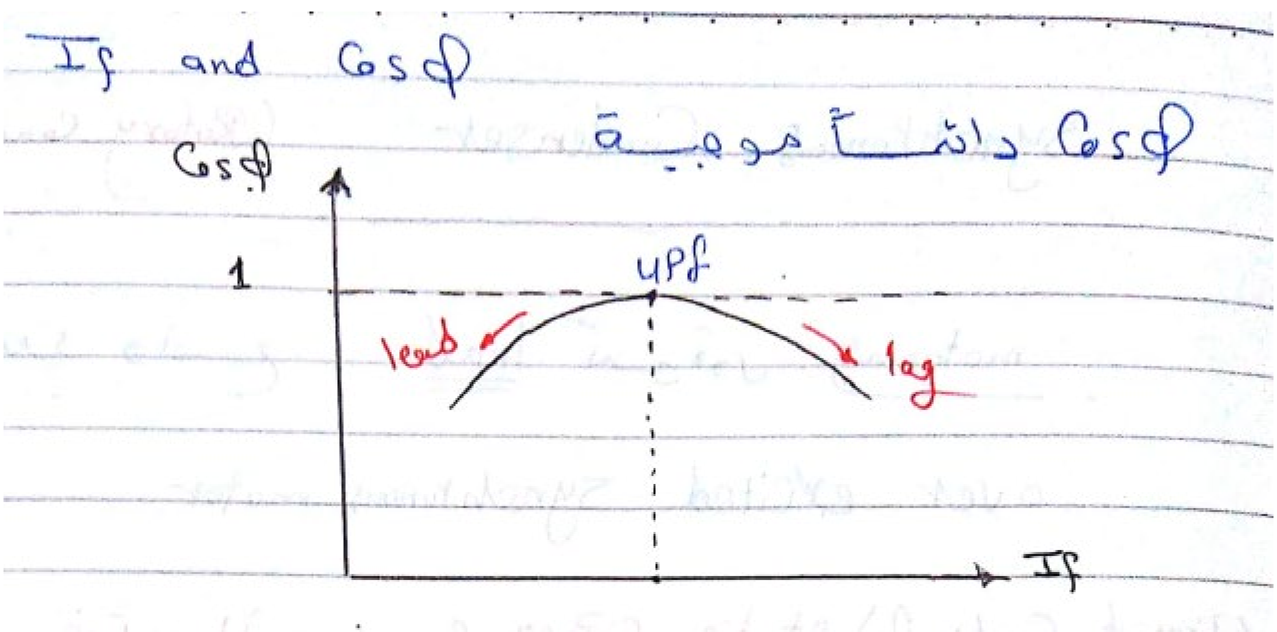


<u>NOTE</u> V curve is the Same for Motor but swap lag and lead areas

<u>NOTE</u> Synchronous Motor is mostly used at high excitation as (LEAD PF) source (Condenser) used as a compesnator

4.9 Excitation Effect on PF

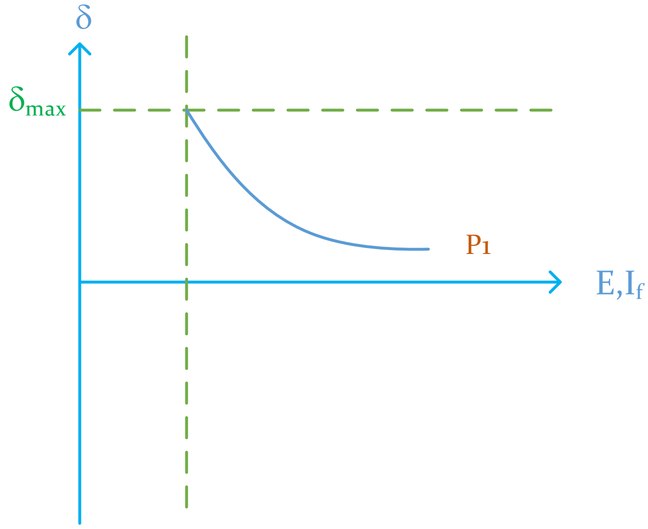




When P increases We need More Excitation $P\uparrow \rightarrow E\uparrow$ at UPF

In V curve we would find that P2 over P1

4.10 Excitation Effect on δ



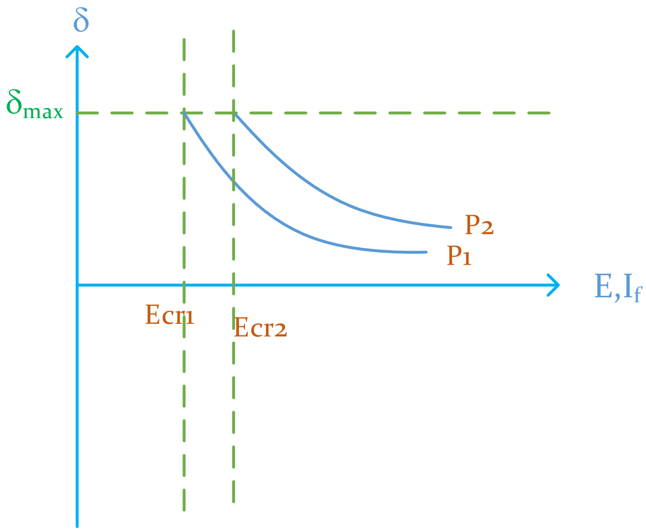
δ **Doesn't have critical point** نقطه انقلاب

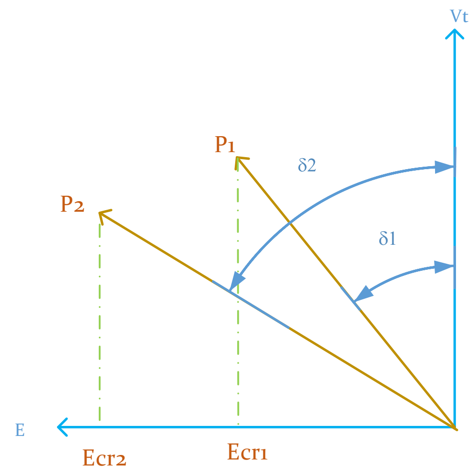
$Excitation \downarrow \rightarrow \delta \uparrow$ or $I_f \uparrow \quad then\ \delta \downarrow$

Till $\delta = \delta_m = 90(R_a = 0)$ **then it's unstable afterwards**

Now if Power increases at same excitation we can get higher δ

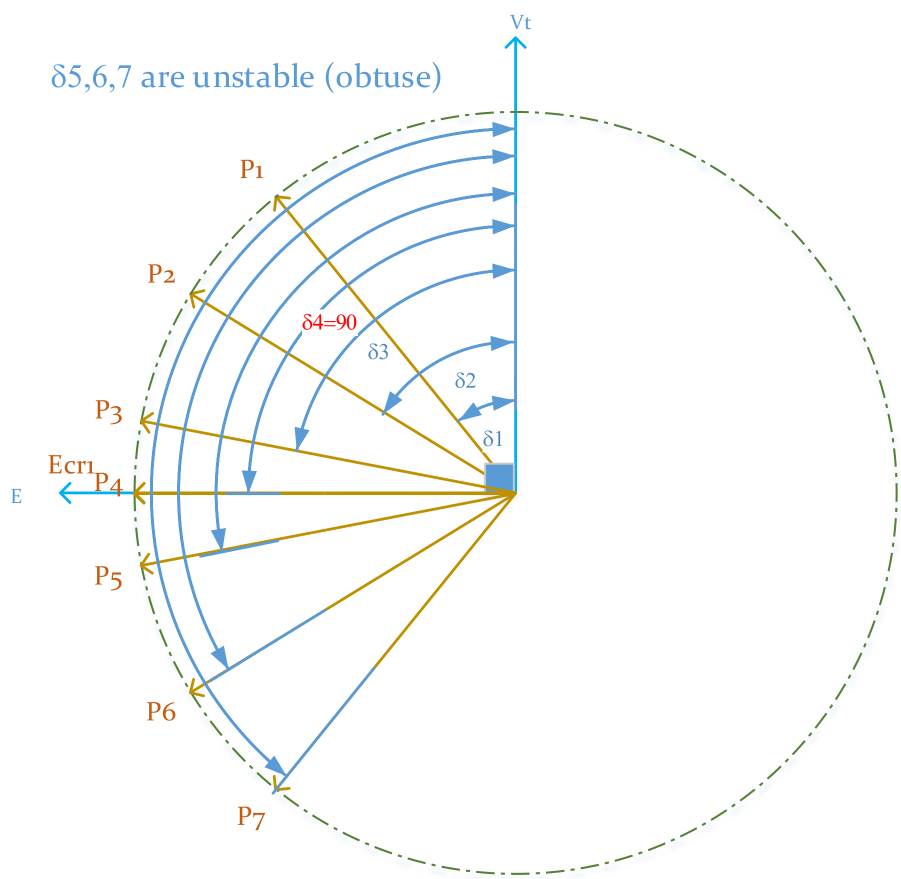
When we increase Power the Critical Excitation Allowed increases



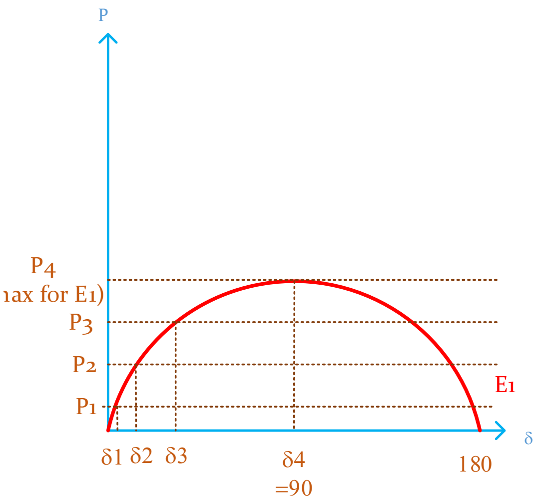


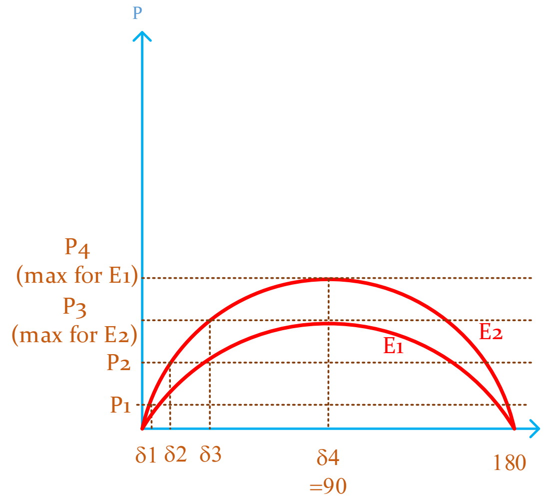
4.11 Power and δ Characteristics

AT CONSTANT EXCITATION



P4 is max possible for that Excitation

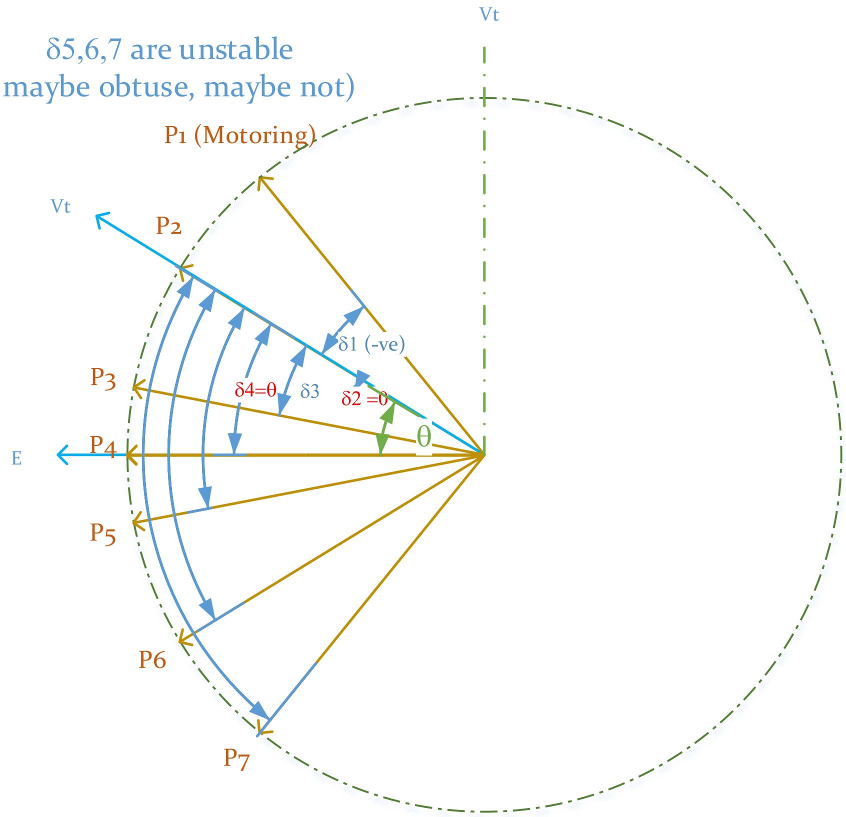


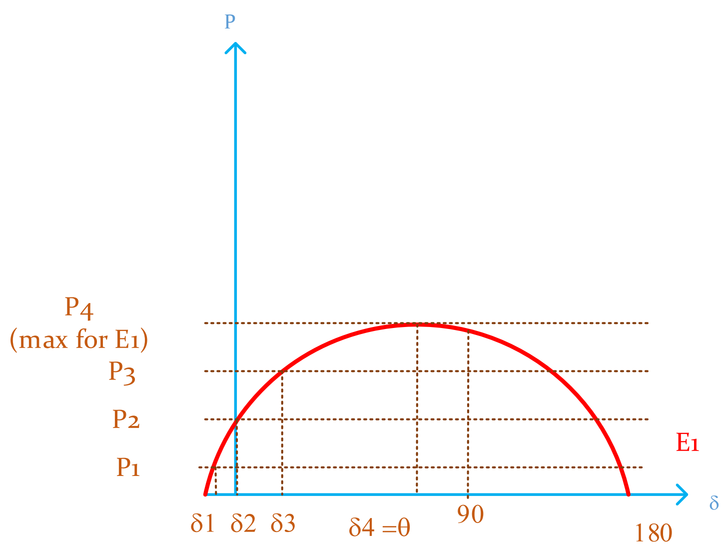


Note to keep safe from P_{max} we increase E (from E1 to E2 to operate at $\delta 3$ safely)

4.12 Power and δ Characteristics (Considering Ra)

We will note that Vt is no more Vertical, it tends by angle θ





<u>NOTE</u> Power at P2 is (Special Case) as $\delta = 0$ and E is on Vt exactly

Here max power is at $\delta_m = \theta$

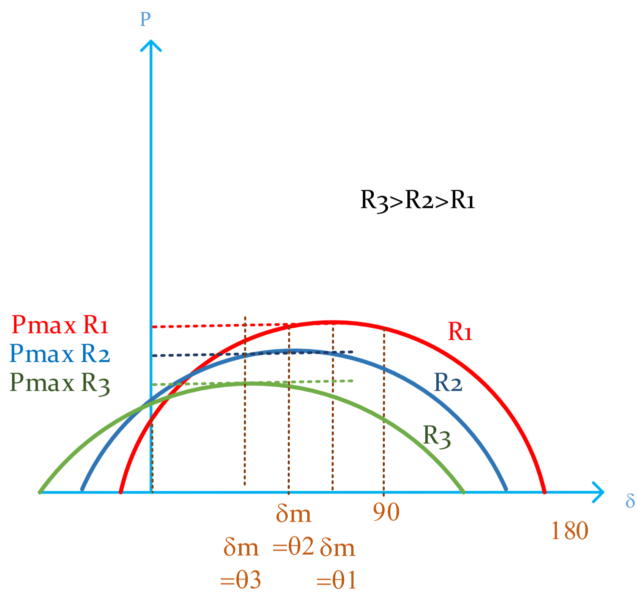
$$for\ R_a = 0\ \ , at\ P = 0\ then\ \delta = 0\ , 180$$
$$for\ R_a = value\ , at\ P = 0\ then\ \delta = \ -ve\ , < 180$$

Now here angle can be not obtuse like 80 but still unstable

4.13 Effect of Ra on P

When $R_a \uparrow$ then $P_{Max} \downarrow$

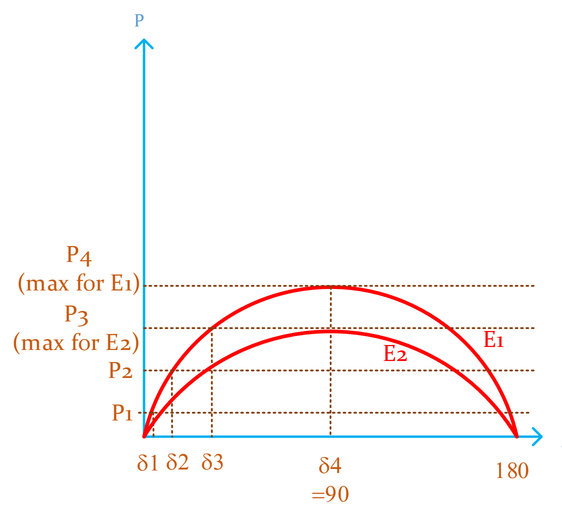
When $R_a \uparrow$ then Curve goes to the left of vertical line



At certain E when $P \uparrow$

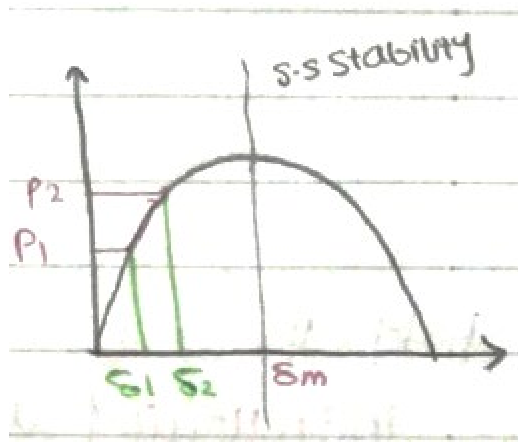
1- More near to unstability
2- More near to Lead PF

So, If we need high power without entering instability region we **<u>increase Excitation</u>**



4.14 Stability of synchronous generators

If P increases from P_1 to P_2 Suddenly then angle δ increases from δ_1 *to* δ_2



4.14.1 Steady-State Stability

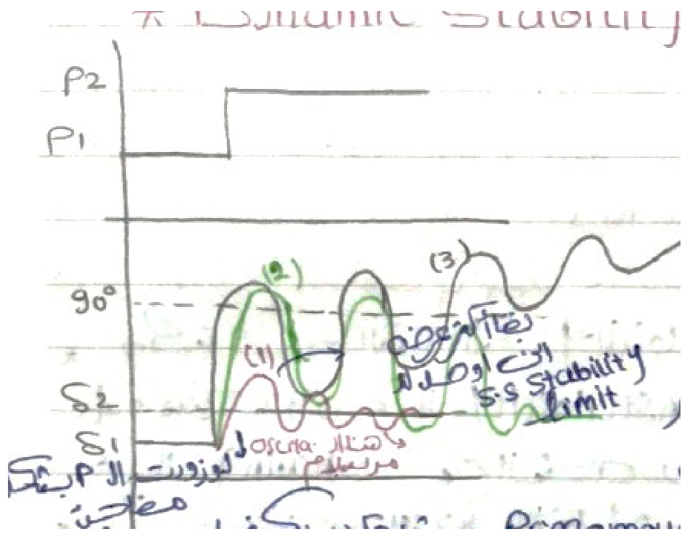
$$\delta : angle\ between\ rotor\ and\ stator\ poles$$

If it increases gradually under 90° then the machines maintains it's stability

4.14.2 Dynamic Stability

If P increases from P_1 to P_2 **Suddenly**

Then we have 3 Possibilities



(1) It increase with **a small oscillation** and didn't exceed the 90 limit then it's
Stable

(2) It increase with **a large oscillation** and exceeded the 90 limit but it was *damped by (strong inertia of Prime Mover (W_{stored})*
Stable

(3) It increase with **a large oscillation** and exceeded the 90 limit and wasn't damped (no enough inertia or W_{stored})
UNSTABLE

NOTES

- maybe increasing the same amount (10%) from 20% to 30% be stable and from 40% to 50% not stable although they still under P_{max} but Dynamic Response of the machine takes it out of stability.

-A Method to study dynamic stability is the Equal Area Criteria

- To sustain stability, we either
1- increase Excitation for short time of load increase

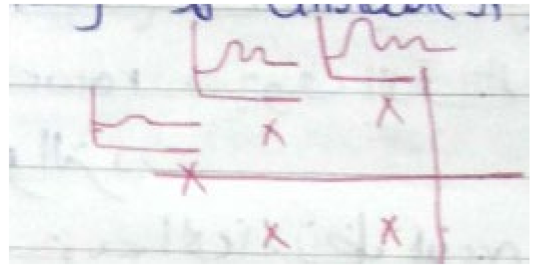
2- drop some of the loads

- if the Prime mover is weak and has a sudden change in P then it's speed will have oscillations and as well the V and f will oscillate

- If the Prime mover has a high capability then if it has a sudden change in P the V and f won't be affected

- in motors sudden load increase is rare as mechanical sys is much slower than electrical one

4.14.3 How to stabilize S.G.

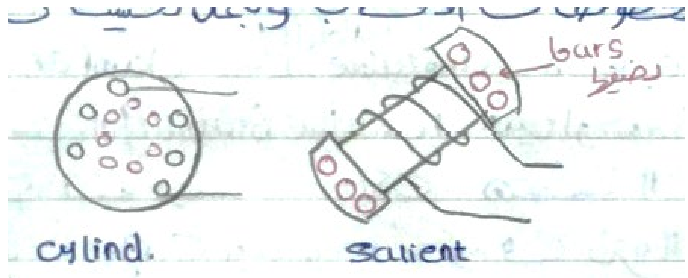


1- Through Control System
   Making the system poles more to the left and more on the line

2- Through Design (Damper Winding)

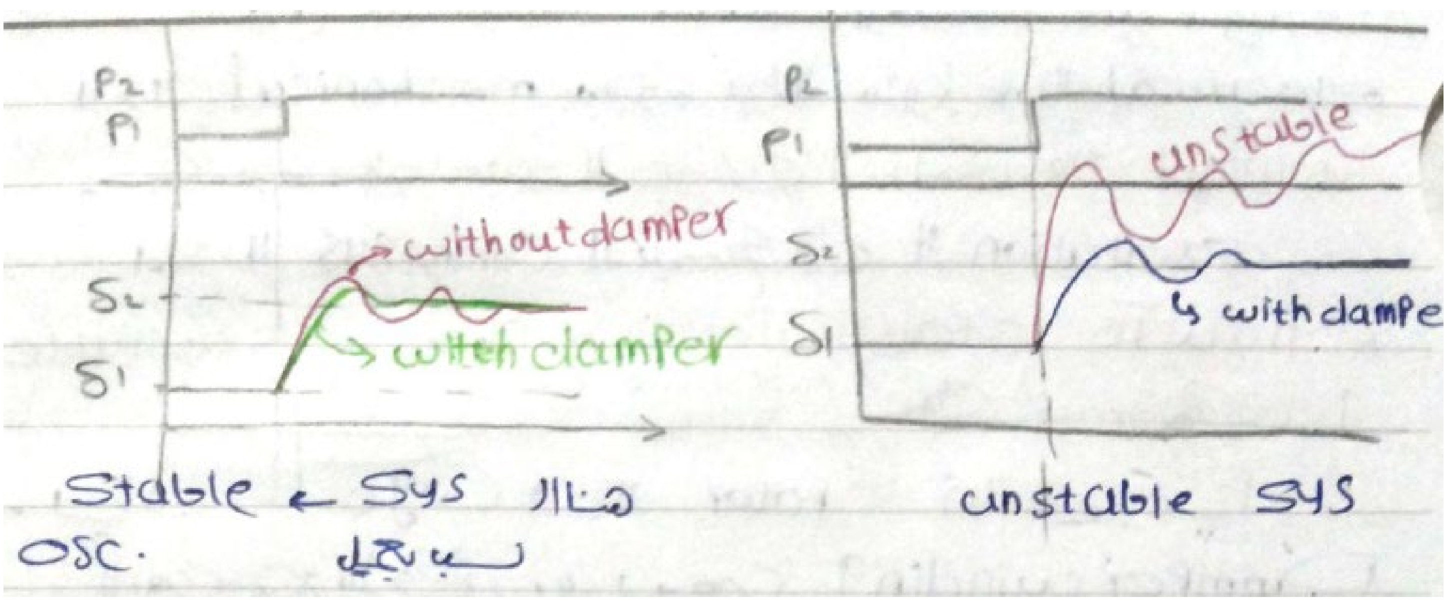
4.14.4 Damper Winding

we add a cage in the rotor (it acts as an IM inside the SM)



it improves stability as follows

during disturbance it induces and emf that creates a torque that acts against the disturbance



It improves

Absolute Stability	If it was unstable It will make it stable
Relative Stability	If it was stable with Osc It will damp Osc. (improve stability)

During Transient (Dynamic)

The cage creates emf and Torque (against disturbance)

During Normal Operation

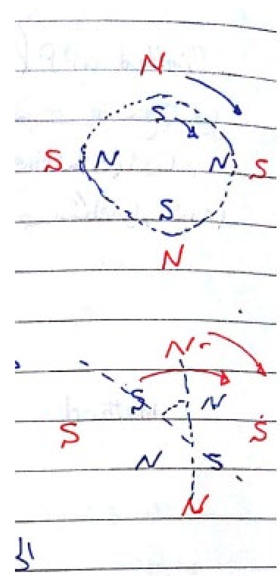
It will see stationary poles so emf =0 (cage has no effect)

5 SYNCHRONOUS MOTOR (CYLINDRICAL ROTOR)

<u>We will discuss</u>

- Theory of operation
- Equivalent CT (Done Before)
- Phasor Diagram (Done Before)
- T-δ (equiv. P-δ)
- Power flow (Done Before)

5.1 Theory of Operation



Motor consists of stator's 3ϕ windings (Y,Δ) supplied from a 3ϕ balanced supply

Thus, it creates a group of Poles (N,S)s
these poles are rotating

While, The Rotor has a (N,S) stationary

So Stator Poles (N,S) line up with rotor Poles (S,N)

And the group move at synchronous speed N_s

They are attached together with angle $\delta < 90$

If $\delta > 90$ Poles won't be attached anymore it will get out of synchronism

5.1.1 Problem : of No starting Torque

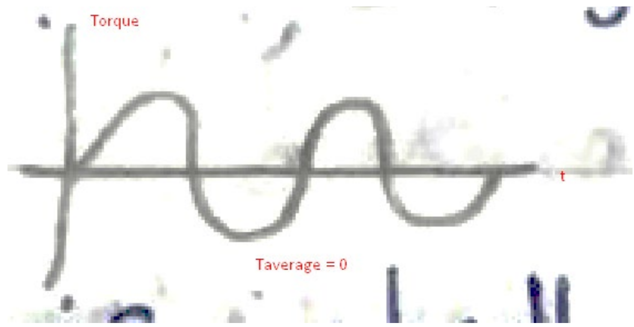
Rotor stationary , Stator's MMF rotating by Ns – and due to inertia of rotor it won't be able to catch up with stator's MMF

So no Energy conversion will happen till Nrotor=Ns

For Synchronous Motor

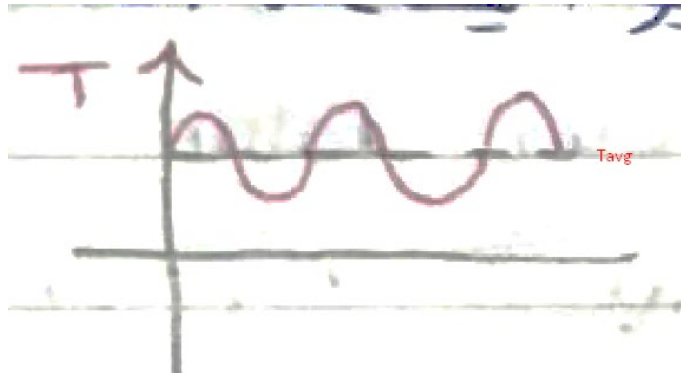
At Starting :

Torque is Osc. And $T_{av} = 0$ so there is no starting torque produced



At Operation (Rotating Machine)

Torque Osc but $T_{av} \neq 0$



5.1.2 Disadvantages of SM

- Needs a DC Excitation for the field (Brushes , Slip rings)
- There is no Starting Torque

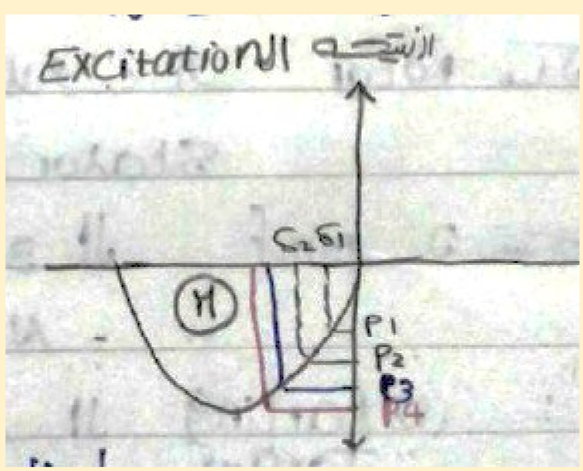
5.1.3 Advantages of SM

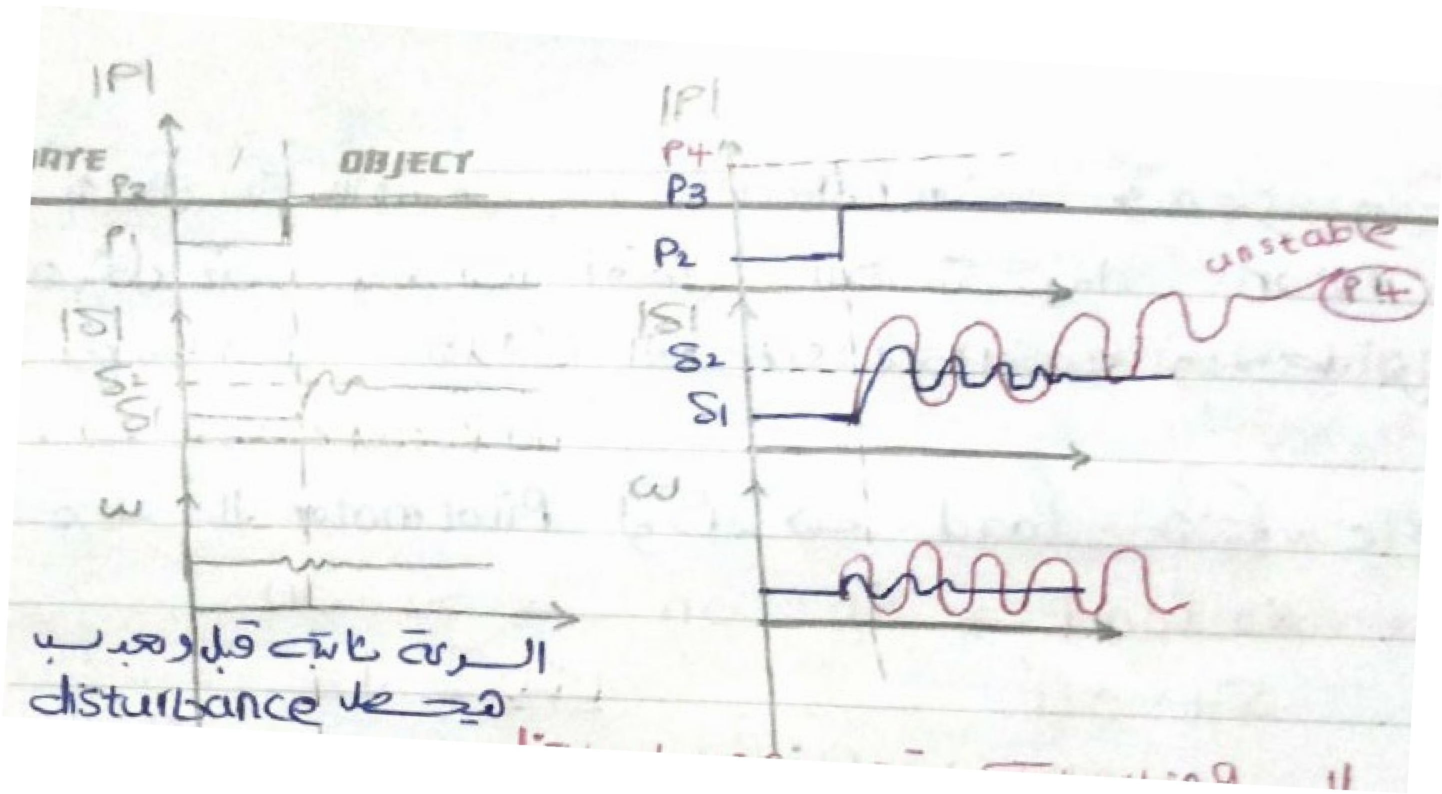
- Constant Speed N_s whatever was the load
- High Energy Convergence capability

5.2 Stability

NOTE

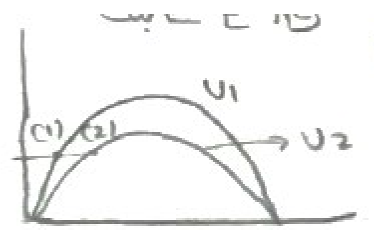
in Motor we can say that $\delta\ and\ P\ are -ve$ **compared to Generator**
but we will consider the absolute value in our discussion





- Starting is considered a strong disturbance (speed from 0 to Ns)

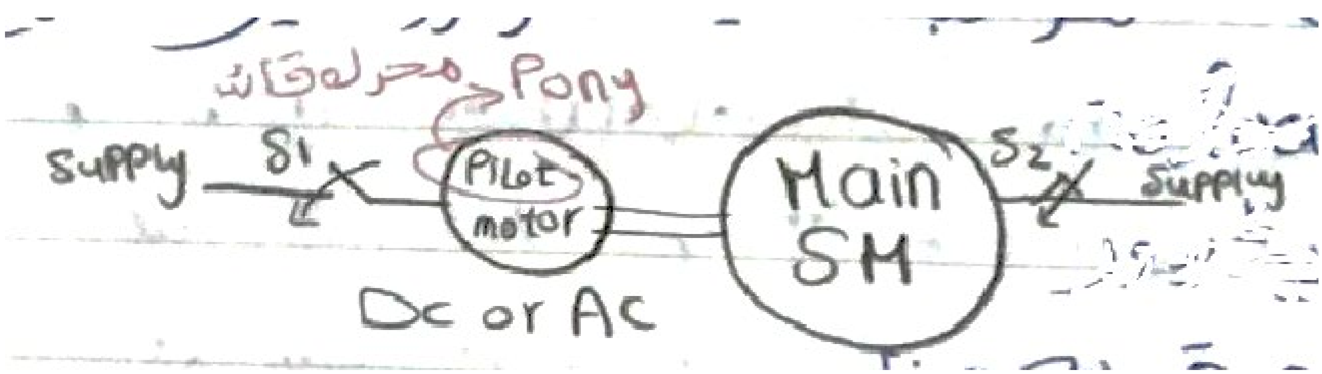
5.2.1 Instability causes



- Sudden change in the voltage $T \propto V$
- Sudden load on the machine
- Starting is strong disturbance (V=0 then V=Vr)

5.3 Starting of Synchronous Motor

5.3.1 Pilot Machine (AC (IM or SM) or DC)



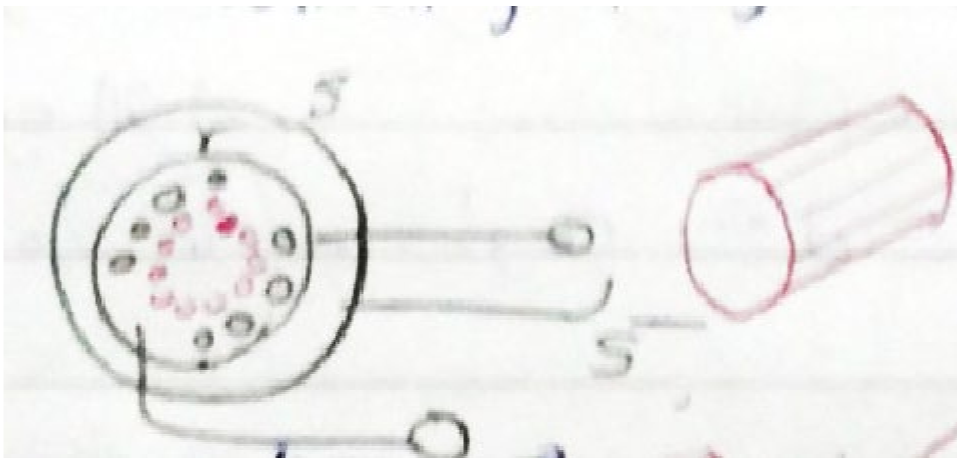
Our objective is for Rotor poles to rotate up to Ns

So we use another machine to rotate the SM shaft (with no load) to Ns or a near synchronous speed

So sequence of operation

- Close S1 till rotor rotate
- Close S2 to supply SM
- Open S1 so SM work on its own
- Add your Mechanical Load to Synchronous Motor

5.3.2 Using Cage winding (damper winding)



Note the cage bars reduce area for flux for rotor so might need to increase machine volume

As discussed now it acts as an induction machine inside the SM so now, we have 2 Torques

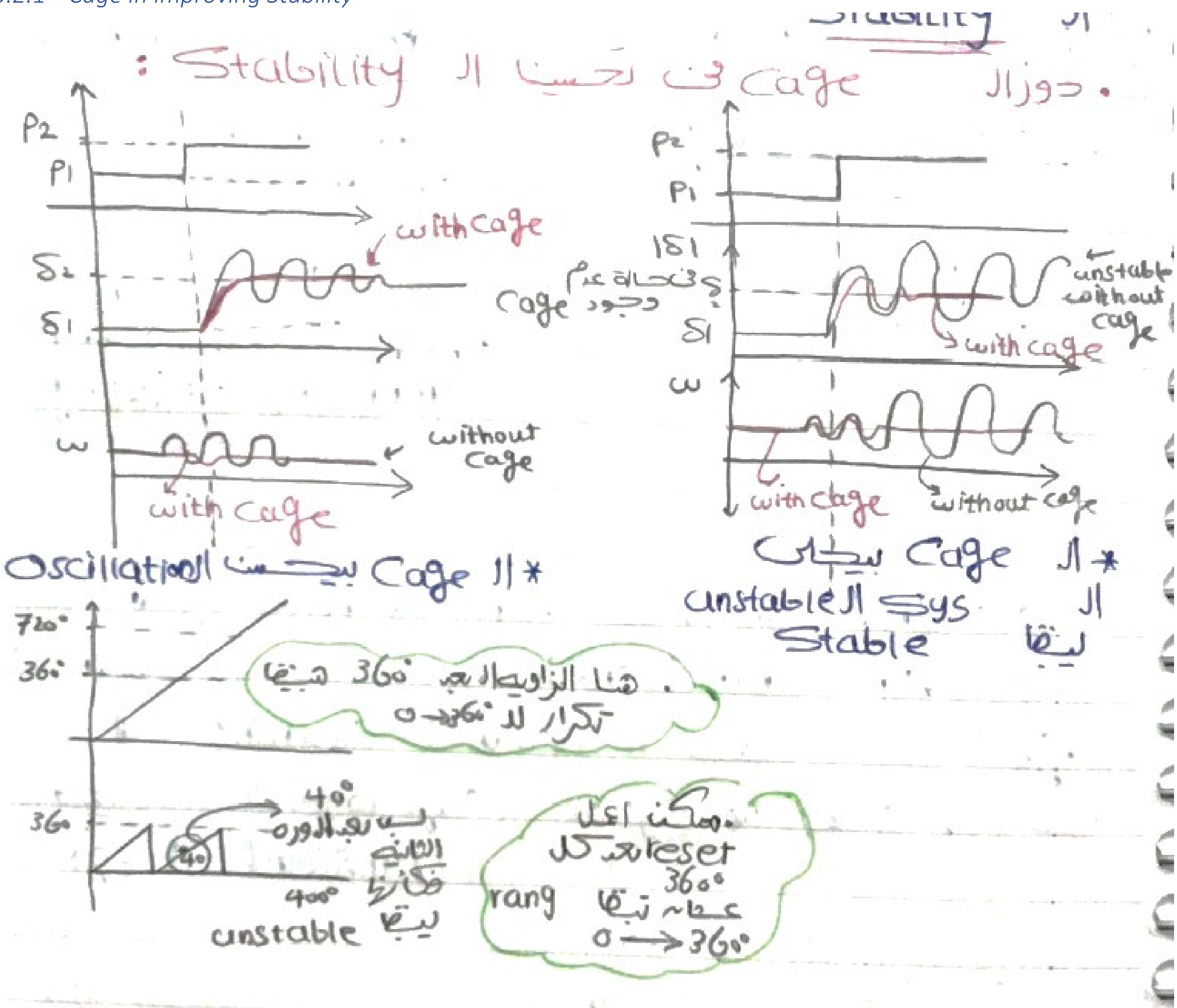
At Starting:

1- Torque is Osc. And $T_{av} = 0$ so there is no starting torque produced
2- Induction Torque$\neq 0$ so it makes rotor speed accelerate until it reaches a speed near the Ns so the poles now can get attached to each other and the group rotates at Ns

At Operation (Rotating Machine) (SS)

1- Synchronous Torque Osc. but $T_{av} \neq 0$
2- Induction Torque = 0 as there's no change between the two poles (but it works to improve stability)

5.3.2.1 Cage in improving Stability



5.3.2.2 Comparison between Synchronous Torque and Induction Torque

Synchronous Torque	Induction Torque
$T = \frac{EV}{\omega_m X} \sin\delta$ رسوماتك عارفها من فوق	الرسمه المشهورة بتاع الاندكش
Due to excitation and saliency(if exists)	Due to cage winding
$T_{avg} = 0$ *at starting* $T_{avg} \neq 0$ *at Synch Speed*	$T_{avg} \neq 0$ *at all speeds* $T_{avg} = 0$ *at Ns*
Exists only at S.S.	Appears in dynamic states
Only on normal operation	Helps in starting Improves stability

5.3.2.3 Cage disadvantages

1- Need larger rotor for SM during Design
2- Cage losses during transient periods and starting

With Cage	Without Cage
• synchronous Torque excitation T_1 • induction Torque T_2	• synch Torque only T_1
Torque T_2 (I) appears only: • at starting • at transient ie (load applied or remov)	T_1 at stady State only يعني مش هيوصل steady خالص. لانه بيبدأ من NL.
at starting $T_1 = 0$ $T_2 =$ له قيمة	at starting. $T_2 = 0$ $T_1 \leftarrow$ له قيمة

5.3.3 Using Variable Frequency drives (VFD) (frequency converters)

At starting the MMF rotates Ns and rotor speed is 0
if they are near each other the problem will be solved

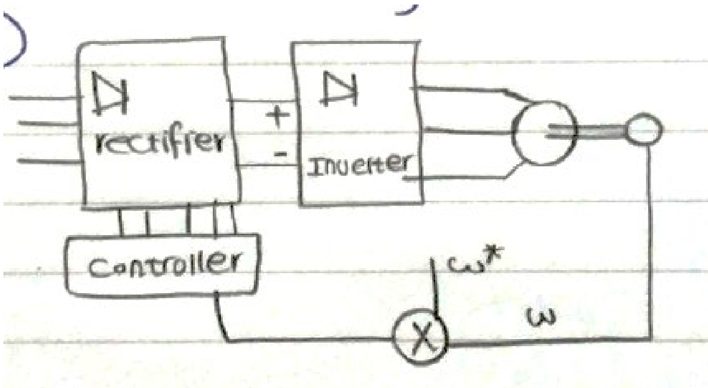
So instead of increasing rotor's speed ,, why don't we decrease stator's MMF speed ?!

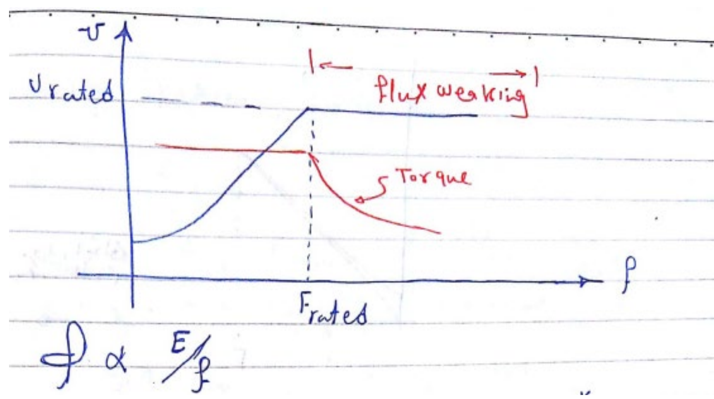
Then after they attach to each other we will start increasing f gradually till we reach Ns

We measure speed using <u>speed sensor </u> and comparing it to a ref.

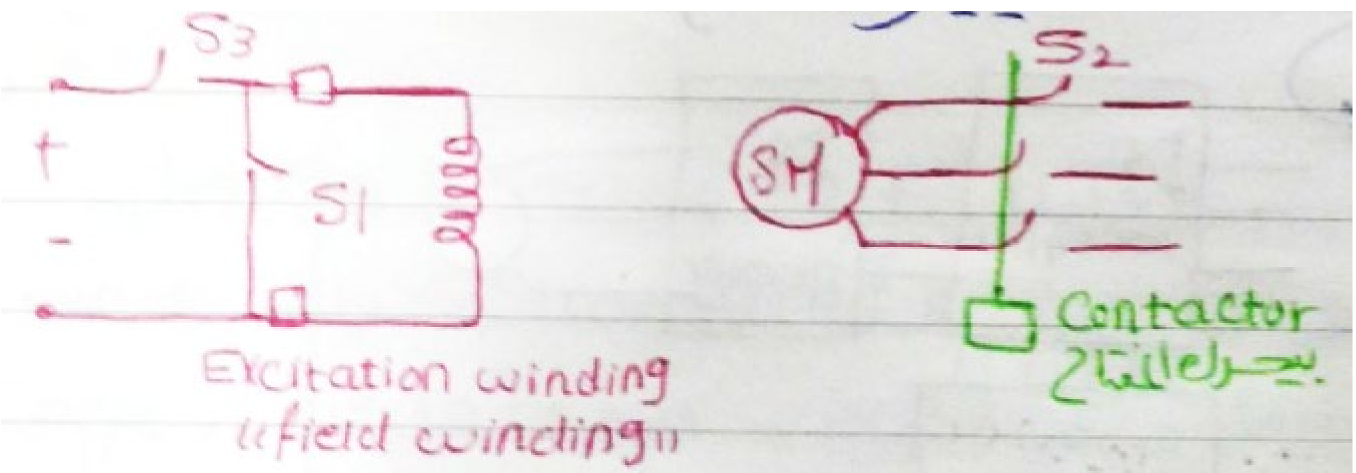
5.3.3.1 So this method advantages

1- Helps in Starting
2- Provides Speed control
3- Improves stability





5.3.4 Using Field winding as cage

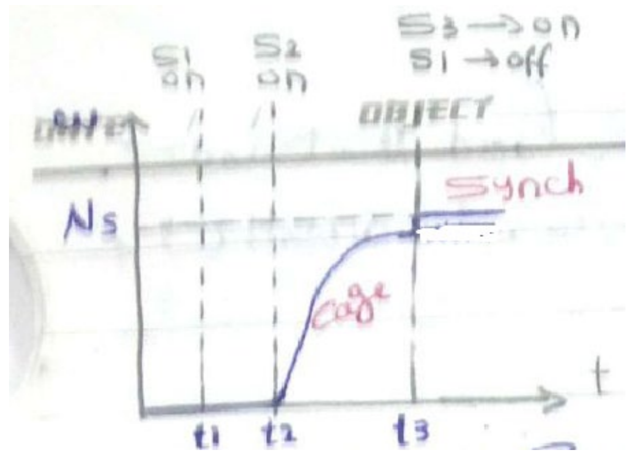


Operation Sequence

1- We close S1 to start the machine so the field winding acts as a cage (SC)
2- close S2 to feed the machine to start to rotate
3- when it reaches speed near Ns
4- open S1 then close S3

Notes

- We may add resistance | **<u>(leading resistance)</u>** with S1 to limit SC current and so if (S1 and S3) close won't SC the supply too.
- This method helps only in starting and doesn't affect stability
- If S1 and S2 close simultaneously then t1=t2
- Field winding has large number of turns and high inductance which makes
    - Induction Torque small
    - Large time constant and slow response at starting

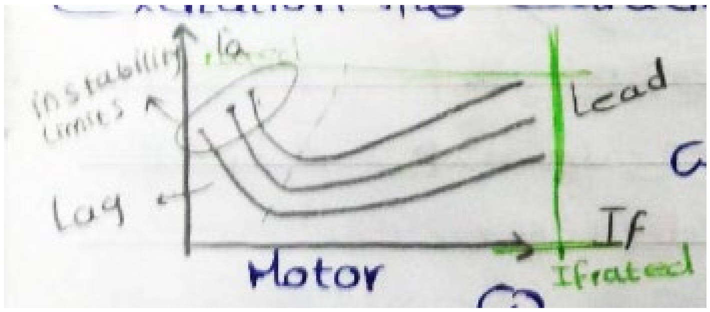


5.4 SM in power factor correction (Synchronous Condenser)

Synchronous condenser is an <u>**over-excited**</u> synchronous motor operating at no load or light load

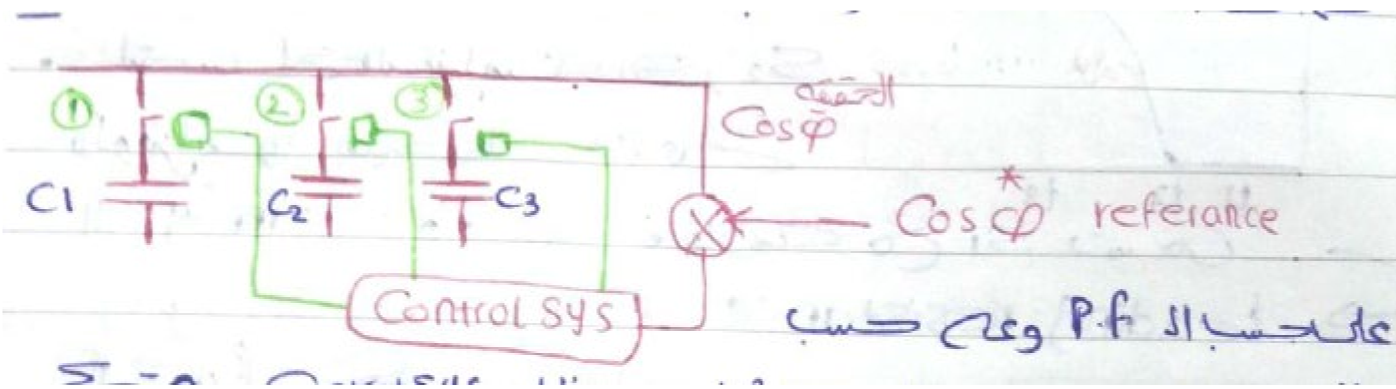
So it Provides the grid with reactive power

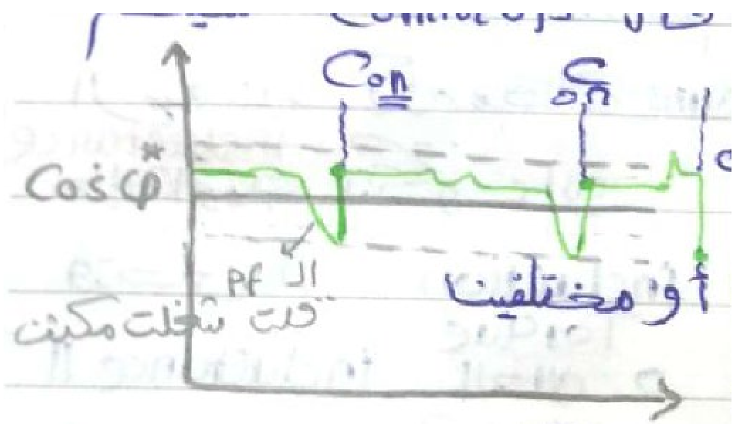
Lesser the load more the Q



> **Note**
>
> $$M \to Lead \to Provide\ Q$$
> $$G \to Lag \to Provide\ Q$$

5.4.1 Capacitors



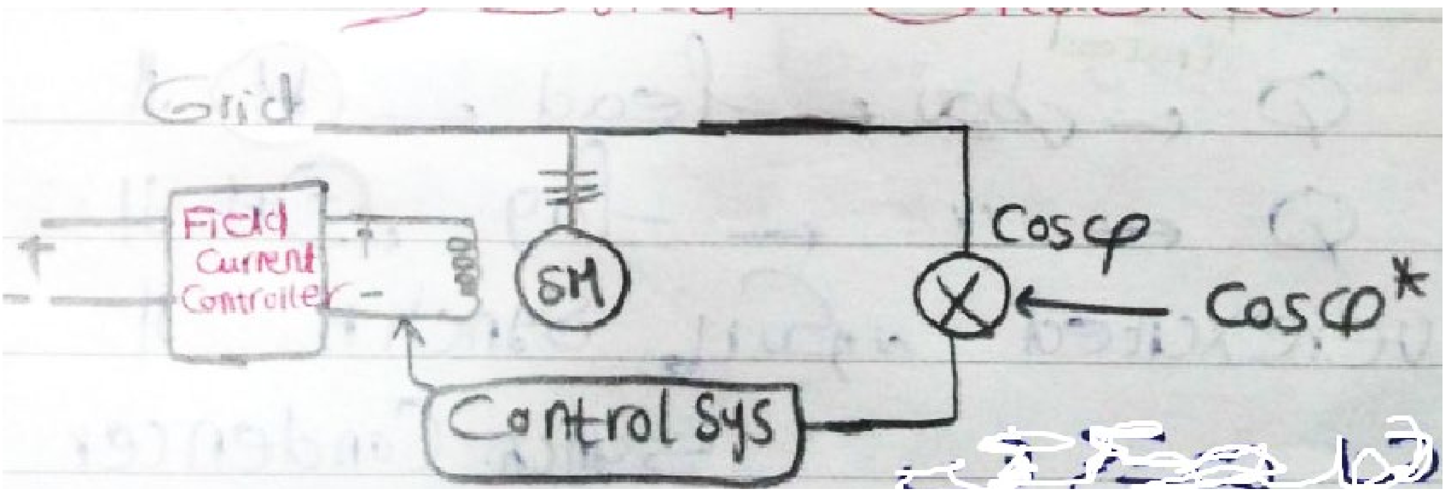


Here control system measure the PF and PF* and the error then it adds or remove Cs to approach the required value (but here it's **steps by the value of C available)**

5.4.2 Synchronous Condenser

increases in a nearly linear fashion until saturation is reached.

field current on the motor's phasor diagram.



Here we control the field circuit (If)

We can control it smoothly

High accuracy control on current and smooth

5.4.3 Capacitors Vs Synch Condensers

Synch. Condenser	Capacitors
Smooth variation	Switched variation
More accuracy	Less accuracy
Without spikes	Spikes (due to switching)
Requires regular maintenance cuz it's moving and brushes et cetera	Less maintenance more reliable
	We can make it smooth through switching with Mosfet or IGBT it's used with coils to smooth but it will cause harmonics capacitors are used to improve voltage profile

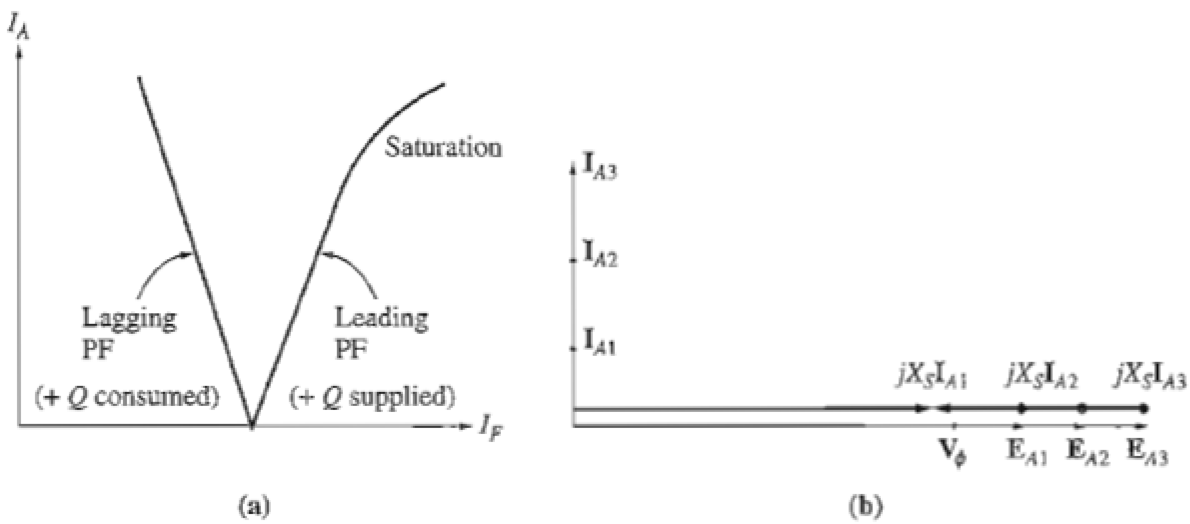


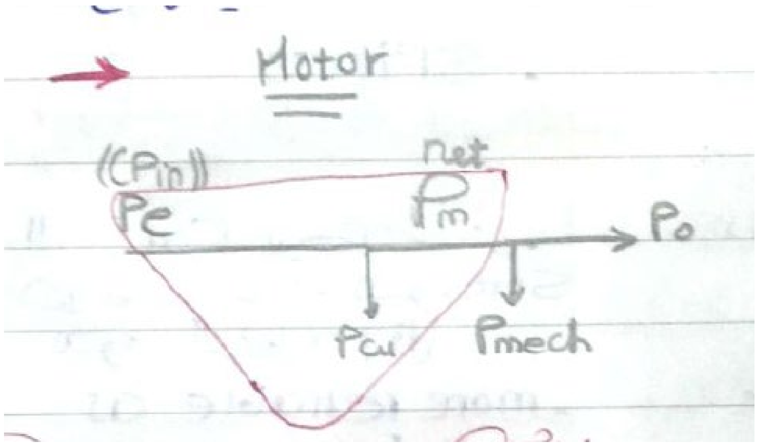
FIGURE 5–15
(a) The V curve of a synchronous capacitor. (b) The corresponding machine phasor diagram.

6 MECHANICAL LOAD DIAGRAM

It's used for

1- MOTOR only
2- We must consider Ra
3- Cylindrical Rotor
4- Per phase analysis

Note for salient there is- no electrical or mechanical load



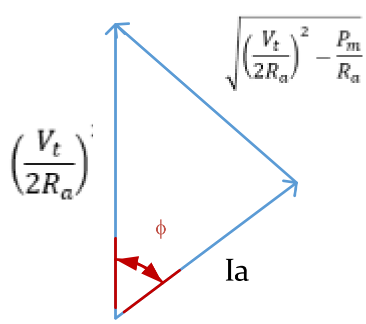
6.1 Analysis first part

$$P_m = P_e - P_{cu}$$

$$= V_t I_a \cos\phi - I_a^2 R_a$$

$$\therefore I_a^2 - \frac{V_t}{R_a} I_a \cos\phi + \left(\frac{V_t}{2R_a}\right)^2 = -\frac{P_m}{R_a} + \left(\frac{V_t}{2R_a}\right)^2$$

$$\therefore I_a^2 + \left(\frac{V_t}{2R_a}\right)^2 - 2\frac{V_t}{2R_a}\cos\phi \; I_a = \left(\frac{V_t}{2R_a}\right)^2 - \frac{P_m}{R_a}$$



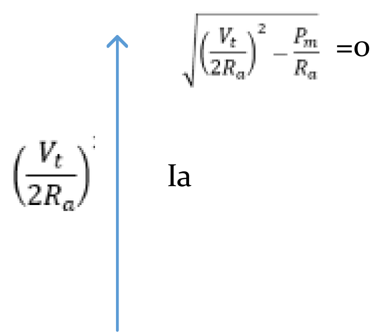
$$\sqrt{\left(\frac{V_t}{2R_a}\right)^2 - \frac{P_m}{R_a}}$$

6.1.1 Variables are

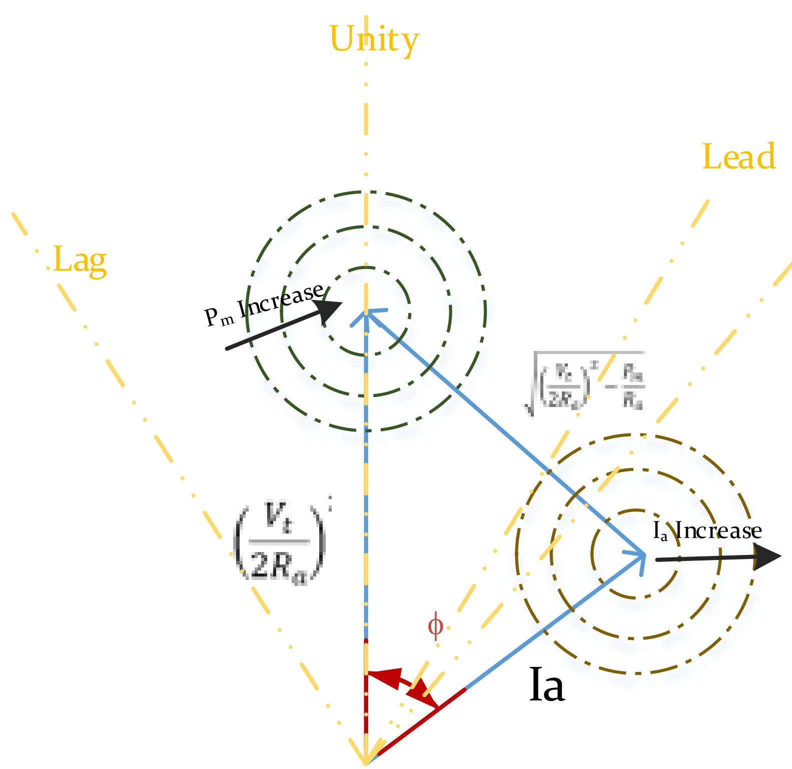
$$given\ (V_t\ , R_a)$$

$$Variables:\ \ P_m, \phi, I_a$$

6.1.2 $\phi = 0\ \ P_{Max}$



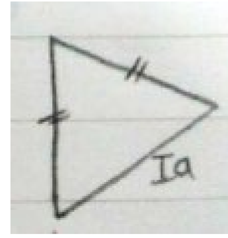
6.1.3 Loci



Increase Ia increases circle

Increase Pm decrease diameter ($P_m = 0 \rightarrow \sqrt{\left(\frac{V_t}{2R_a}\right)^2} = \frac{V_t}{2R_a}$ *so it becomes*

So it increases until circle diameter =0



$$\frac{P_{Max}}{R_a} = \left(\frac{V_t}{2R_a}\right)^2$$

$$P_{Max} = \frac{V_t^2}{4R_a} \text{ max power from that motor}$$

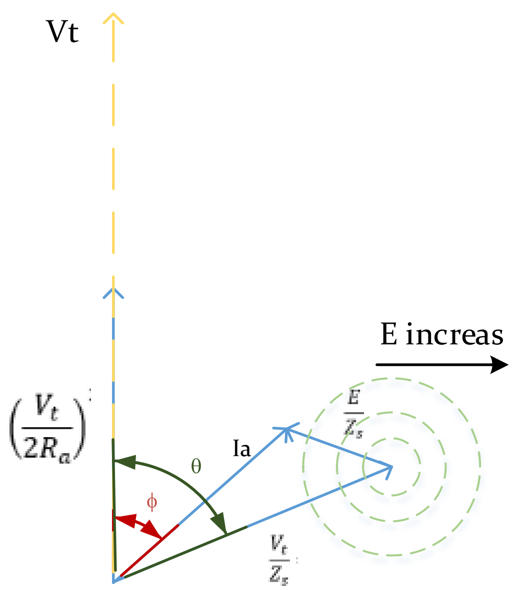
6.2 Second Part

To get certain case through both parts

$$V_t = E + I_a Z_s$$

$$\frac{V_t}{Z_s} = \frac{E}{Z_s} + I_a$$

as$Z_S = |Z_s|\angle\theta$



Pm is limited in increase has Pmax when circle diameter =0

E increase up to no limit (by insulation in practical)

6.2.1 Variables

Given (θ , Z_s , V_t., R_a)

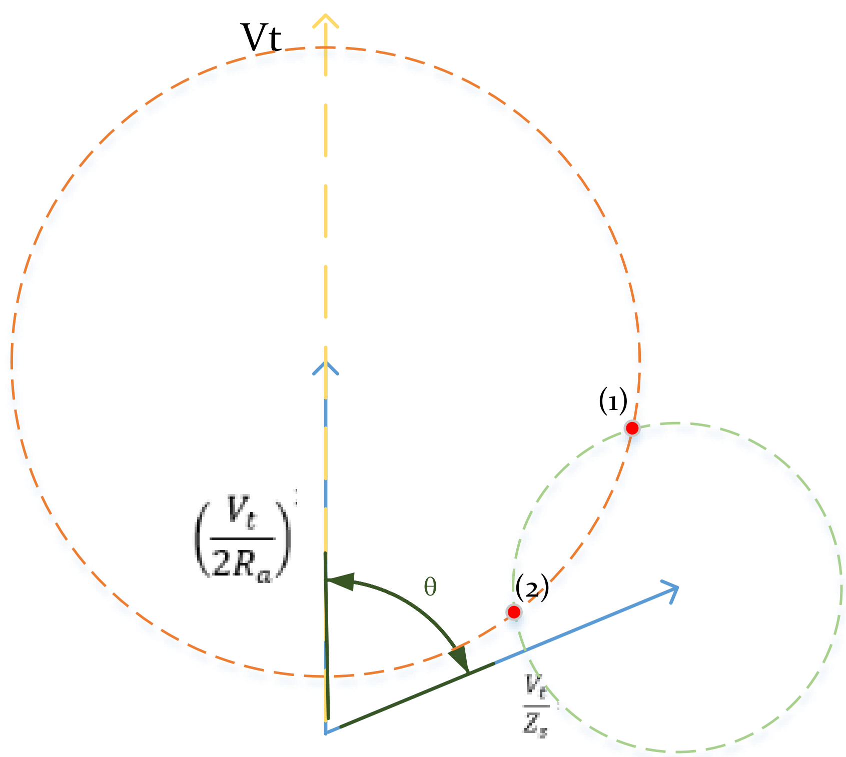
Variables (E , I_a , ϕ)

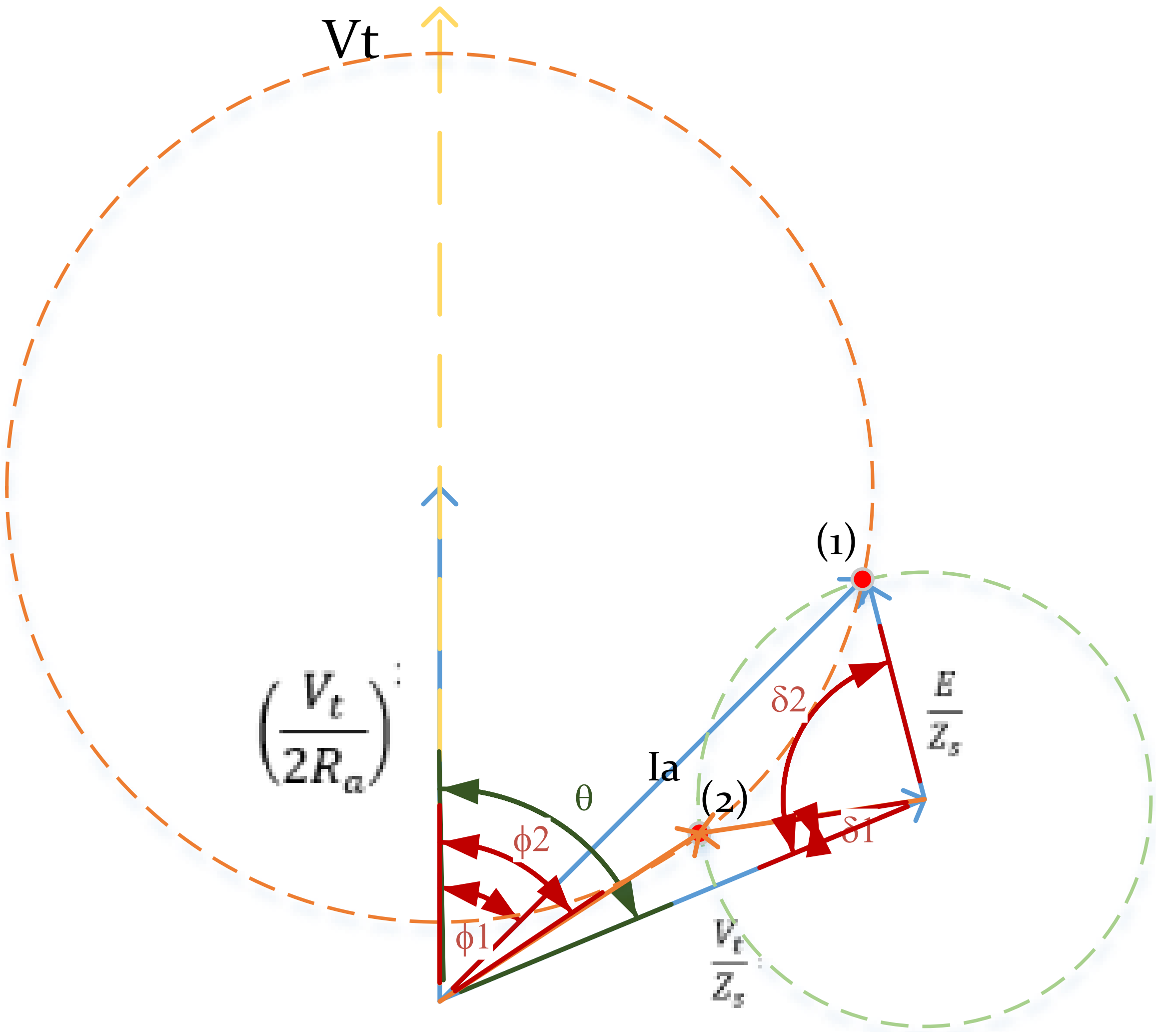
6.2.2 For given Pm and E (paramters given)

The two circles will have 2 points of intersection

We choose one with smaller δ to be more stable

As we consider R_a *then* $\delta_{Max} \neq 0$

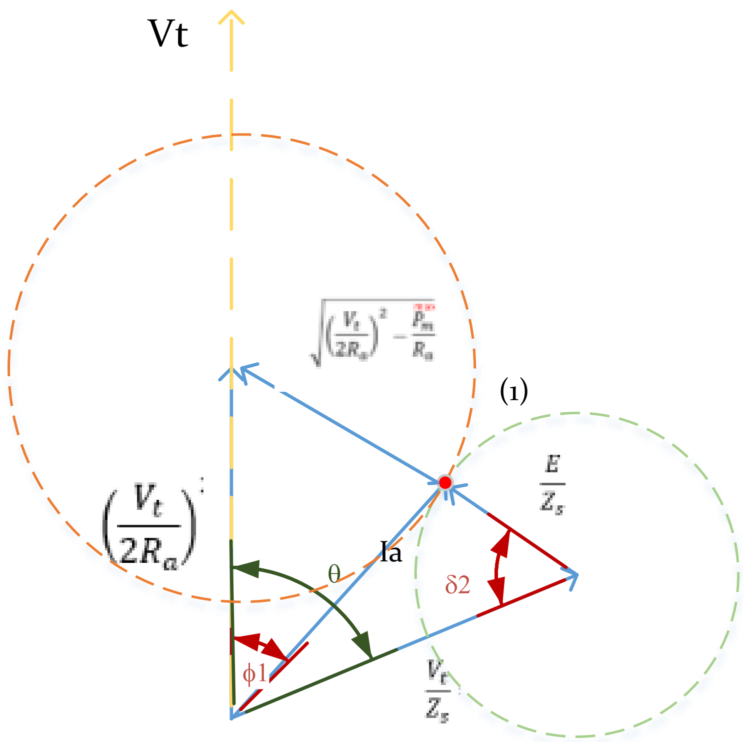



Vt
$\left(\frac{V_t}{2R_a}\right)$
θ
Ia
(1)
(2)
φ2
φ1
δ2
δ1
$\frac{E}{Z_s}$
$\frac{V_t}{Z_s}$

6.2.3 Given Pmech -> Minimum Excitation

6.2.4 Given Excitation ->Max Power to operate at

NOTE :
If two circles just touch then it's the Max Power for that Excitation
Here there is angle $\delta_m < 90\ (consider\ R)$ **if we increase more than it it will be unstable**

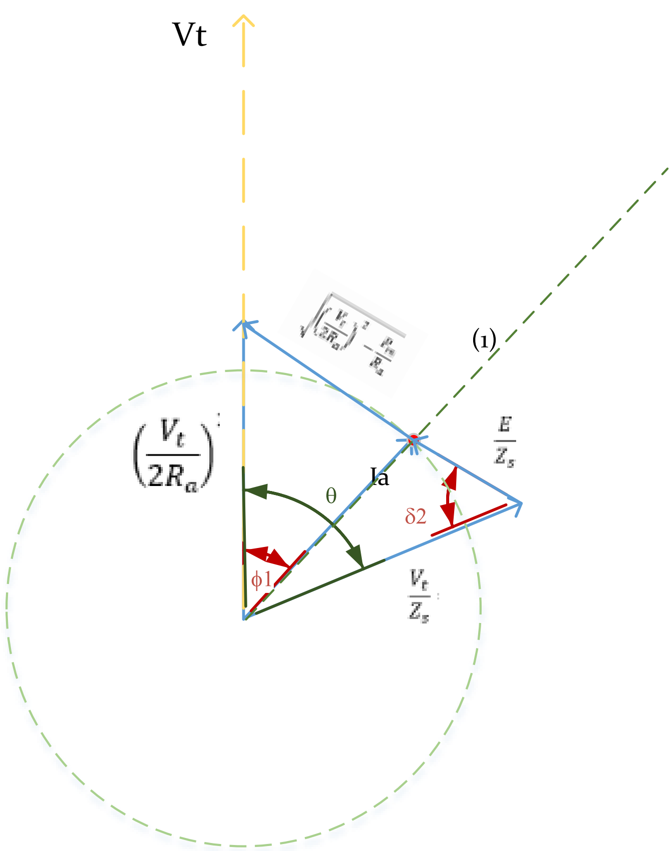


NOTE :
<u>Mechanical</u> Load Diagram -> Phasor <u>Current</u>

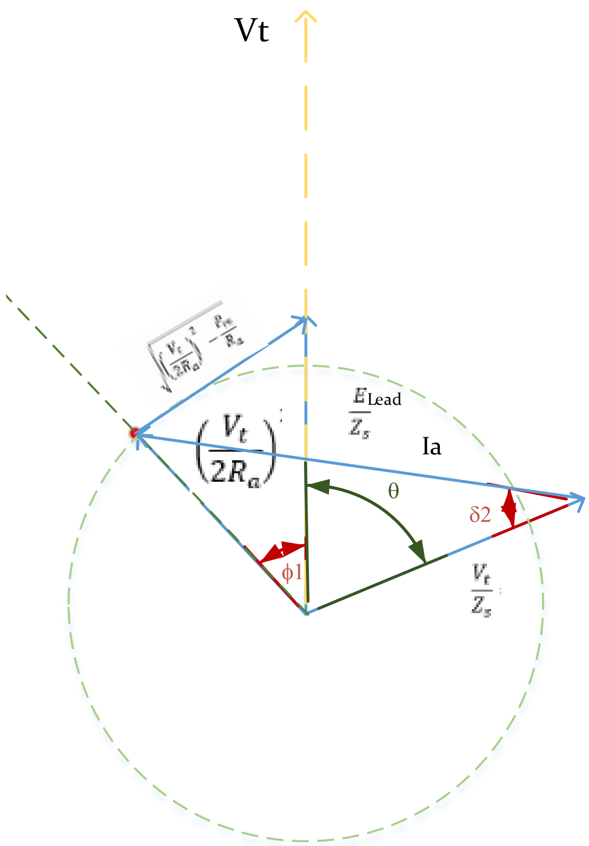
<u>Electrical</u> Load Diagram -> Phasor <u>Voltages</u>

6.2.5 Given Ia and cos ϕ (Lead or Lag)

<u>assume Lag , Excitation is low</u>

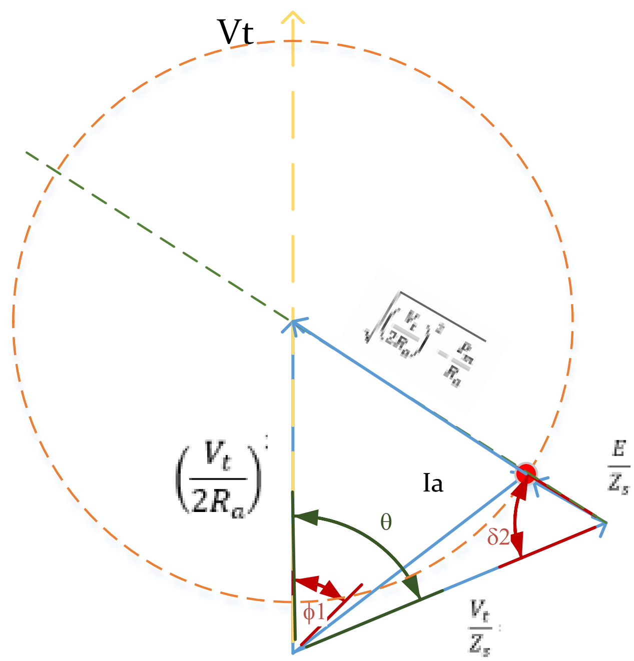


assume Lead , Excitation is High

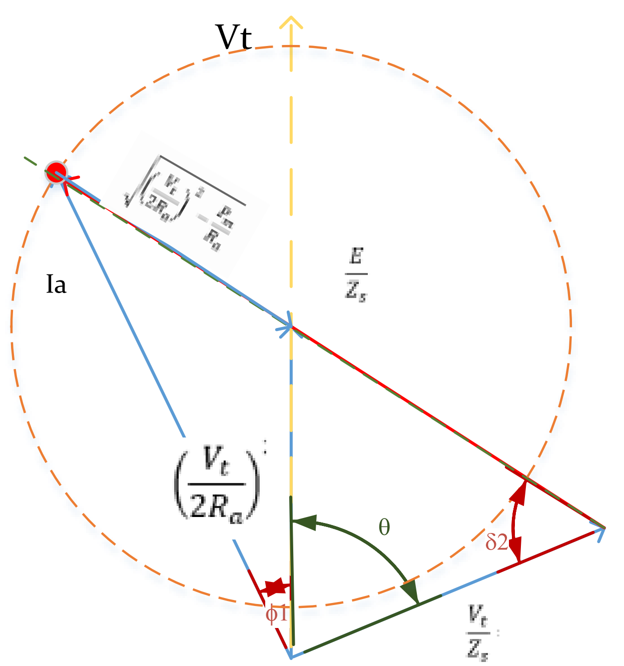


6.2.6 Given $\boldsymbol{\delta}$, $\boldsymbol{P_m}$

LAG Case , Low Excitation

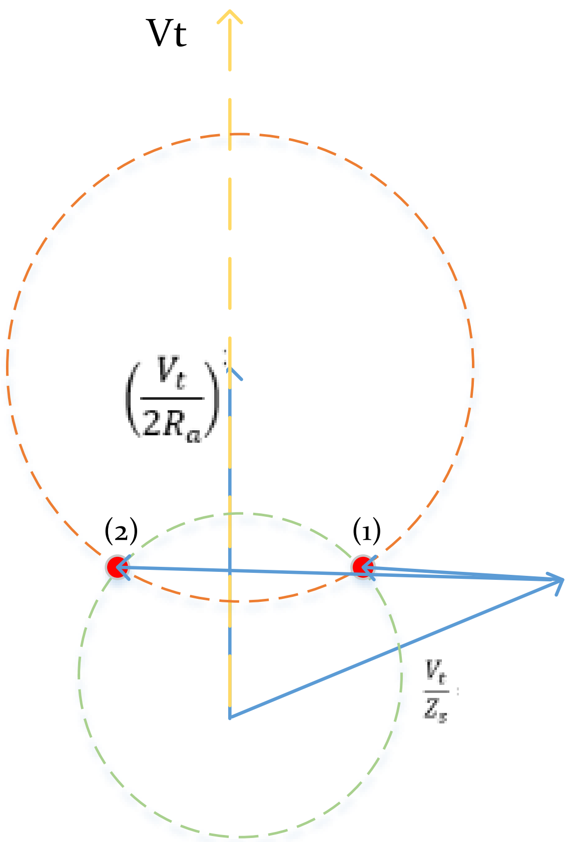


LEAD Case , HIGH Excitation



ANNOUNCEMENT :
For following MLDs we will draw Op.Point without the other details

6.2.7 Given Pm and Ia

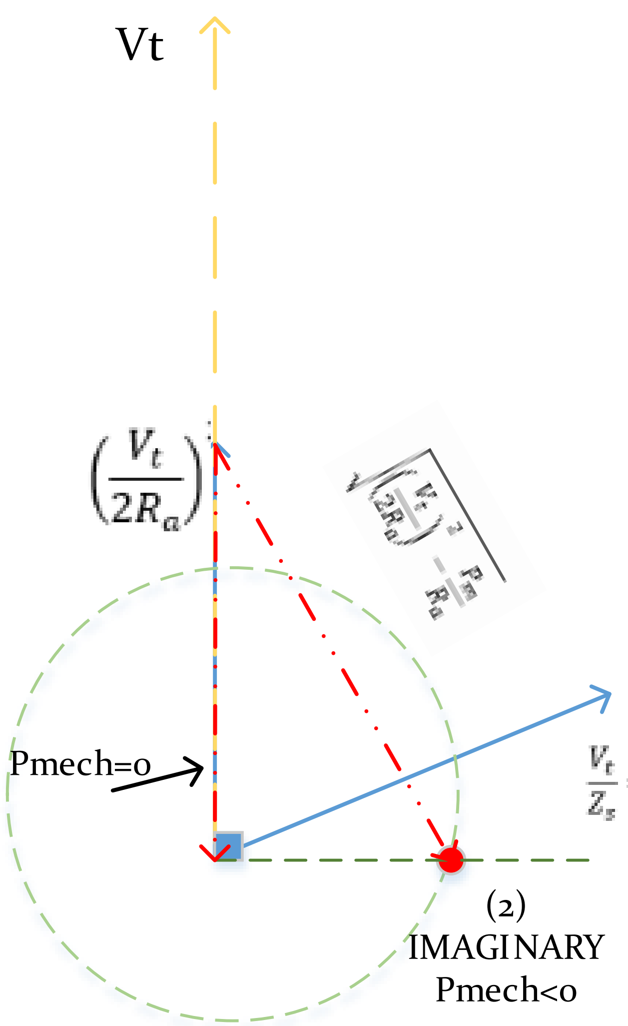


GENERAL NOTES :
1-The smaller δ the more stable operating point

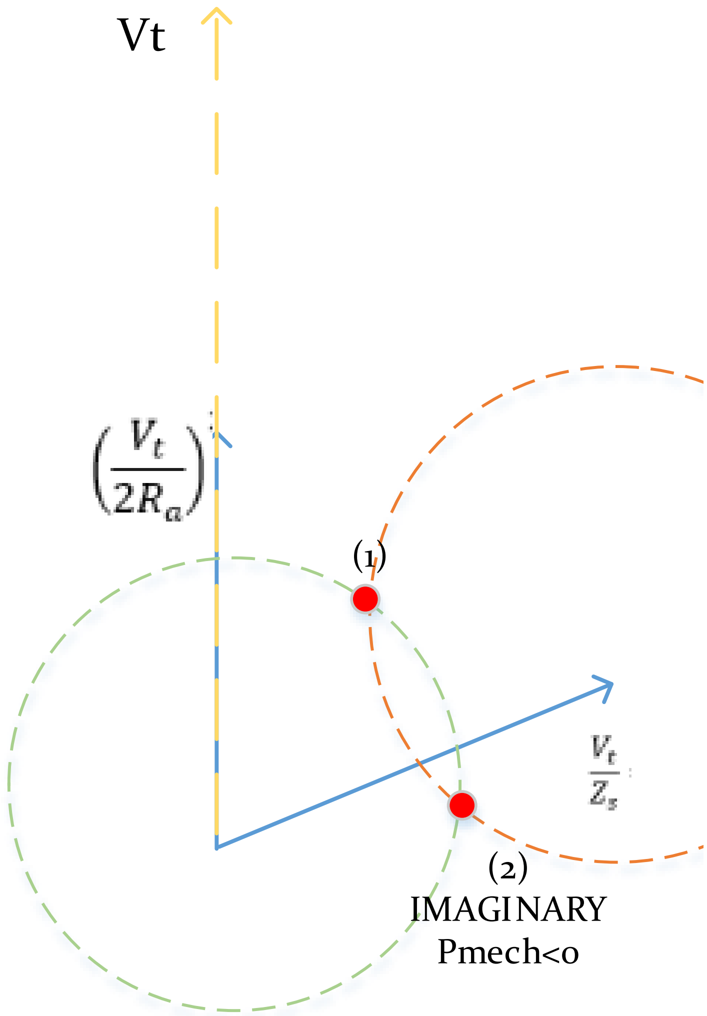
2- The lower Excitation it's LAG
3-The Higher Excitation it's LEAD

6.2.8 Given Ia $,\boldsymbol{\phi} = \mathbf{90}$

$$P_m \downarrow \Rightarrow r \uparrow$$
$$untill\ P_m = 0\ when$$
$$\sqrt{\left(\frac{V_t}{2R_a}\right)^2 - \frac{P_m}{R_a}} = \frac{V_t}{2R_a}$$

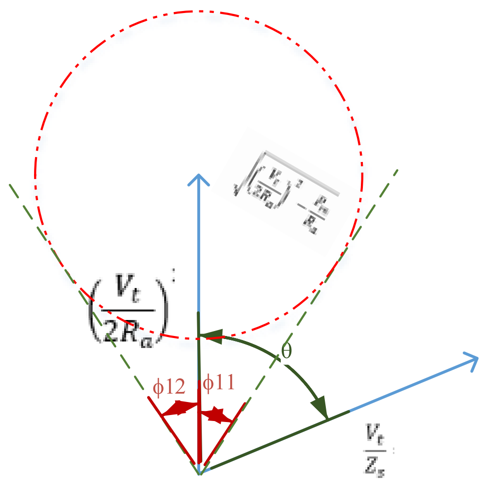


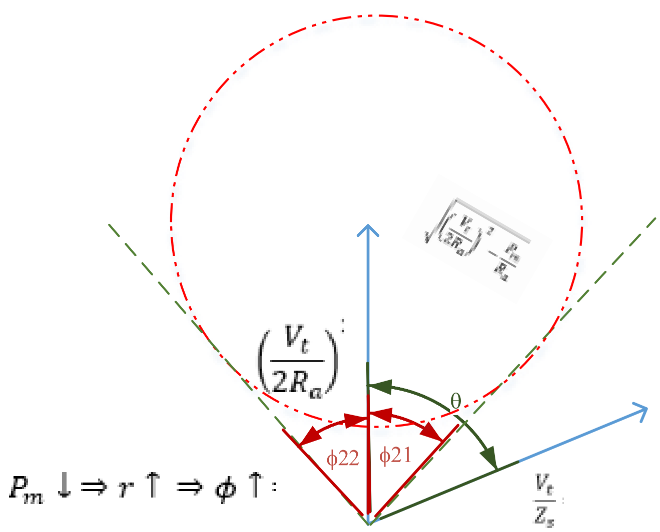
6.2.9 Given E and Ia



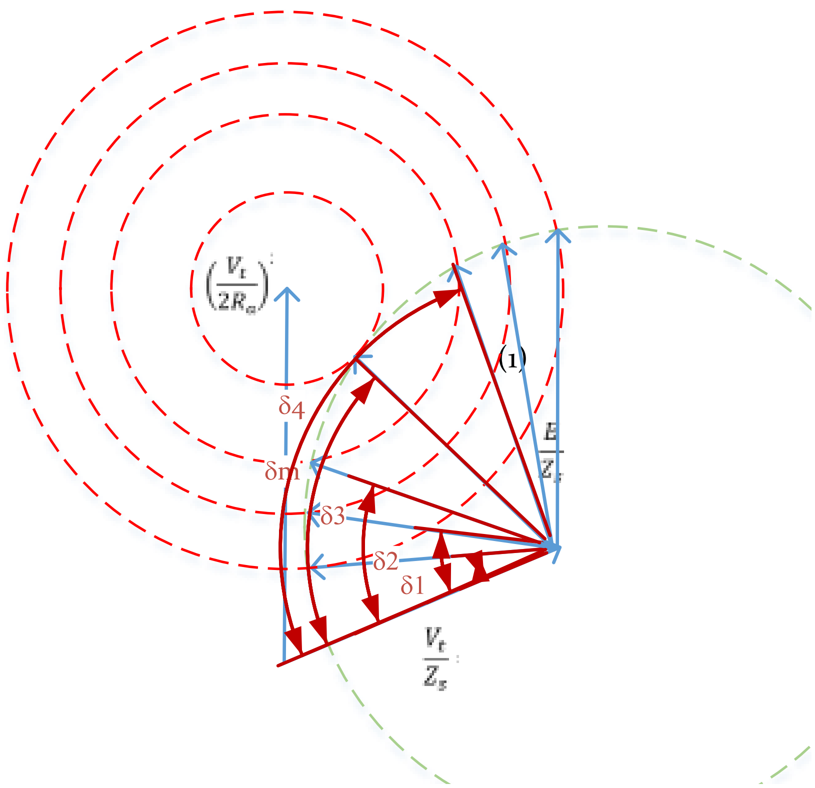
6.2.10 Relation between P_m and PF or Q $(reactive\ Power\ )$

$$P_m \downarrow \Rightarrow r \uparrow \Rightarrow \phi \uparrow \Rightarrow Q_{reactive} \uparrow$$

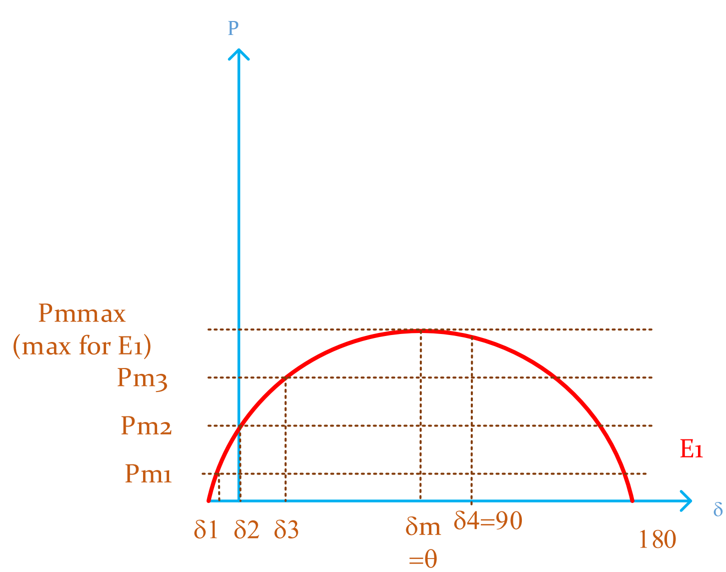




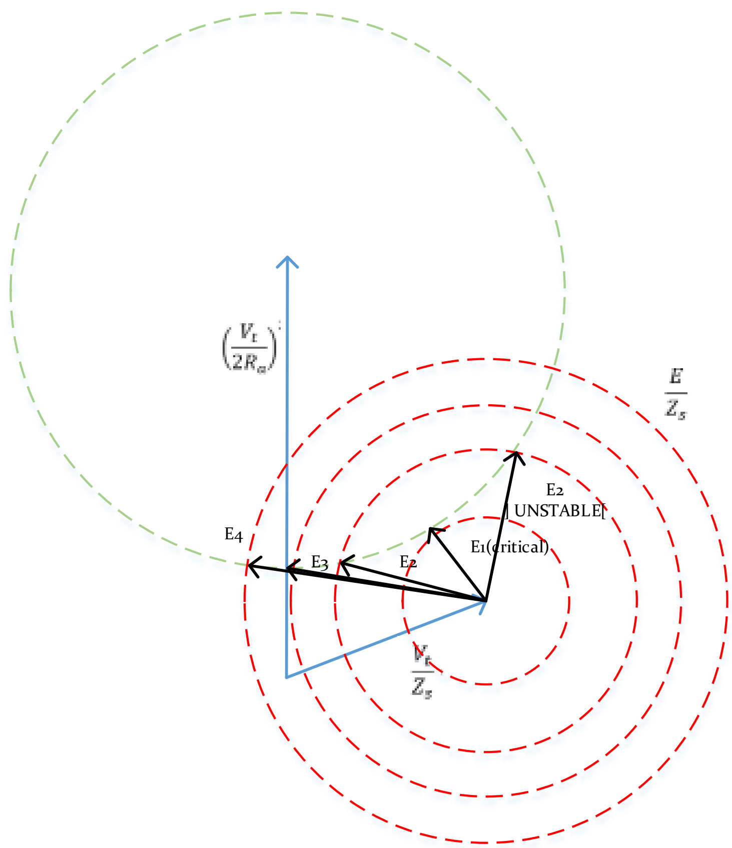
6.3 Power Against δ



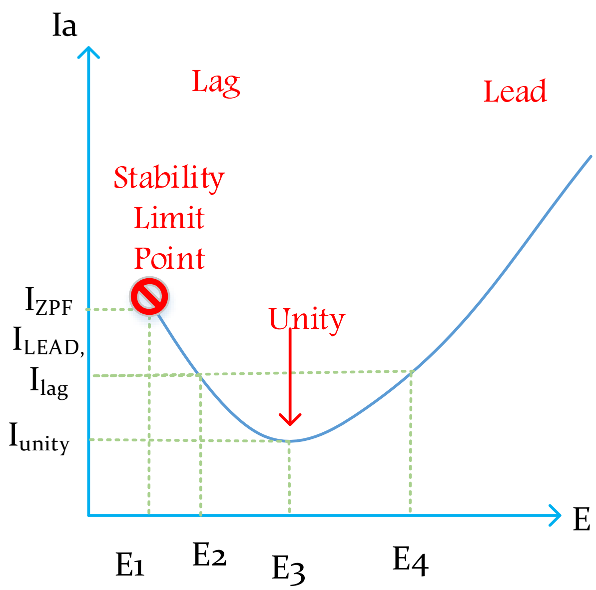
Pm1 <Pm2<Pm3<Pm4



6.4 Relation between Ia and E (excitation) for Pm (V-curve)



V – Curve (Certain Pm) (Motor)

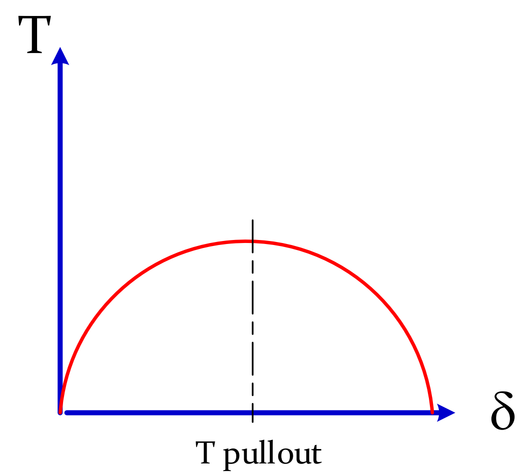


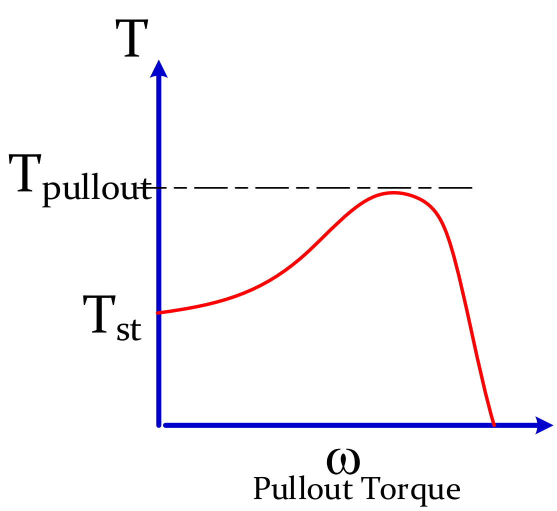
So E is limited by Stability (MinE) and Insulation (rating) (MaxE)

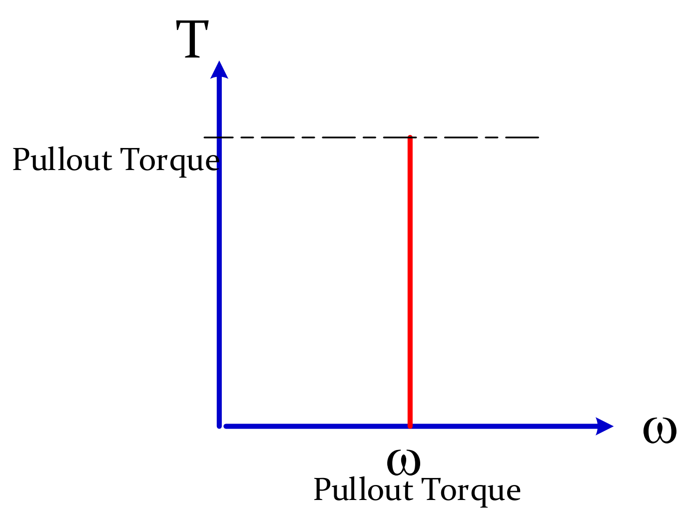
7 VOLTAGE REGULATION

7.1 Comparison between IM and SM

Induction Motor	Synchronous Motor



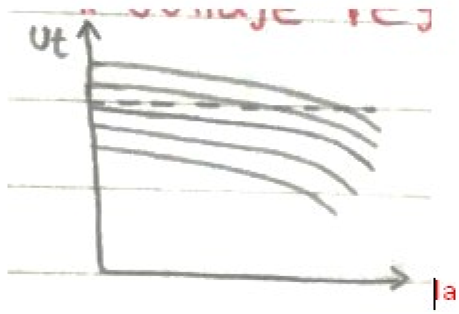




7.2 Voltage Regulation Definition

It's an indication how will the machine withstand changes in the load

As we can note that during increasing load the terminal voltage drops ($I_a \uparrow \Rightarrow V_t \downarrow$)



7.3 Methods to improve VR

7.3.1 By Prime Mover Speed

By changing steam governor , so that the speed of prime move increase and curve shifts up

Field Change -> Changes Both Voltage and Frequency

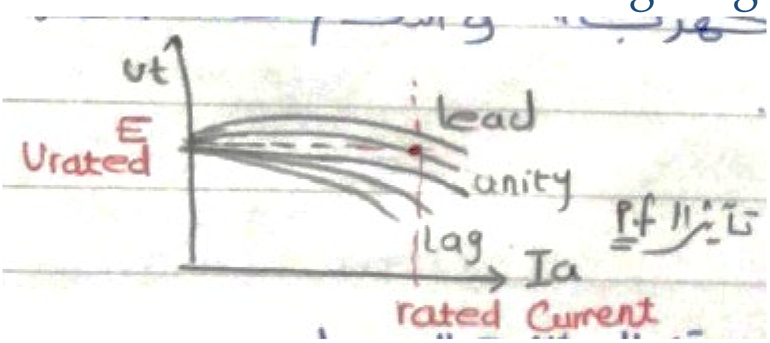
7.3.2 By Controlling Field

We change Excitation to shift curve up ,

It's preferred as it's Electrical system **Faster Response** than the mechanical one

Field Change -> Changes only Voltage

7.4 Effect of Load PF on voltage regulation (E const)

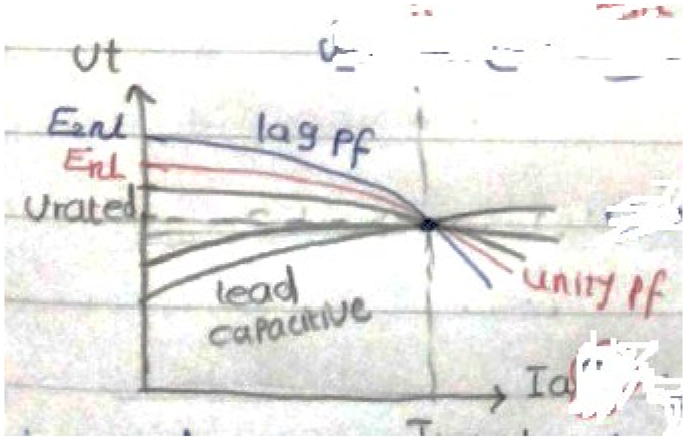


Here Lead Power Factor make voltage increase – Unity and Lag make it decrease

Here for I_{rated} we operate at voltage other than V_{rated} (lag , Unity) $V_{op} < V_{rated}$

At unity , there is R so there is V drop ! that's why it decreases !

7.5 Achieving Irated at Vrated (control E)



To make machine at Vrated give Irated we have to control excitation

NOTES

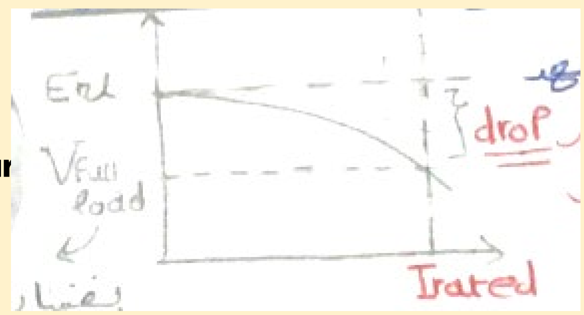
-In SM slip speed =0 , Machine has same speed for any load

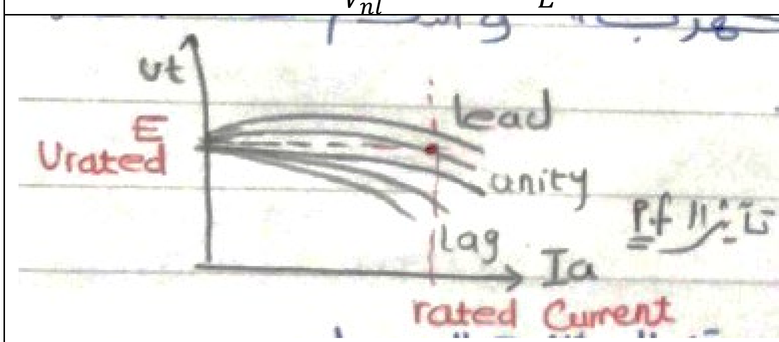
-Loading increase voltage drop ($\delta \uparrow$, $I \uparrow$)

-Then for Full load to be obtained we increase voltage and cur

-The Drop value changes from a machine to another

-Curve and drop is affected by voltage drop



$V_{Reg} = \dfrac{(V_{nl} - V_{fl})}{V_{nl}} = \dfrac{(E - V_{fl})}{E}$	$V_{Reg} = \dfrac{V_{nl} - V_{fl}}{V_{fl}}$
 This equation represents the voltage drop if machine is fully loaded	This equation represents how voltage will be increased if it was initially loaded with the full load and then it was removed
VOLTAGE PERCENT DROP WHEN FULL LOAD AT SPECIFIC PF IS <u>APPLIED</u>	VOLTAGE PERCENT RISE WHEN FULL LOAD AT SPECIFIC PF IS <u>SWITCHED OFF</u>

7.6 Methods to calculate Vreg

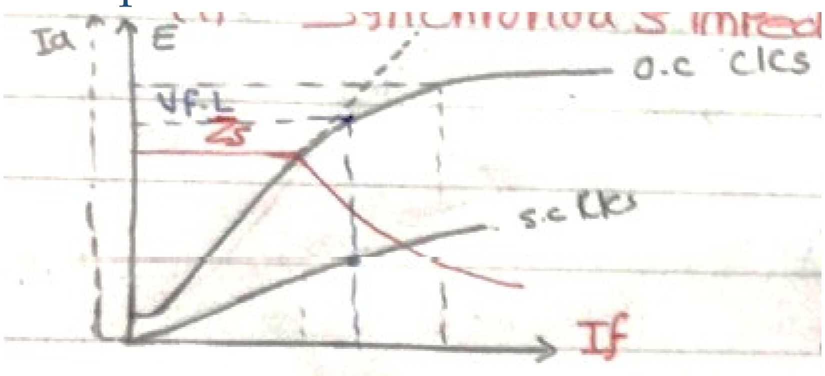
7.6.1 Machine Parameters Acquisition

DC TEST	R_a
O/C TEST	OCC Ch/c
S/C TEST	SCC Ch/c

7.6.2 Methods

(1) Synchronous Impedance Method
(2) MMF (AT) Method
(3) Zero PF Method (Poitěr) [needs ZPF Test -> ZPF Ch/c to be more accurate]

7.7 Synchronous Impedance Method



For a Vfl ((given)), required Vnl at a certain PF((given))

Step 1

Get Ra from DC Test

Step 2

From curve at certain I_f

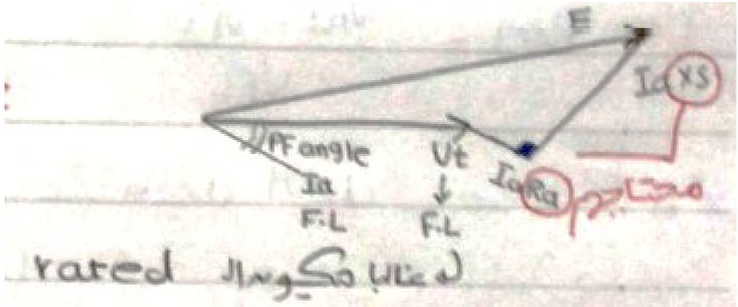
$$Z_s = \frac{E_{oc}}{I_{sc}} \quad (at\ certain\ I_f)$$

$$R_a\ known$$

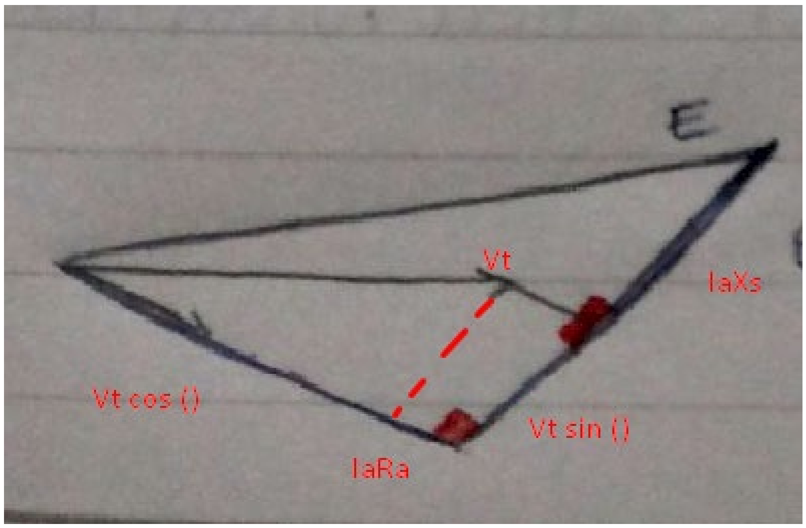
$$X_s = \sqrt{Z_s^2 - R_a^2}$$

$$E = V_{fl} + \mathrm{I_a}(R_a + jX_s)$$

Phasor Diagram Calculation



From it



So

$$E = \sqrt{(V_t \cos\phi + I_a R_a)^2 + (V_t \sin\phi \pm I_a X_s)^2}$$

+ (lag) or - (lead)

7.7.1 Disadvantages

It neglected saturation between OCC and SCC

Neglected that Xs decreases in saturation

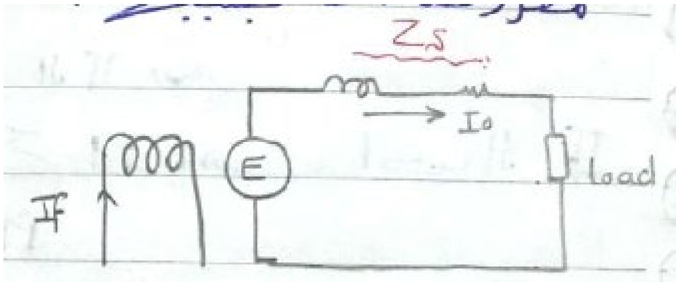
We neglected **leakage** flux

7.7.2 Advantages

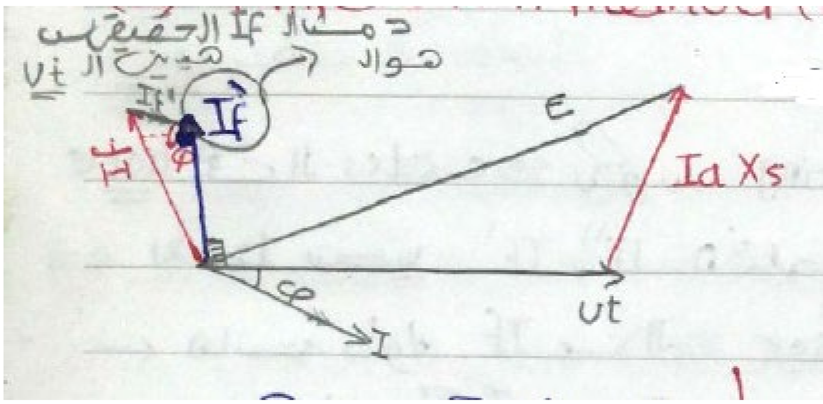
It's easy method

7.8 AT Method

For a Cylindrical Rotor , Synchronous Generator



For a certain I_f we can get E



$$V_{Reg} = \frac{E - V_t}{V_t} * 100$$

7.8.1 METHOD

So , to make Vt the same

<u>At no load</u>

$$V_t = E$$

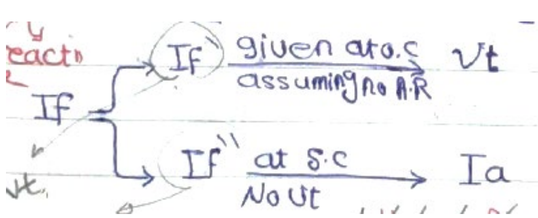
As there is no drop (Ia=0) and AR =0

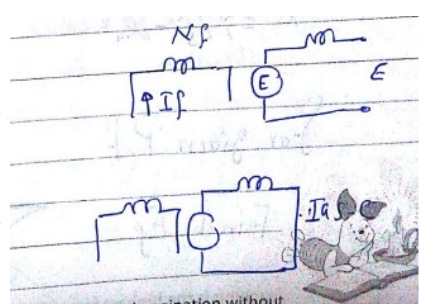
<u>At loading</u>

We have to increase the E↑ to maintain the same V_t

Increase in field can be divided into 2 components

(1) I_f' to get to Vt
(2) I_f'' react to AR





7.8.2 For Lag Power Factor Load

NOTES

$$I_F' \ \ is \perp V_t \ as \ it's \ its \ job \ to \ get \ it$$

$$I_F'' \ is \parallel I_a \ \ as \ it's \ against \ AR \ caused \ by \ it$$

$$I_F \ is \perp E \ as \ its \ job \ to \ get \ it$$

So we get $I_f' \rightarrow I_f'' \rightarrow I_f$ $(vector \ sum)$

Vt mustn't be in <u>linear</u> region

If rating is small

7.8.3 Steps of solution

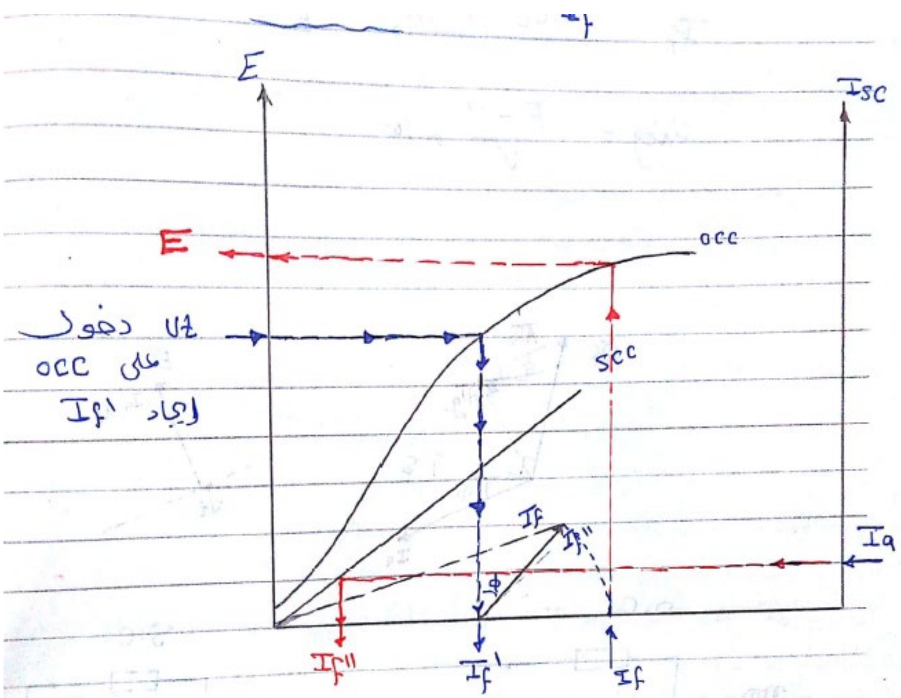
1- Get Vt and from OCC get If'
2- Get Ia (rated for load) from SCC get If''
3- From following triangle phasor group or equation get If

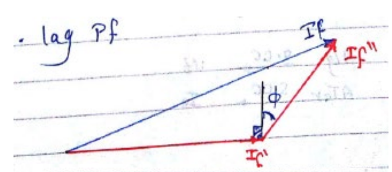
$$I_f^2 = {I_f'}^2 + {I_f''}^2 - 2I_f'I_f'' \cos(90 + \phi)$$

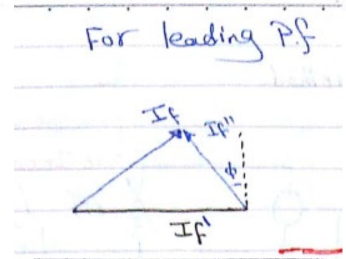
4- From If and OCC get E req
5- VR = $\frac{Ereq - Enl}{Enl}$

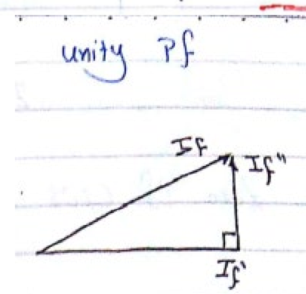
The less the ϕ

the better the regulation









7.8.4 Advantages

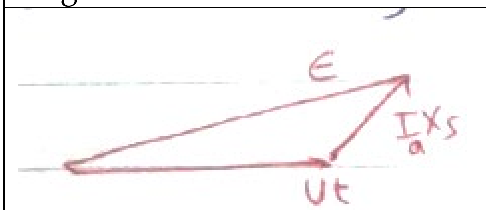
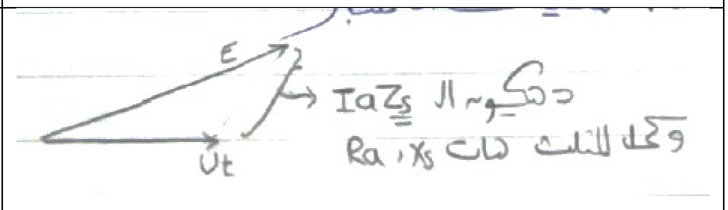
1- We took saturation into consideration

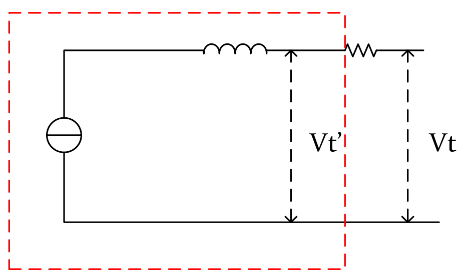
(we usually We enter saturation by 20%)

7.8.5 Disadvtanage

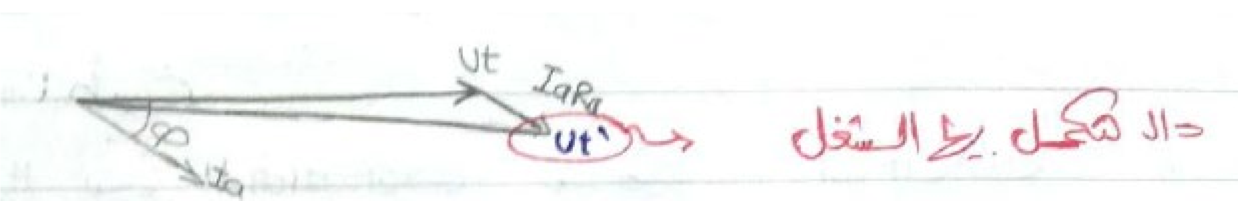
We neglected **leakage** flux

7.8.6 Taking R into consideration (we neglect it's effect on ϕ)

Neglect R	Take R
	



So we use given R to get Vt' and then complete problem without R



7.9 ZPF Method

7.9.1 Advantaged:

Takes leakage into account

give accurate results

8 METHODS OF EXCITATION

Excitation : Current Passing Through Coil , Producing MMF (Magnetic Field).

Exciter **:** is the device or machine providing Excitation.

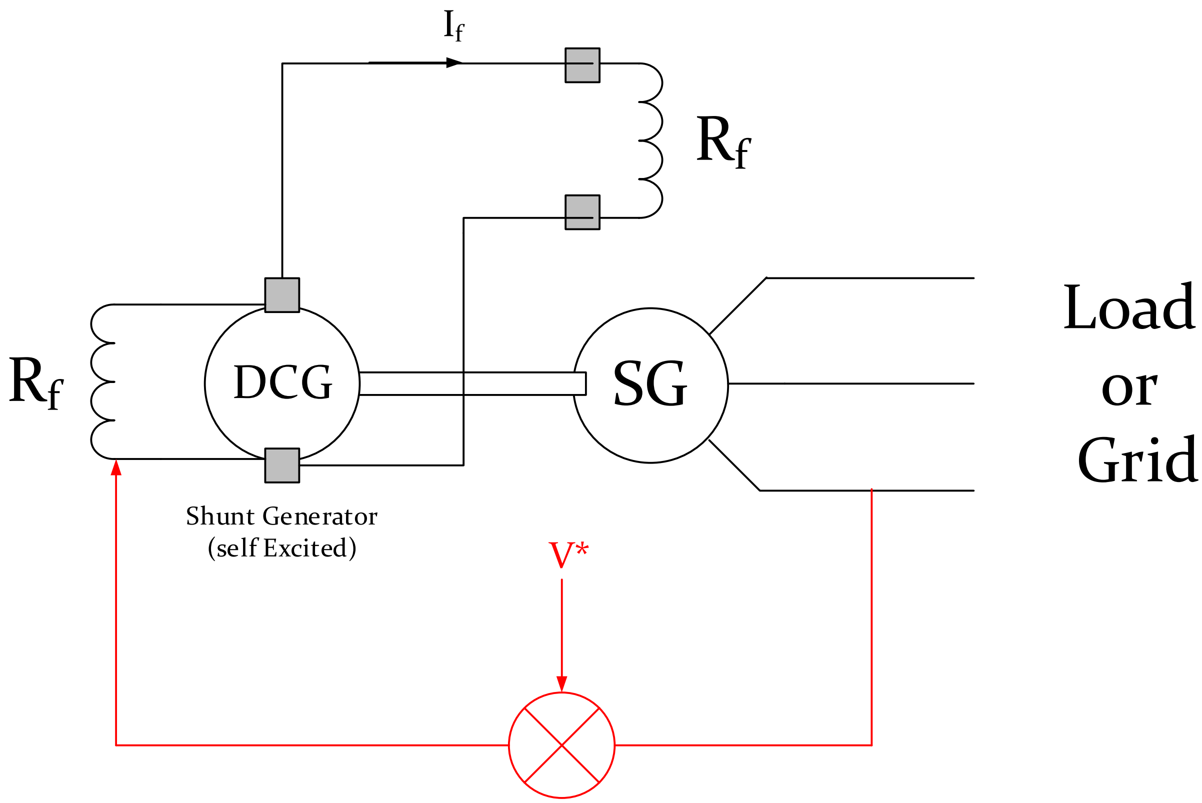
Notes :

1-We need brushes, to feed rotating part (rotor)

2-To feed it with DC we use BRUSHES + SLIP RINGS

3-To feed it with AC we use BRUSHES + COMMUTATOR

8.1 DC Excitation with (DC Genrator)



8.1.1 Disadvantages:

1- Brushes at SG
2- Brushes at DCG (Exciter)

8.1.2 For stand alone

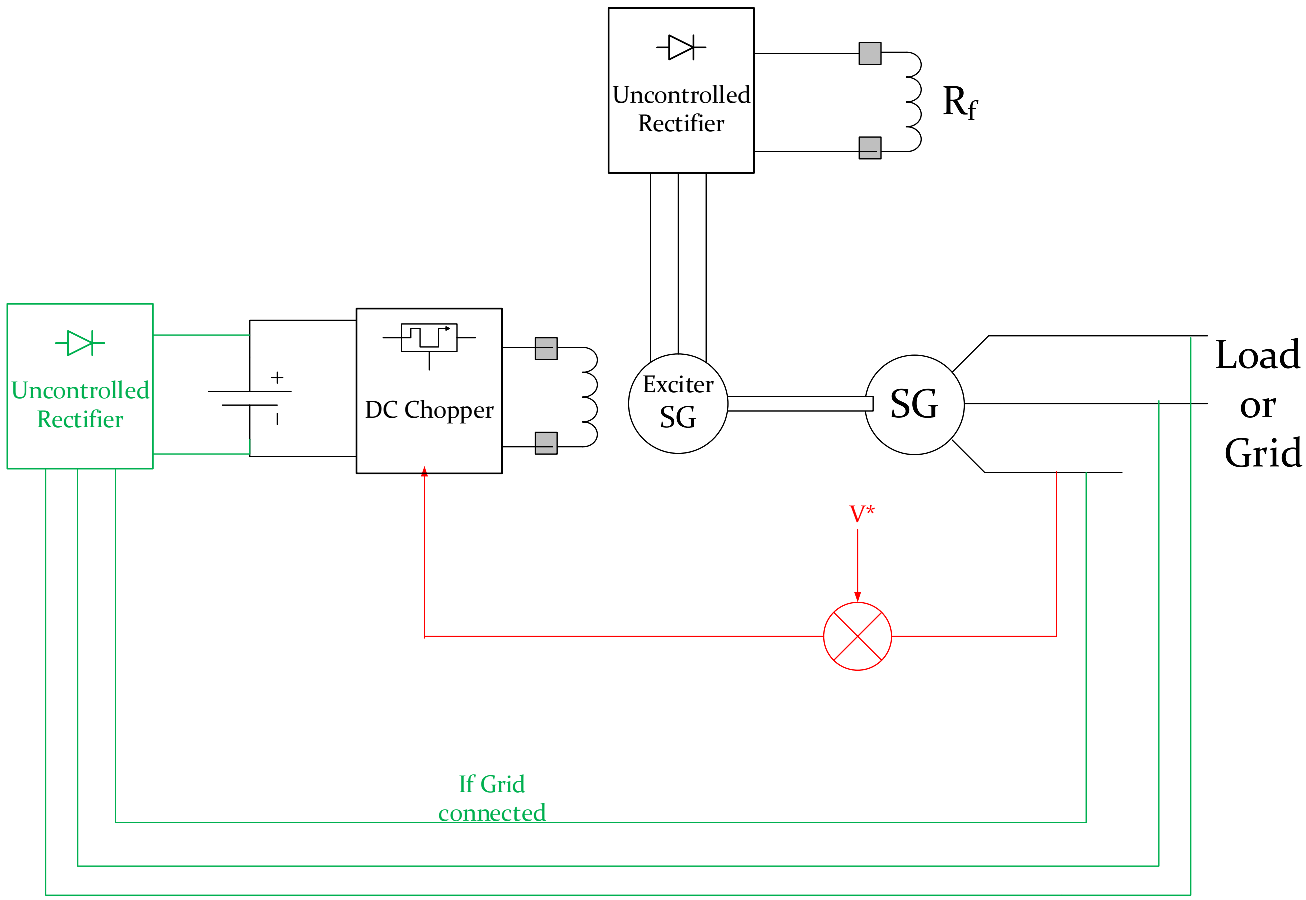
- We can control **Exciter field to control *output voltage***

8.1.3 For Grid Connected

- Vt is constrained to the Grid voltage
- So changing **Exciter field affect *PF***

8.2 AC Excitation

8.2.1 (A) USING SG (AC rotating Excitation)

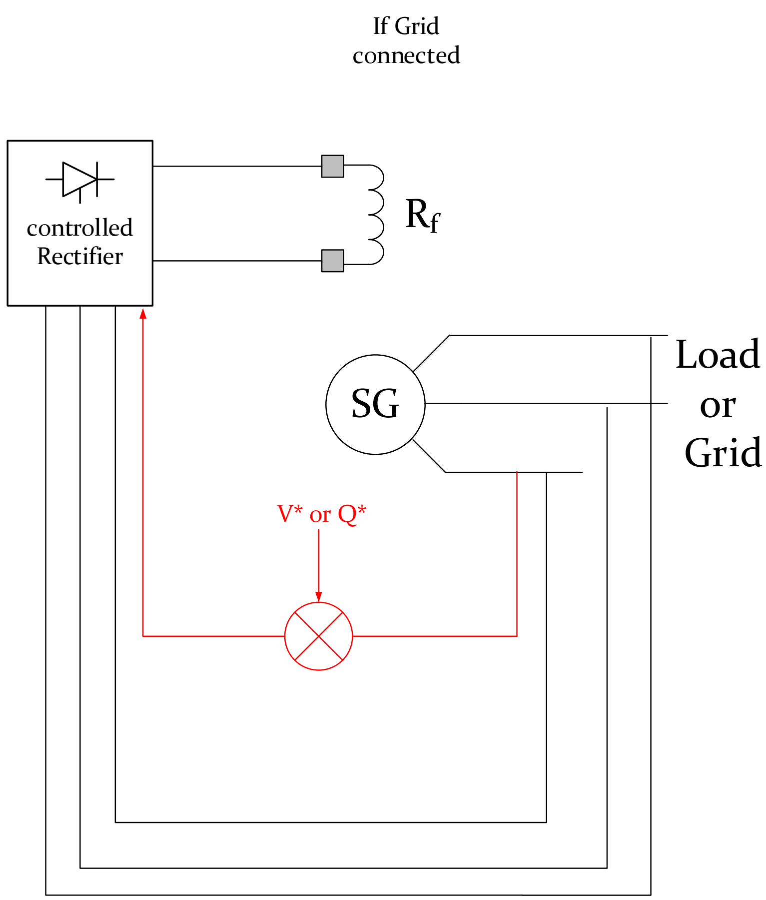


8.2.2 (B) USING Rectifier (AC STATIC EXCITATION)

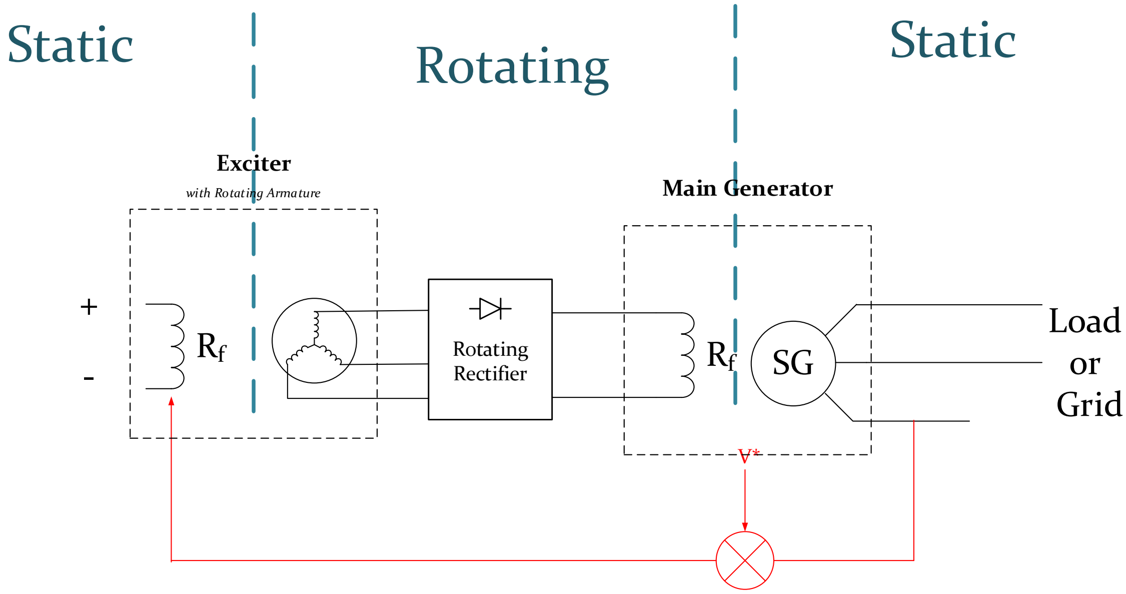
We use it if system is grid connected ,

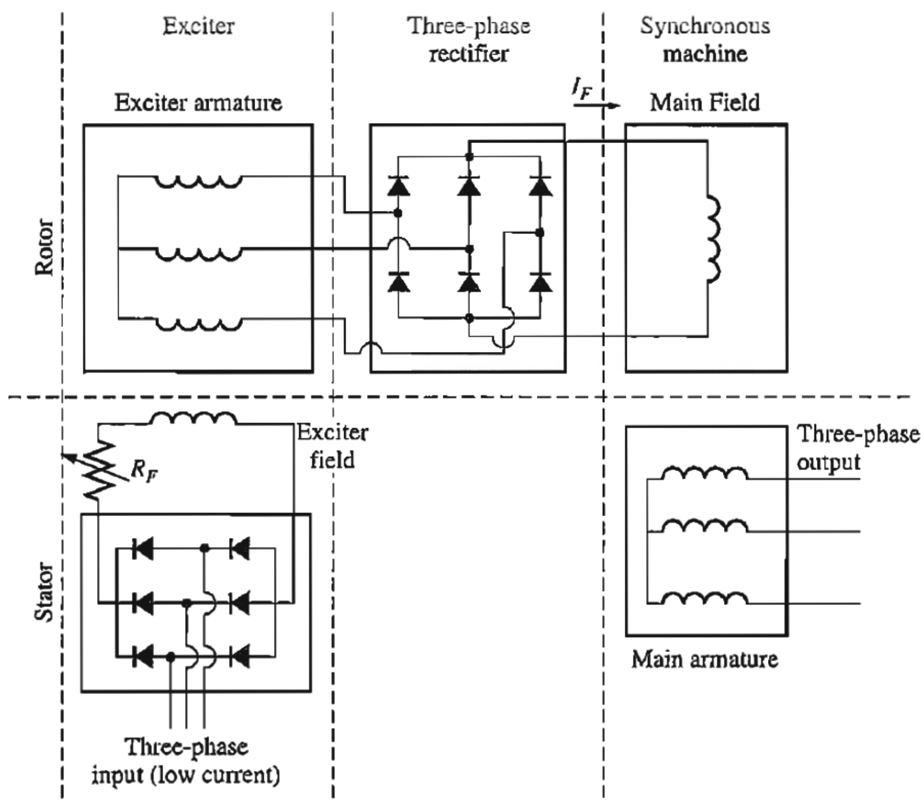
E changes , -> affects PF and Produced Q , not Voltage

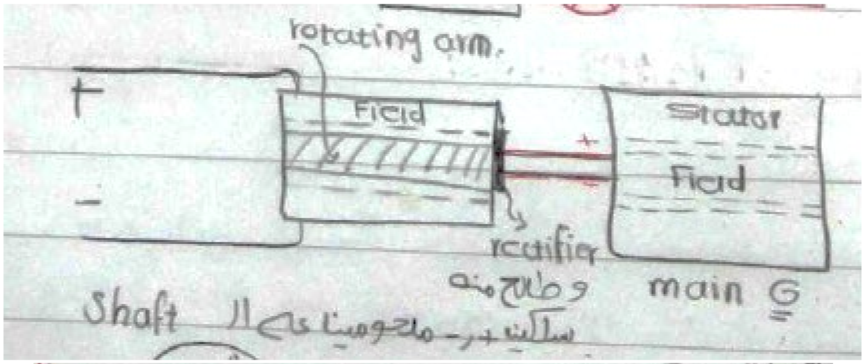
Disadvantage : High Power Electronic Rectifier

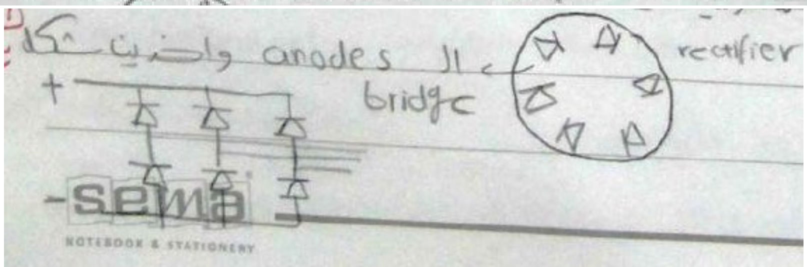


8.3 BRUSHLESS EXCITATION SYSTEM









Here we can make it self-excited from the generator it self

To make it self excited, it has to have some <u>residual magn.</u> To be able to build up(step up)

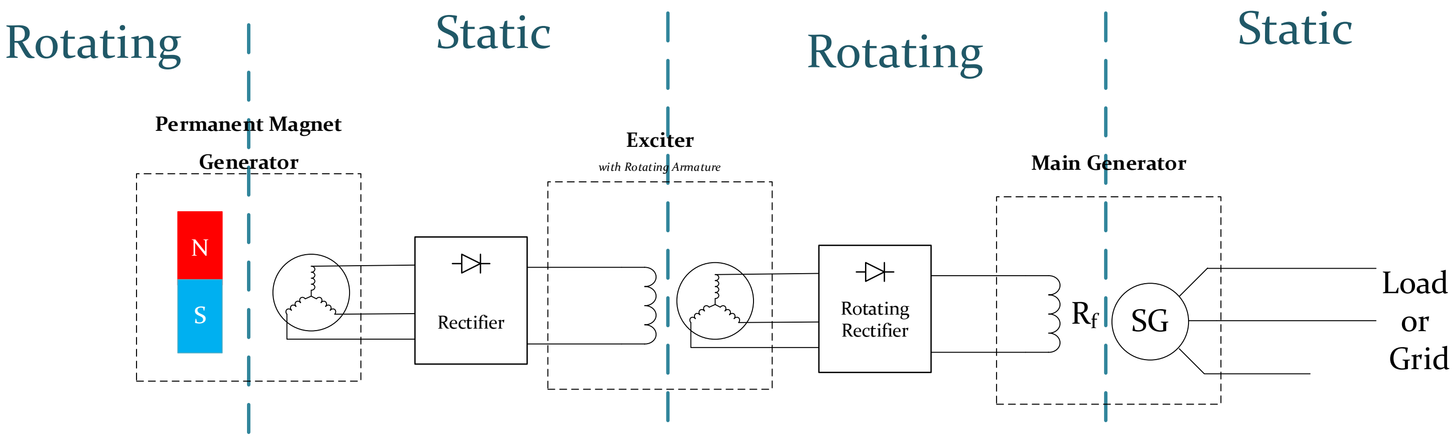
8.3.1 Advantage:

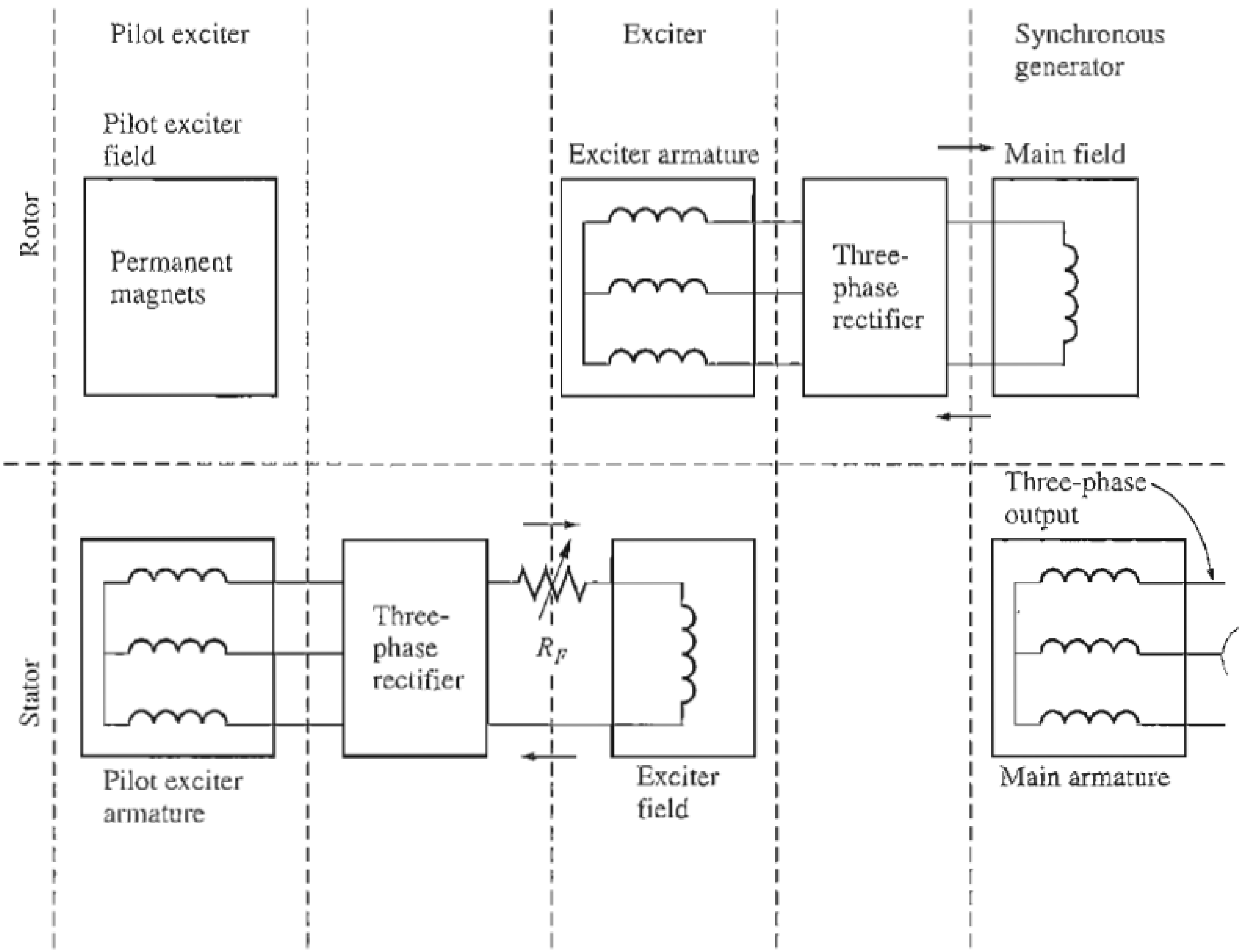
We don't need brushes any more

8.3.2 Disadvantage

To Build Up voltage, there must be <u>residual magnetism</u>

8.4 Permanent Magnet Excited Sys





Or we could just use PM for main generator

But, then we wouldn’t be able to control it easily

8.4.1 Disadvantages

Adding all these machines , reduces efficiency

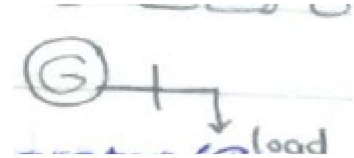
Increase Cost

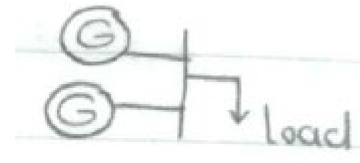
8.4.2 Advantage

More reliable

Less Maintenance

9 PARALLEL OPERATION OF SYNCHRONOUS GENERATORS





In this topic we study how to connect a generator to

1- Stand Alone
2- Another Generator
3- Weak Grid
4- Infinite Grid ((const V & f))

9.1.1 To Weak Grid

Weak Grid is affected by adding a generator

- Generator will affect the grids <u>Performance</u>
- It will affect <u>Power Sharing</u>

9.1.2 Infinite Bus (Strong Grid)

In this grid, it's not affected by adding a generator , as it's voltage and frequency are constant !!

It will just hange load sharing as the generator will <u>Provide</u> some power to the grid

9.2 Parallel Operation

1- Importance
2- Requirements
3- Methods of Synchronization
4- Load sharing (P , Q) between [G-G] [G – Grid]
5- Synchronizing Current, Power and Torque

9.3 Importance - advaTAGES

9.3.1 Reliability

As we assure that there will be electricity, even if one of the generators go out

Supply Continuity **<u>in the case of Fault and Maintenance</u>**

At the required Const V and frequency

9.3.2 Economic

- Decreasing Running Cost
- Decreasing Initial Cost
- The Exploitation of resources and being able to add multiple generation at suitable places

9.3.3 Technical

- No need for technical assistance ,reliability
- supply a bigger load than one machine by itself.
- Less Power Losses
- Better Efficiency,
  as each generating unit can operate at the point of max Efficiency
- Saving starting power
- If some generator goes out it can be restarted using power from other generators

9.3.4 Management

- Can manage the load sharing between multiple generators or renewable sources to provide the highest efficiency and least running cost

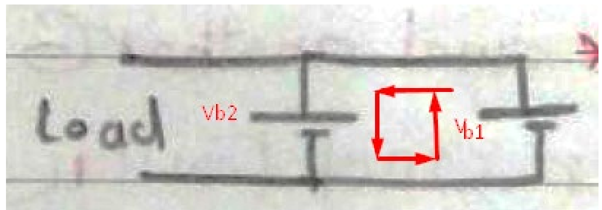
9.4 Requirements

9.4.1 Example with dc battery

If we connect 2 generators (sources) there will be moments when they are at differenct polarity or ones voltage is higher than the another, these two cases can be represented using DC batteries as follows :

9.4.1.1 Vb1 > Vb2

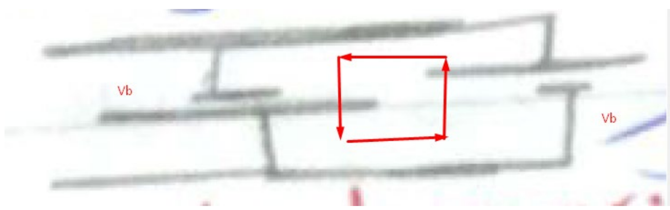
If one voltage is higher than the other, there will be some circulating current , in a SC path , which is VERY DANGEROUS



- But practically, there is some internal impedance which limits this current , but it still exists as a problem $I = \frac{v_1 - v_2}{r_{internal}}$
- We can accept small circulating current (for small v1-v2) or (high r) for short time until the 2 sources are connected at proper conditions

9.4.1.2 Vb1 = -Vb2

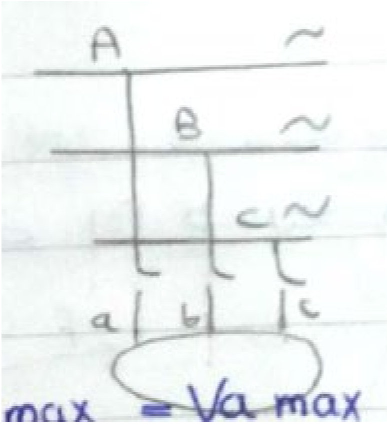
There will appear very high current as now $I = \frac{2Vb}{r}$

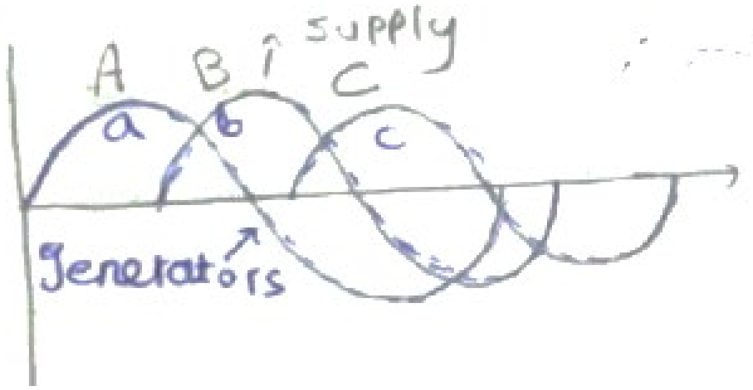


So for **<u>2 DC battery REQUIREMENTS ARE</u>**

1- Same Polarity
2- Same Voltage

9.4.2 For $3-\phi$ Generators





The generator output voltage , must be identical to the grid voltage (group voltage)

(1) <u>Same Phase Sequence</u>

Two phase sequences (abc – acb)

MUST (ABC-abc) or (ACB – acb)

<u>Positive Combinations :</u> (B)C and (b)c

<u>Negative Combinations :</u> (A)C and (a)c

(2) <u>Same Phase Shift between corresponding phases (A-a , B-b , C-c) [$\alpha = 0$]</u>

(3) <u>Same Voltage Magnitudes</u>

$$V_{A_{peak}} = V_{A_{peak}}$$

<u>Same Frequency</u>

(*oncoming generator,* **must be** slightly higher than the frequency of the running system.)

(1) <u>120 ° phase shift between each phase and the next</u>

9.5 Methods of Synchronization

9.5.1 For sync. Phase sequence

There is a device Phase Sequence Indicator , it tells you whether is +ve or -ve seq

So we connect Generator Terminals and Grid Terminals and they must be at the same sequency

If not ?

1) Just **SWAP** two cables of the generator
2) Change the rotation direction of Prime Mover

9.5.2 For sync. Voltage

We can control voltage through **excitation**

Why not speed of Prime Mover? CUZ IT WILL Fing CHANGE THE Fing Frequency

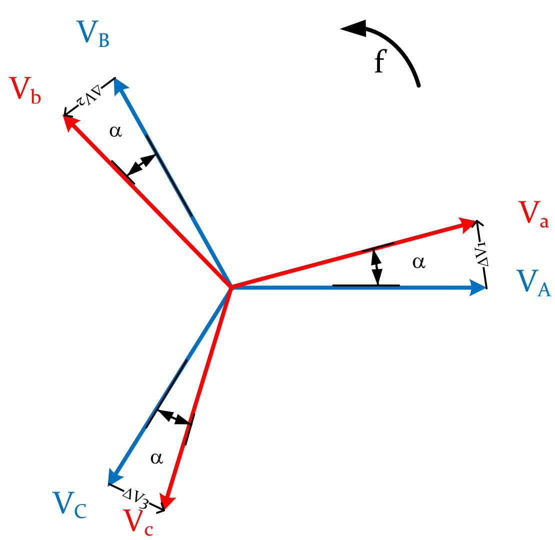
9.5.3 For sync. Frequency

From changing speed of rotation .

Practically, we use governors to control speed of turbines by increasing steam. But it's not that easy

So, we prefer the gates of High Dam Power Plant

9.5.4 For sync. Phase Shift



We need $\alpha = 0$, so we

Increase speed of PM, if angle decrease $\alpha \downarrow$ we keep until it's zero

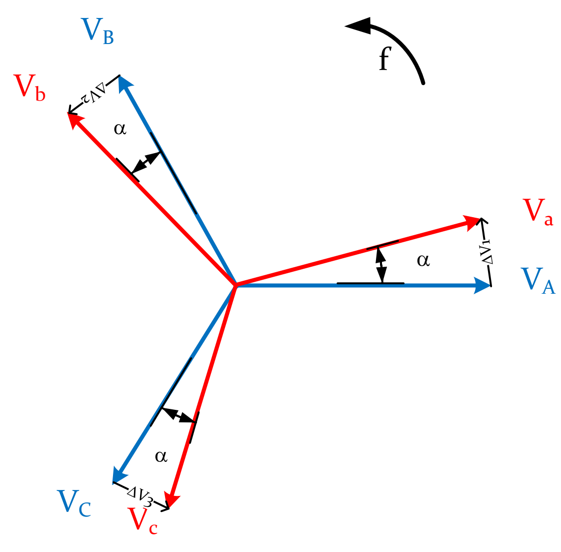
Else, if it increases $\alpha \uparrow$ we decrease speed

Or, Vice Versa

At Lab we use the **<u>Synchronoscope</u>** which indicates same phase shift with a GREEN LED If there is difference then ther will be a <u>circulating</u> RED LED speeding if $\alpha \uparrow$

9.6 Vector Representation we can visualize different cases of out of sync

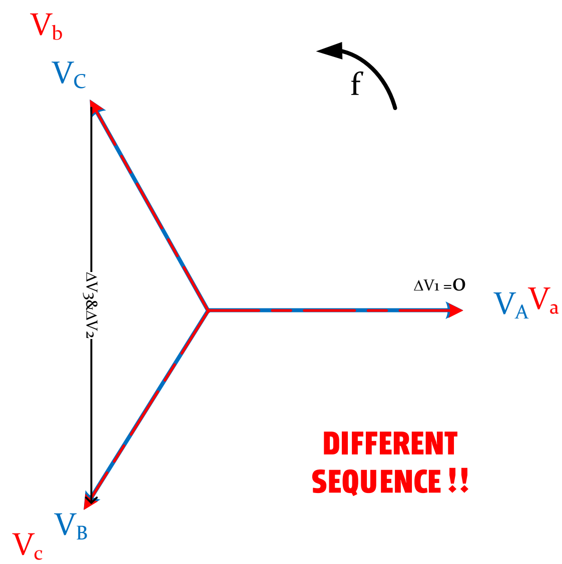
9.6.1 Difference <u>Phase Shift (α)</u>



Note:

1- Same $\Delta V_1 = \Delta V_2 = \Delta V_3$ (same sequence)
2- Both rotating for same f (same freq)
3- α *is const value* (not same phase shift)
4- Voltage magnitude the same , but different angles

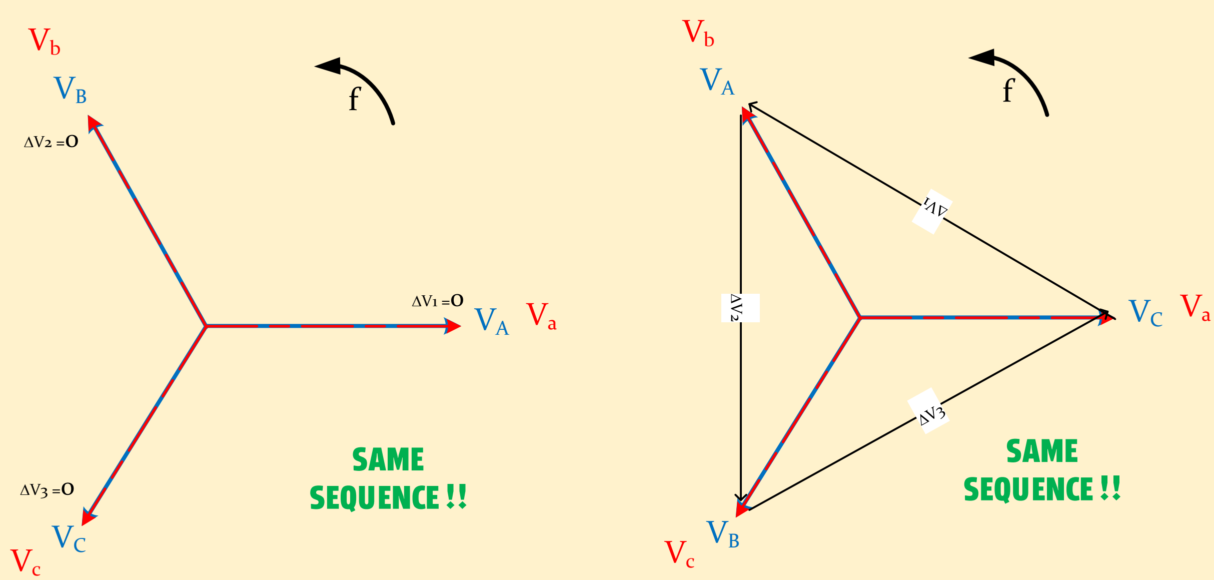
9.6.2 Different Phase Sequence



We can detect difference in phase sequence through

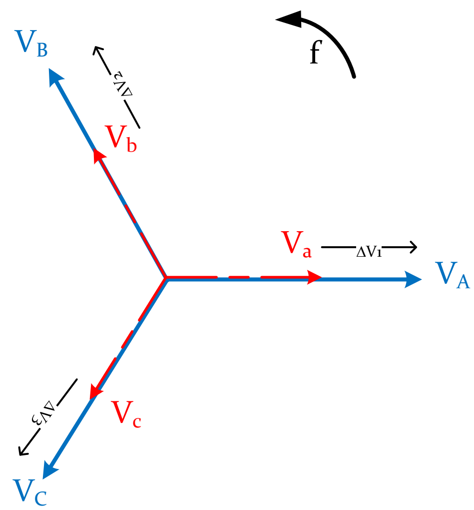
$$\Delta V_1 = 0$$
$$\Delta V_2 = \Delta V_3 = Large\ VALUE$$

NOTE :



SAME SEQUENCY WHEN $\Delta V_1 = \Delta V_2 = \Delta V_3$

9.6.3 Different Voltage

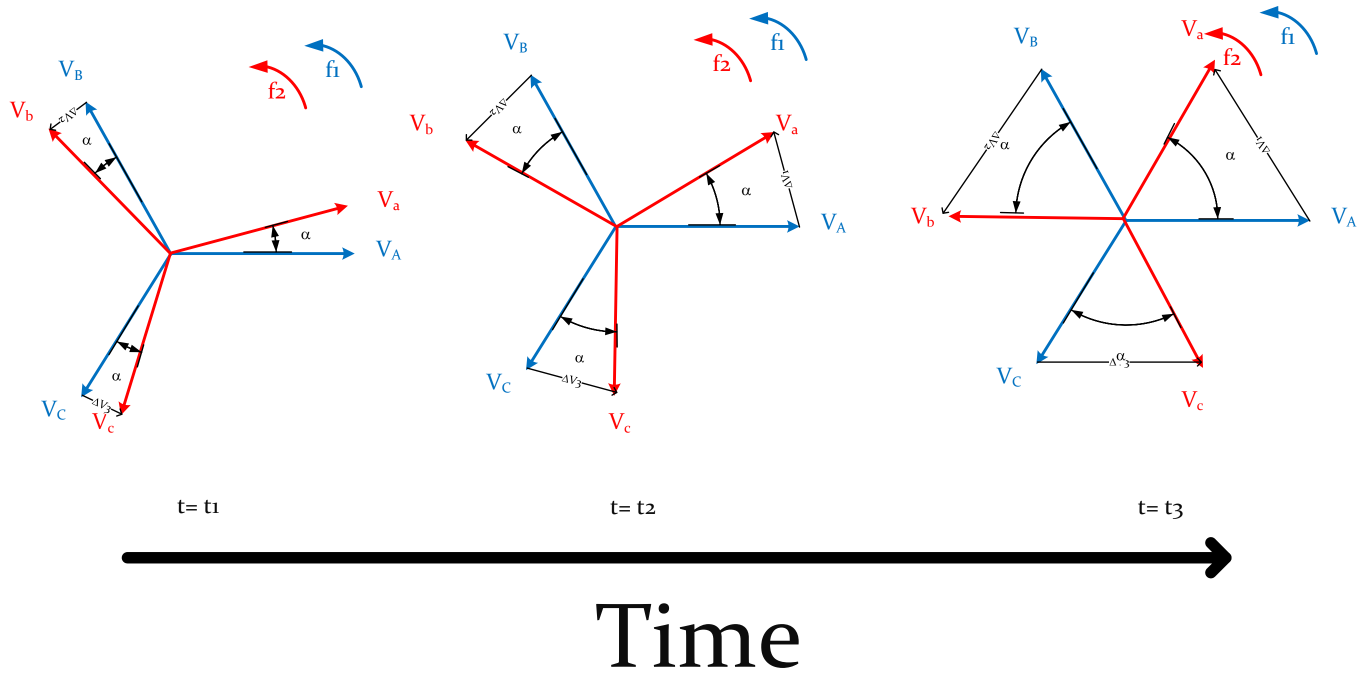


Note

$$\Delta V_1 = \Delta V_2 = \Delta V_3$$

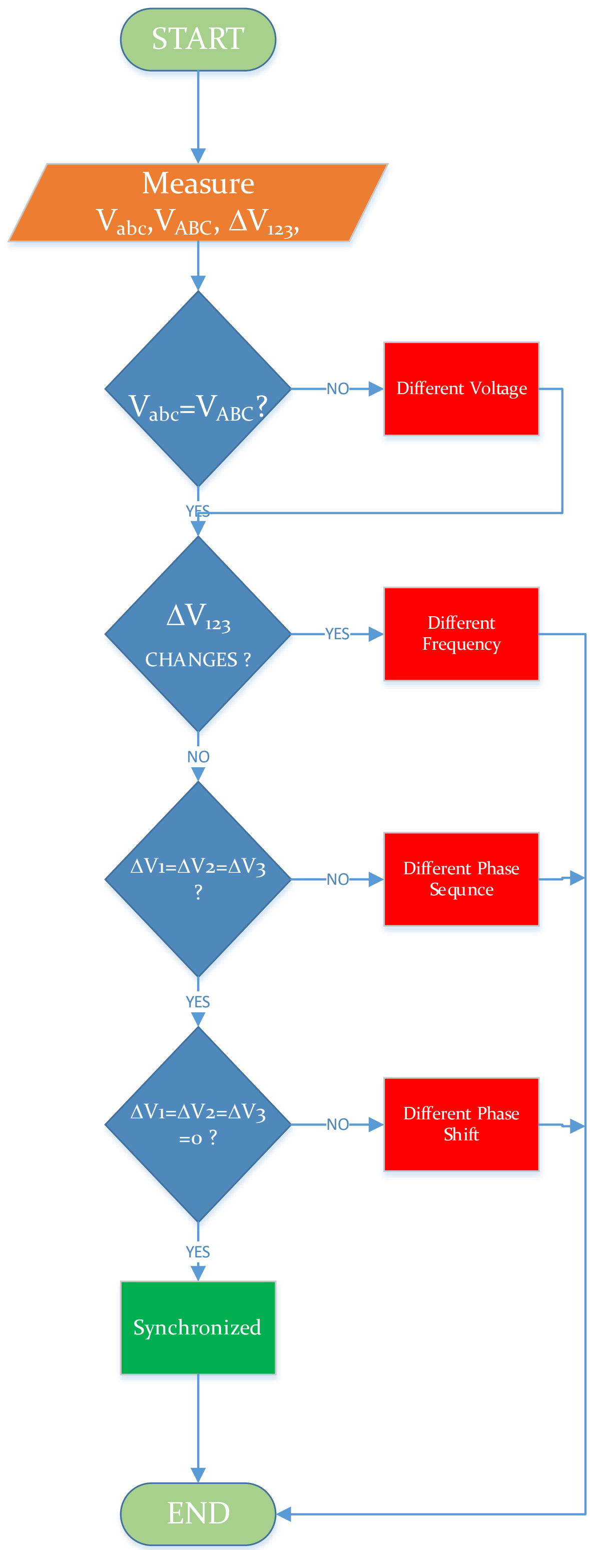
But VA > Va and VB > Vb and VC >Vc

9.6.4 Different Frequency



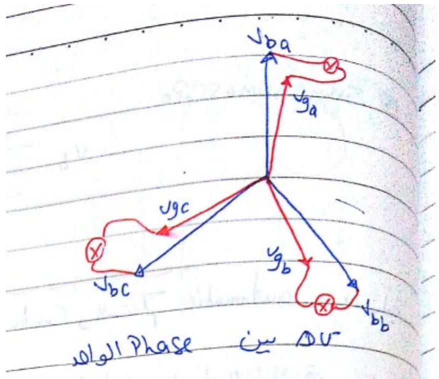
Different speeds f1 and f2 , so ΔV will increase and decrease

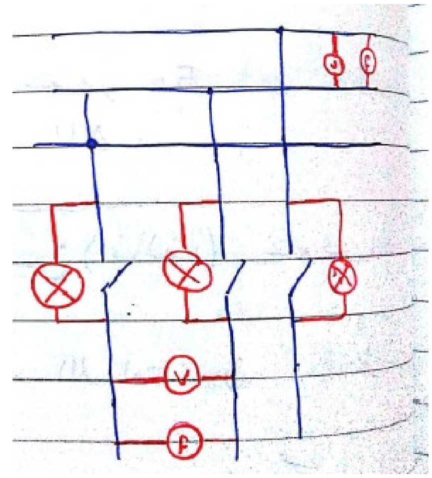
9.7 Flow Chart for Vector Representations



9.8 3-lamps method (Bright and Dark Lamps)

From previous flow chart – you can tell sync or not and why from V and $\Delta V = [V_{1aMax}\sin(\omega t) - V_{2aMax}\sin(\omega t + \beta)]$





A common method to calculate ΔV is the **3 lamps or Bright and Dark lamps**

Lamps (a-A , b-B , c-C)

If Synced

All 3 lamps are off (DARK!)

If not

lamps are BRIGHT !

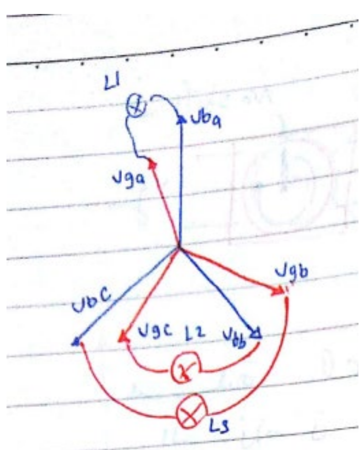
Cause	Seen
phase changes between the two systems	, the light bulbs first get bright (large phase difference) and then get dim (small phase difference
have the same **phase sequence.**	all three bulbs get bright and dark together,
have the **opposite phase sequence**	bulbs brighten in succession,

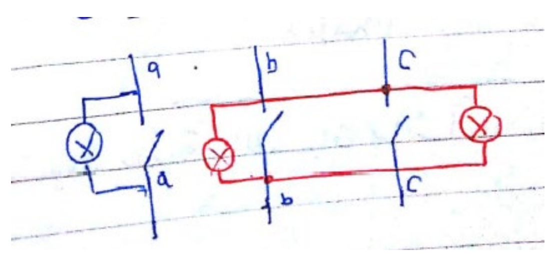
Another Method

Lamps (Cb – bc – aa) ?!?!!

If Synced

- One off , other two BRIGHT

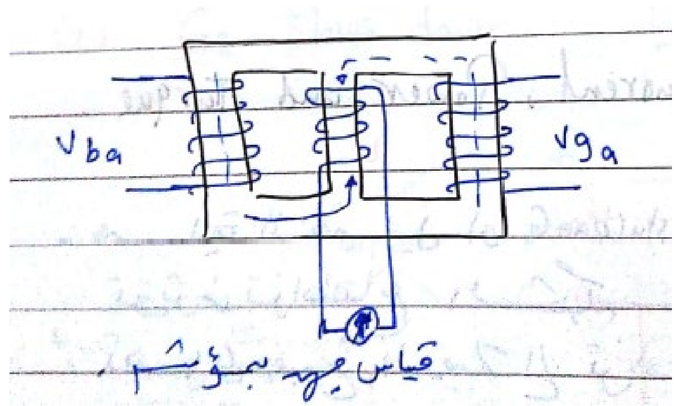




Advantage : Easy , Handy

Disadavntage : Depends on Brightness ! Eye ! واحنا اصلاً بنشوف قدامنا بالعافيه

9.9 Synchronizing Transformer



If Synced the Lamp will be off as MMF(A) = - MMF(a)

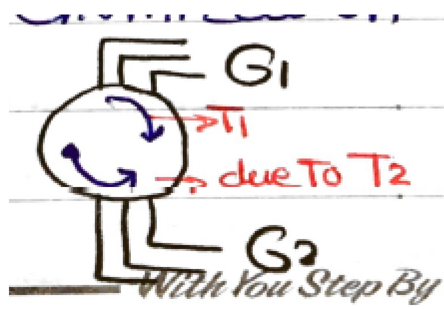
9.10 Synchro scope

Old theory uses small IM ,fed from 2 sources

The two torques tend to rotate it in difeerent direction

Id $\Delta T = Value \ \rightarrow Rotates\,!\,(not\ Sync)$

If $\Delta T = \ 0 \qquad \rightarrow Stops \qquad (in\ Sync)$



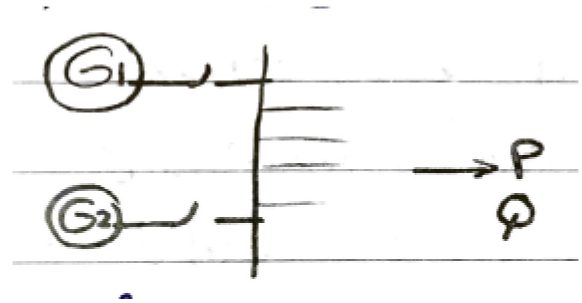
Notice, though, that a synchroscope checks the relationships on only one phase. It gives no information about phase sequence.

Notice, though, that a synchroscope checks the relationships on only one phase. It gives no information about phase sequence

10 LOAD SHARING

We have G_1, G_2 *and Load* (P, Q) each generator contributes with P and Q as they both cover the Load requirements.

$$P_{total} = P_{G1} + P_{G2} \ , Q_{total} = Q_{G_1} + Q_{G_2}$$



10.1 (1) Active Power Sharing

ACTIVE POWER SHARING (P) IS ACHIEVED THROUGH CHANGE IN FUEL AND GOVERNER

Stand Alone	$Fuel \uparrow \Rightarrow \omega \uparrow \Rightarrow V \ \uparrow \Rightarrow f \uparrow$
Grid Connected	$Fuel \uparrow \Rightarrow increases\ active\ power\ SHARING$

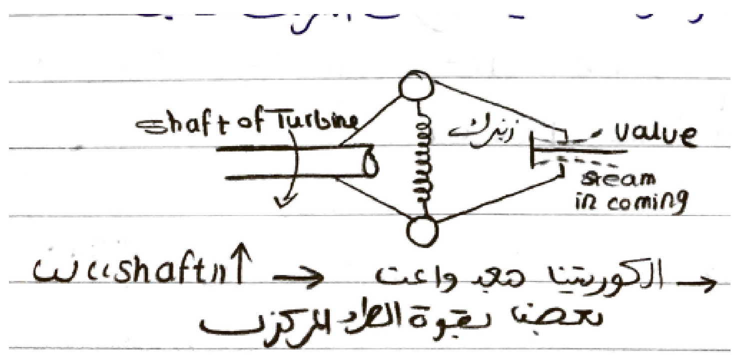
That's why we need speed control and income fuel control

10.1.1 Governer

It's function is to increase fuel to keep const speed

So if $\omega \uparrow$ the two balls will get away from centrifugal force , which will let less steam in which in turn will make $\omega \downarrow$ until it gets to it's set point .

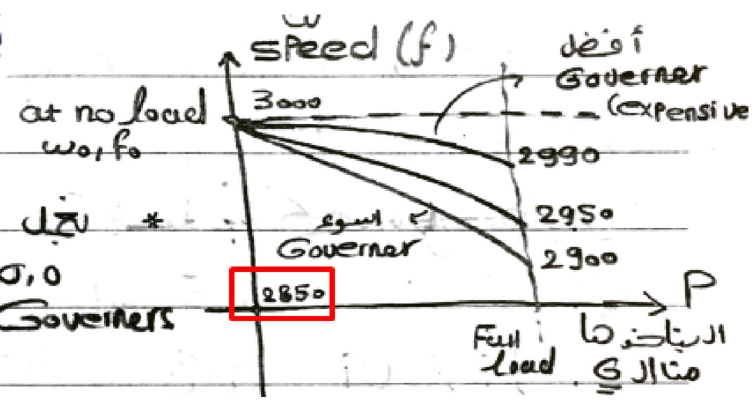
And VICE VERSA !!! JUST MALE ω at setpoint



Governer parametes

- Set point at no load
- Speed at full load

* نجعل Focus منبثث الرسمة من
٥،٥ لنفصلو ٥،٥ فتلاقى كدال
Governers أفقيه



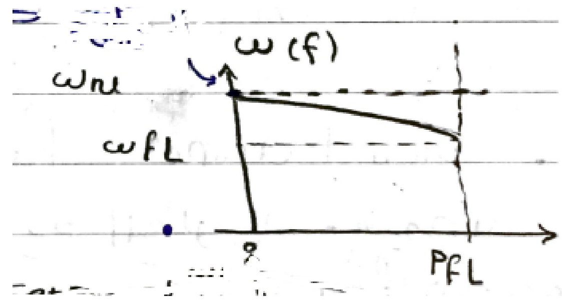
10.1.1.1 Speed Drop

$$Speed\ Drop = \frac{n_{nl} - n_{fl}}{n_{fl}} = \frac{f_{nl} - f_{fl}}{f_{fl}} = \frac{\omega_0 - \omega_{fl}}{\omega_0} * 100$$

$$SD \quad 2\% \rightarrow 4\ \%$$

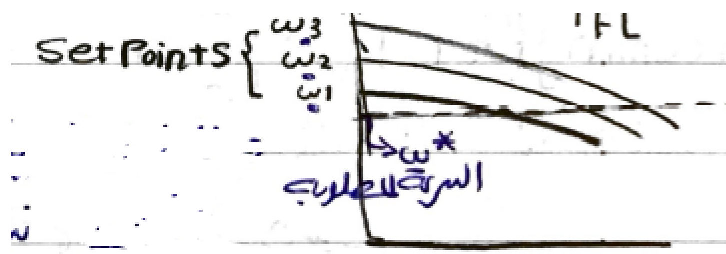
$$S_p = \frac{\Delta P}{\Delta f} = \frac{P_2 - P_1}{f_2 - f_1} = \frac{P_{fl} - P_{nl}}{f_{fl} - f_{nl}} \rightarrow -ve\ slope$$

$$P = S_p(f_{nl} - f)$$



With grid $P = S_p\left(f_{nl} - f_{sys}\right)$

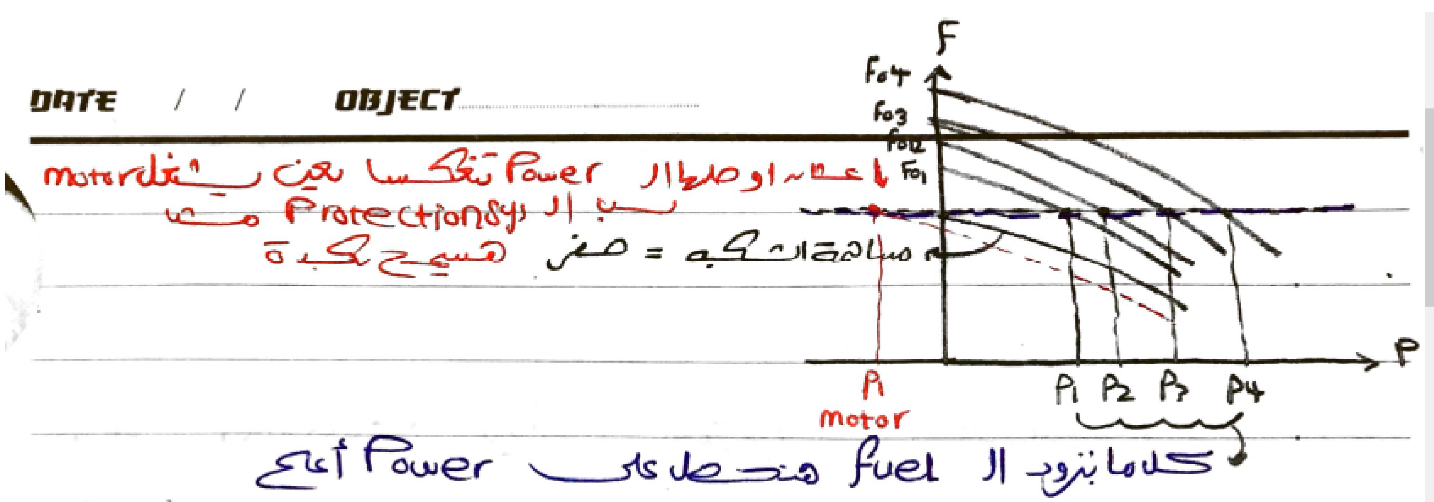
To regain the reference speed after loading we increase fuel, so that the set point shifts up and get at $\omega_{reference}$ at Loading Condition



CONCLUSION :
TO INCREASE P(ACTIVE POWER) INCREASE MECHANICAL POWER INPUT !!

10.1.1.2 EX: Generator with Grid

When connected to grid it will make generator operate at it's frequency and voltage, and we use the (f,P) curve to get how much will the generator share P with the grid



	stand alone	grid Connected
fuel	Speed ↑ & f ↑	P_g ↑
Excitation	V_t ↑	Q_g ↑

<u>Summary (STAND ALONE)</u>

when a single generator is operating alone, the

real power P and reacti ve power Q supplied by the generator will be the amount

demanded by the load attached to the generator- the P and Q supplied cannot be

controlled by the generator's controls. Therefore, for any given real power, the

governor set points control the generator's operating frequency fe and for any given

reactive power, the fie ld current controls the generator's terminal voltage VT.

To summarize, when a generator is operating by itself supplying the system

loads, then

1, The real aod reactive power supplied by the generator will be <u>the amount demanded by the attached load.</u>

2. The <u>governor</u> set points of the generator will control <u>the operating frequency</u>

of the power system.

) 3. The field current (or the field regulator set points) controls the terminal voltage

of the power system.

This is the situation found in isolated generators in remote field

10.1.1.3 Stability

So we now know that the load P is shared between generating units

UNSTABILITU CAUSED BY

1- **Increasing Load too high**

$$P\ (const) = P_{G_1} \uparrow\ + P_{G_2} \downarrow$$
$$but\ if\ P_{load}\ increase\ upove\ capability\ of\ both\ generators$$

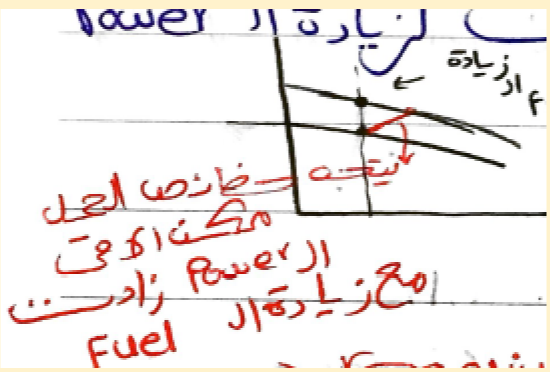
$$UNSTABLE \rightarrow\ P\ (const) > P_{G_1}\ + P_{G_2}$$

2- **Also decreasing power very Low**

Will cause instability due to unstable flame and fuel or we will need to get some generating units out of service

NOTE

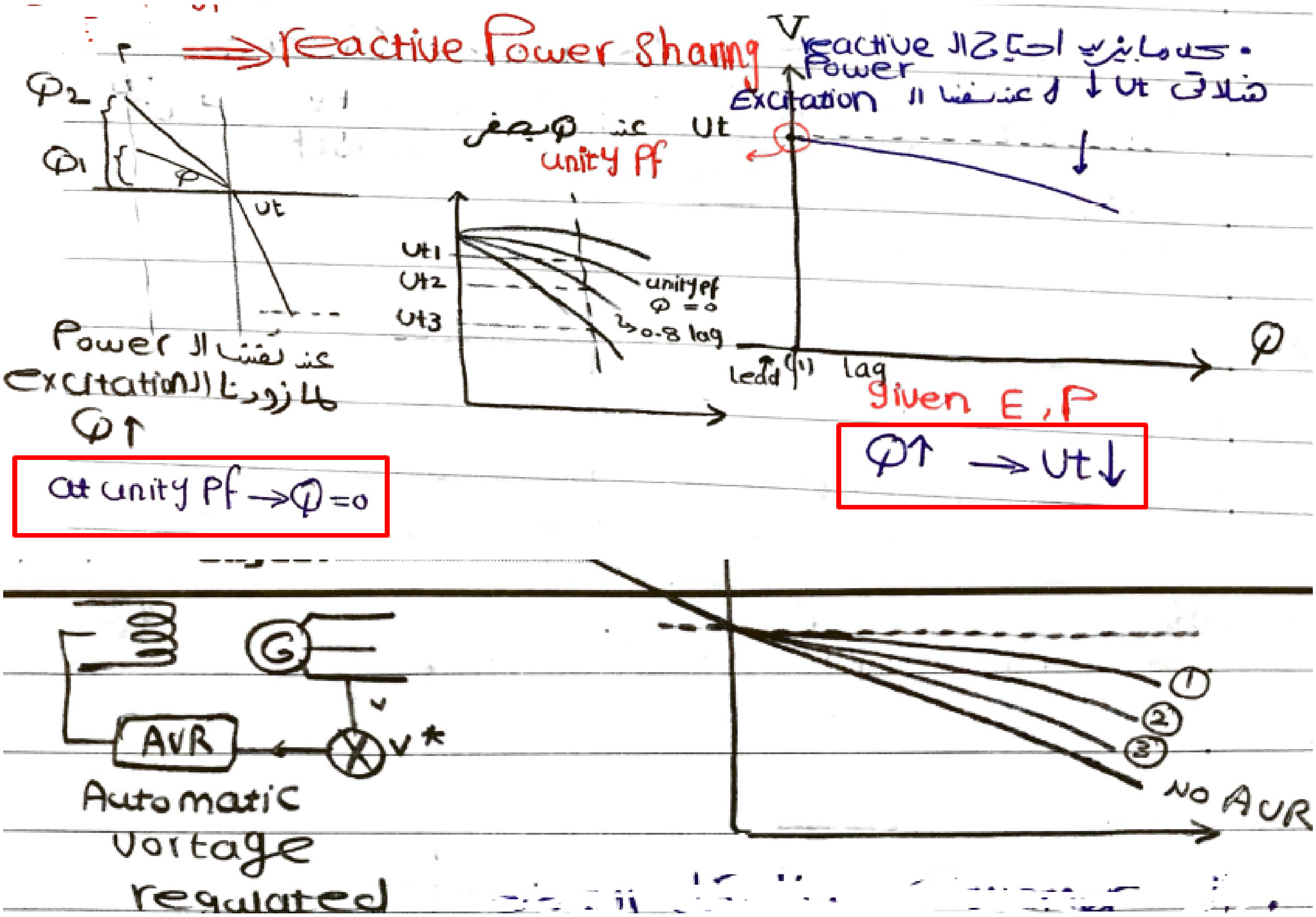
If load nature (affected by frequency) so when we increase Fuel to increase Power it's required Power changes , so it takes different path



10.2 (2) Reactive Power Sharing

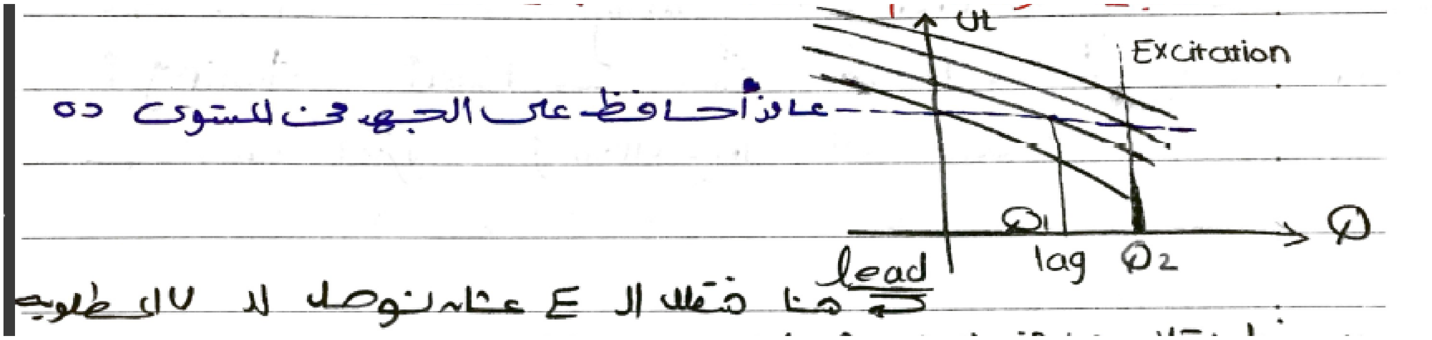
When $Q_L \uparrow$ then $V_t \downarrow$ for same E (excitation)

So we need to increase Excitation to provide load with its required (Q reactive) at same Vt



Automatic Voltage Regulator	Controls Voltage at Machine Terminals
Governer	controls active power share (grid) and frequency (Stand alone)

If we need to exact Q at Exact voltage we night need to decrease Q as follows



Note :

we might enter to the Lead , it's less dangerous than motor (P)

P sharing	FUEL	,f ,speed , mechanical
Q sharing	EXCITATION	Vt ,PF

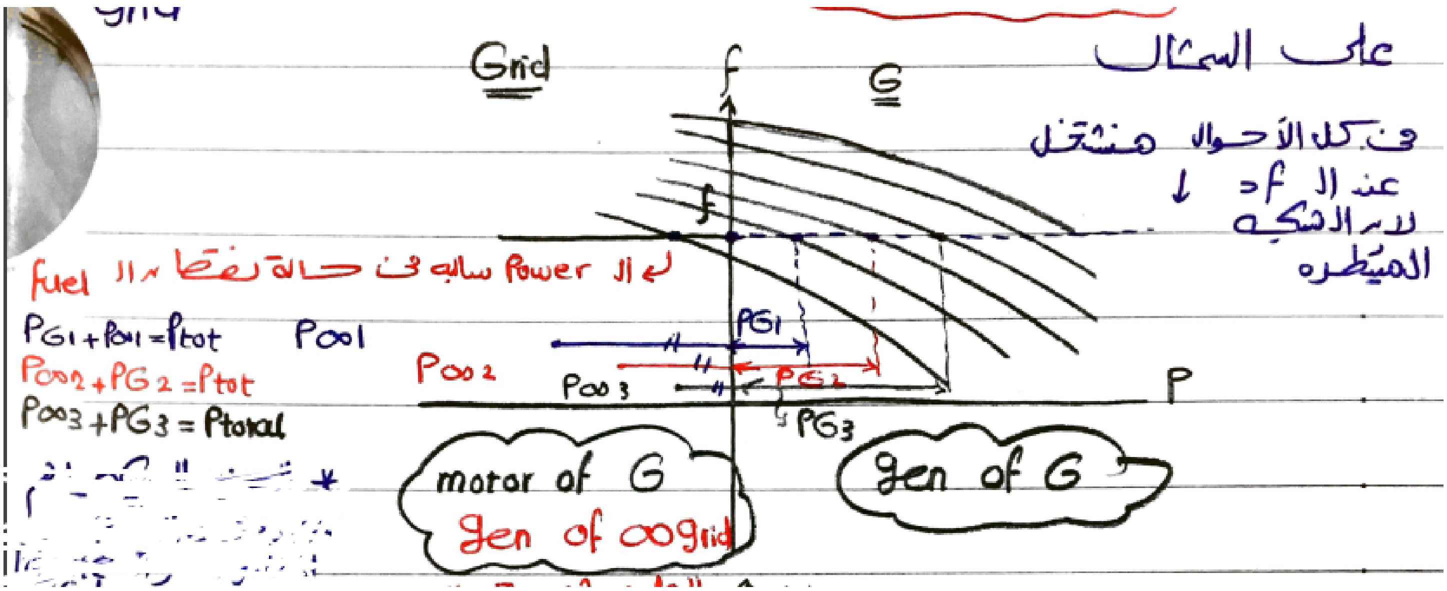
10.3 Load Sharing Between Generator and the Grid

10.3.1 Grid Definition :

It's a very strong source (const Vt and f) , and shares the load with the generator, by giving the generator a load matching its capability and the grid holds the rest , can generate or consume any amount

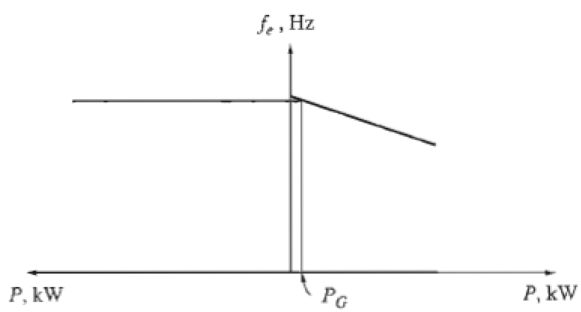
To calculate sharing we use "HOUSE DIAGRAM "

10.3.2 Active Power



It can be

1- Floating (supplys small P and Q=0)
2- Motoring (consuming P)



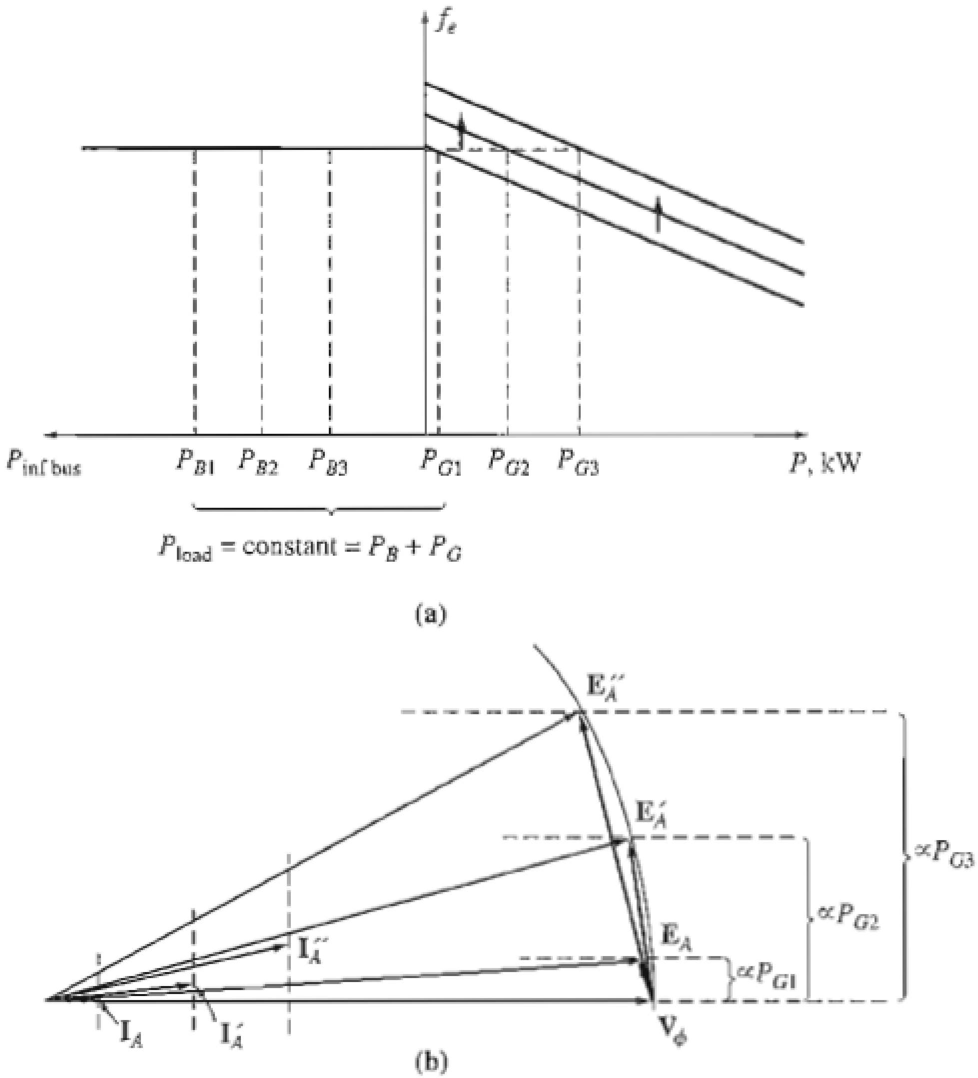
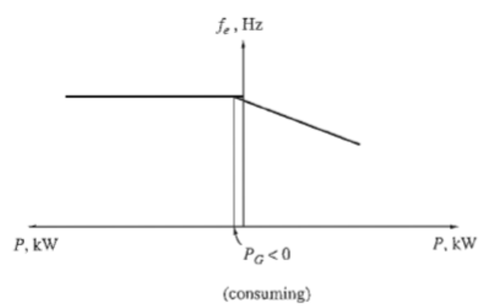
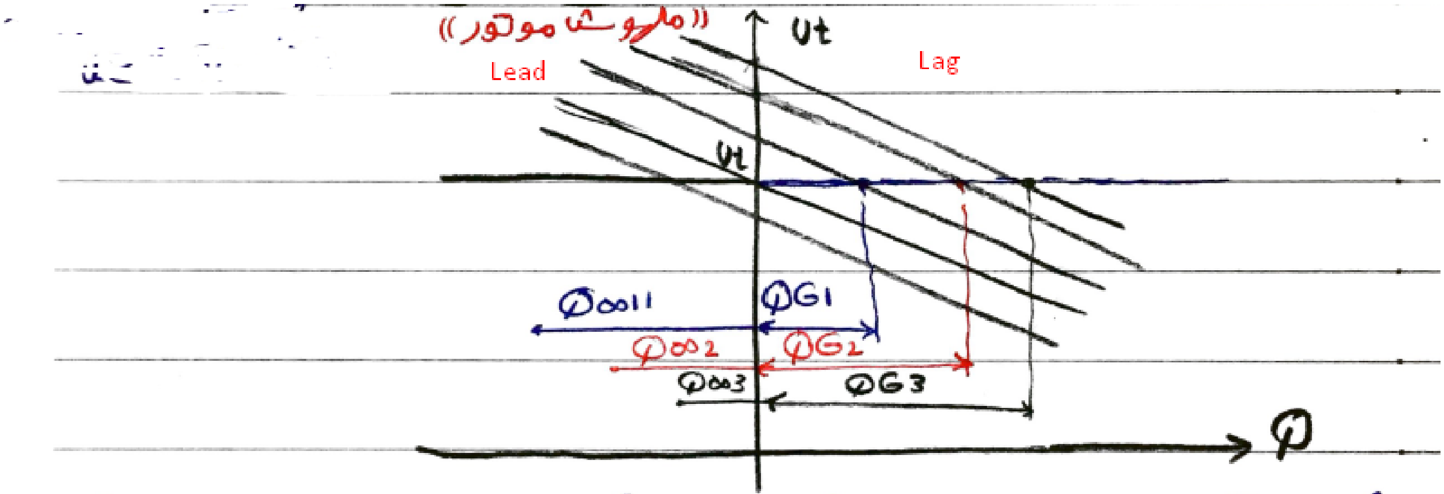


FIGURE 4–36

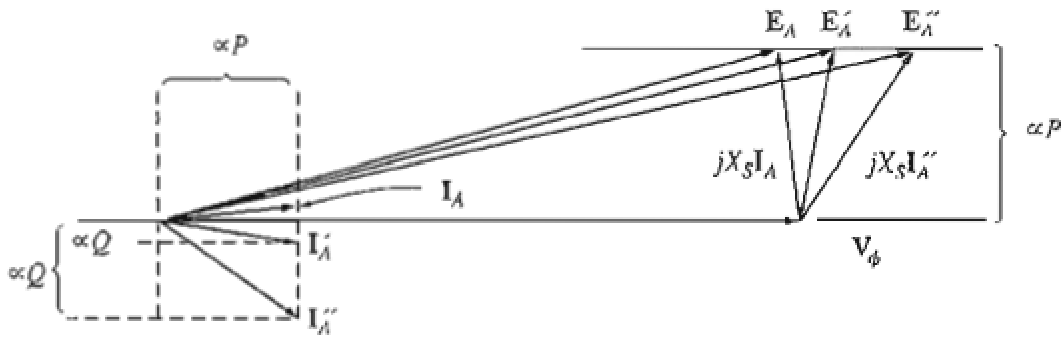
The effect of increasing the governor's set points on (a) the house diagram; (b) the phasor diagram.



10.3.3 Reactive Power



$$\Phi_{\infty 1} + \Phi_{G1} = \Phi_{\infty 2} + \Phi_{G2} = \Phi_{G3} + \Phi_{\infty 3} = \underline{\Phi_{total}}$$



<u>the angle of jXsI$_A$ changes</u> as shown, and therefore the **<u>angle and magnitude of I$_A$ change.</u>**

So it affects $Q(I_A \sin\theta)$

so $I_f \uparrow$ $\; then\ Q\ \uparrow$

<u>FOR GRID</u>

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

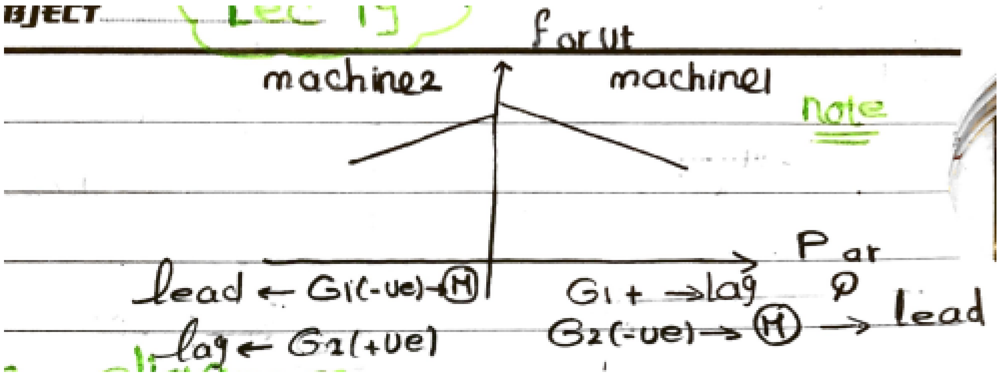
2. The governor set points of the generator control the real power supplied by the generator to the system.

3. The field current in the generator controls the reactive power supplied by the generator to the system.

10.4 House Diagram

10.4.1 Two machines

Each machine works in its half as (Lag , Generator) and at the other half as (Lead , Motor)

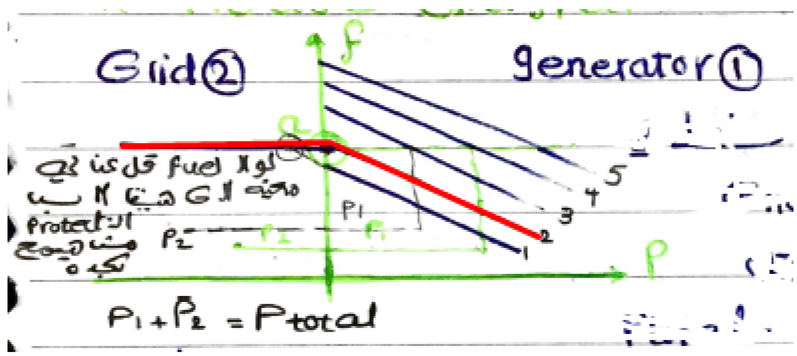


10.4.2 At no load (ACTIVE)

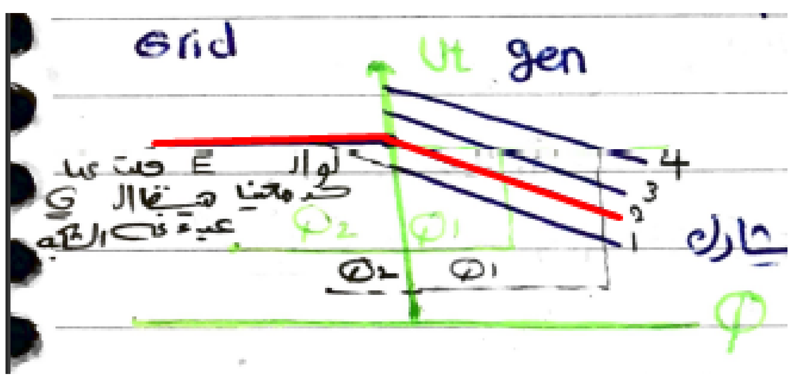
For Grid (50 Hz , 220 V) for example

If fnl= 50 , (line 2) then the machine won't contribute any active Power

$$P_t = P_2$$



10.4.3 At no load (REACTIVE)



Then for Line 2 , Vnl =220 , machine wont' give any Q to the grid

$$Q_t = Q_2$$

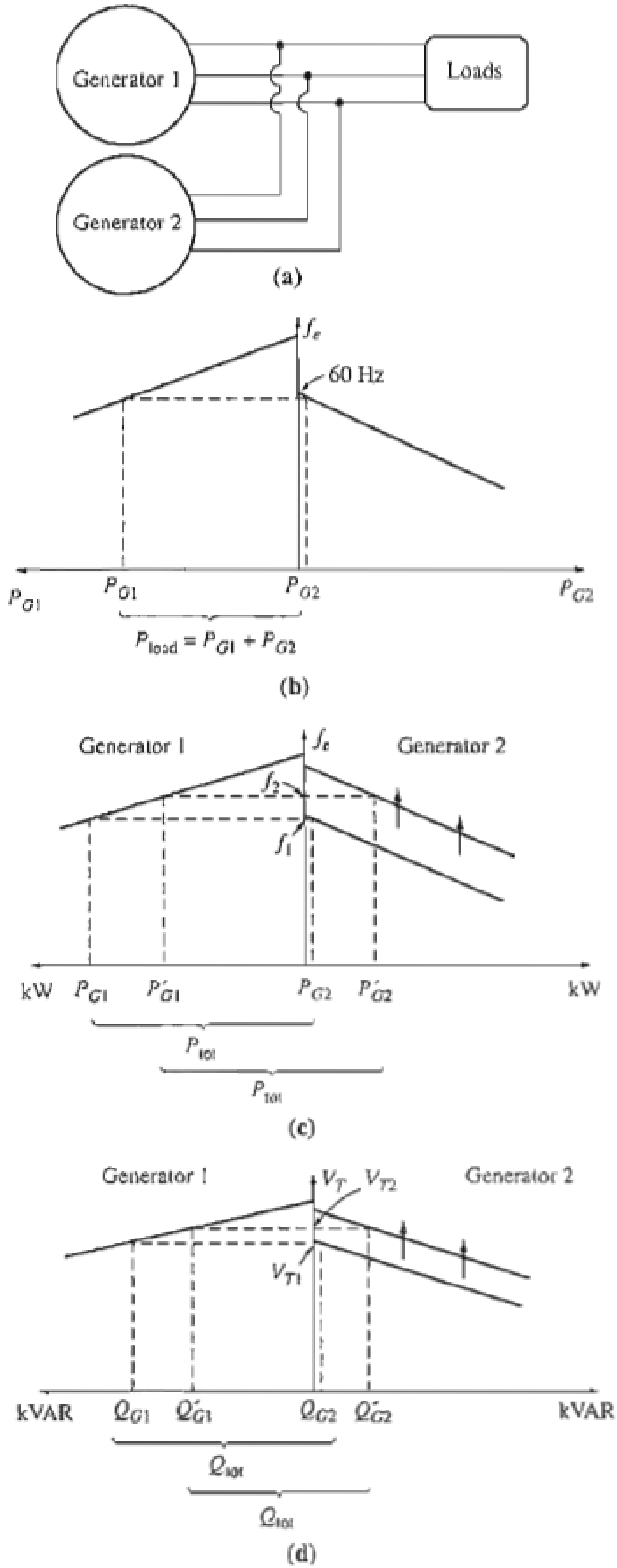
At line (1) machine is a burden on the grid and is fed by Q

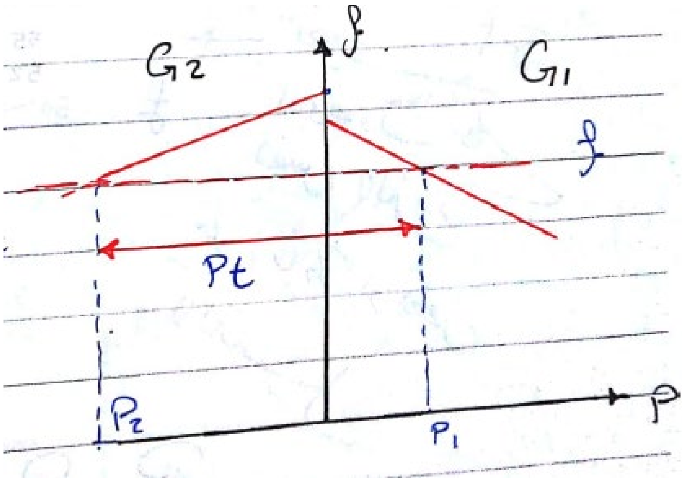
Motor (Lead) - Gives Q
Generator (Lead) - Takes Q

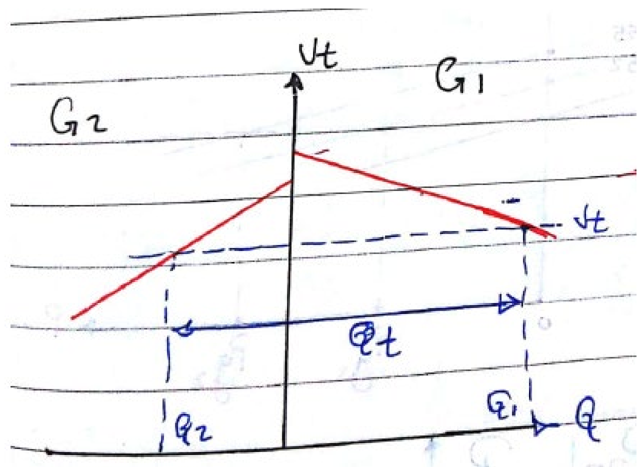
NOTE :

We prefer to increase fnl and Vnl
so that when losses of connection reduces them we won't enter the (Motor or Lead) regio

10.5 Sharing ch/c (with other generator of same size)







- Each motor has a Ch/c Line or curve (Might be the **same (same Slope and Set Point(NoLoad))**
- We have a const Pt , which is shared between them

So when we put it, we have only one loading level

we know

1- the **<u>frequency</u>** at which each motor will operate and

2- **<u>P contributed</u>** by each generator

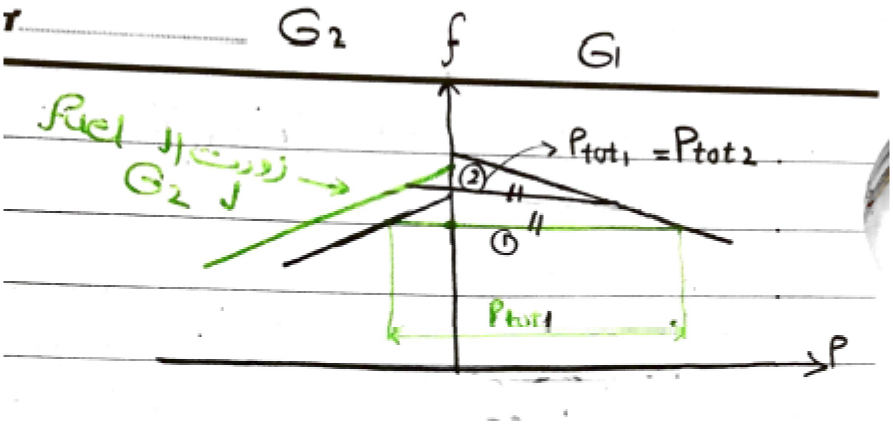
Note

HOW WOULD <u>DECREASING</u> LOAD CAUSE INSTABILITY ?

$$P \downarrow \rightarrow \ \omega \uparrow \rightarrow f \uparrow$$

So if F_{nl} for one generator is smaller than the new f, it will operate as a motor ‼

10.5.1 What happens if we increase Fuel (frequency)



increase in governor set points on one of them

1. Increases the system frequency.

2. Increases the power supplied

If we increase frequency for one generator , while Ptot is the same

The Sharing , will change (it will take more) at new frequency

VICE VERSA

So,

$$f_{1,2} \uparrow \quad then \; f_{group} \uparrow$$
$$f_{1,2} \downarrow \quad then \; f_{group} \downarrow$$

10.5.2 SAME FOR increase (Excitation)(Vt)

When we increase E for one generator it will contribute with more Q

field current of G2 is increased,

1. The system terminal voltage is increased.

2. The reactive power Q supplied by that generator is increased, while the reactive power supplied by the other generator is decreased.

10.5.3 Changing active power sharing without affecting frequency

NOTE

According to nature of load

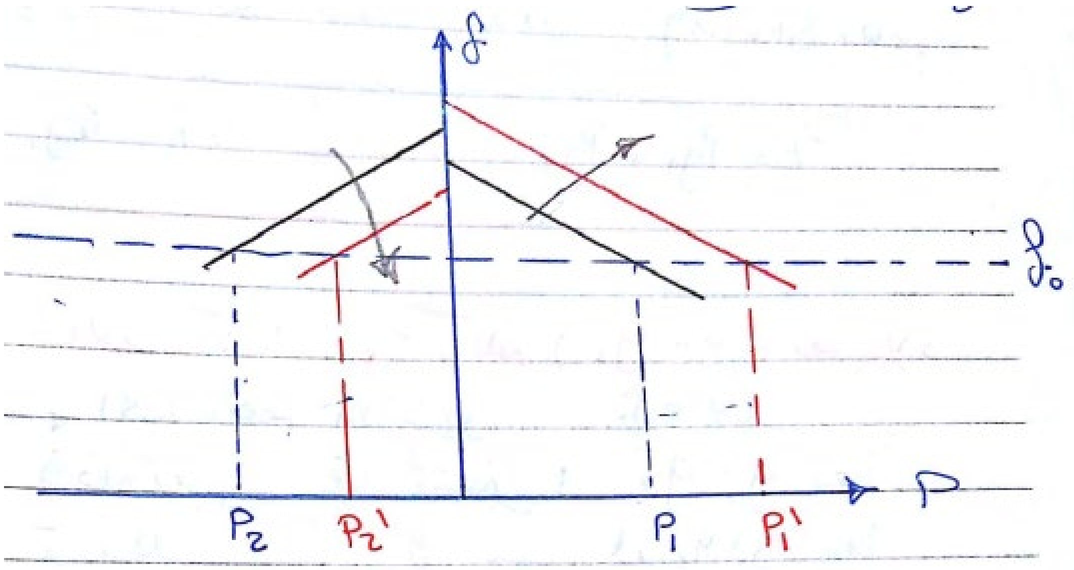
<u>Power</u> is affected by changing <u>frequency</u>

<u>Reactive</u> Power is affected by changing <u>Vt</u>

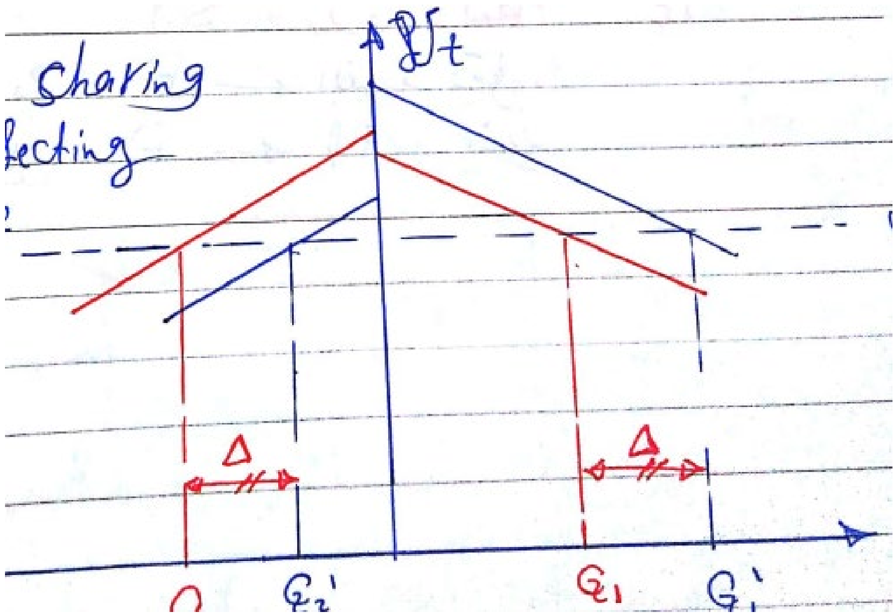
But we assume it's the same

To keep it at the same frequency and same Ptot

We increase f2 while decrease f1



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

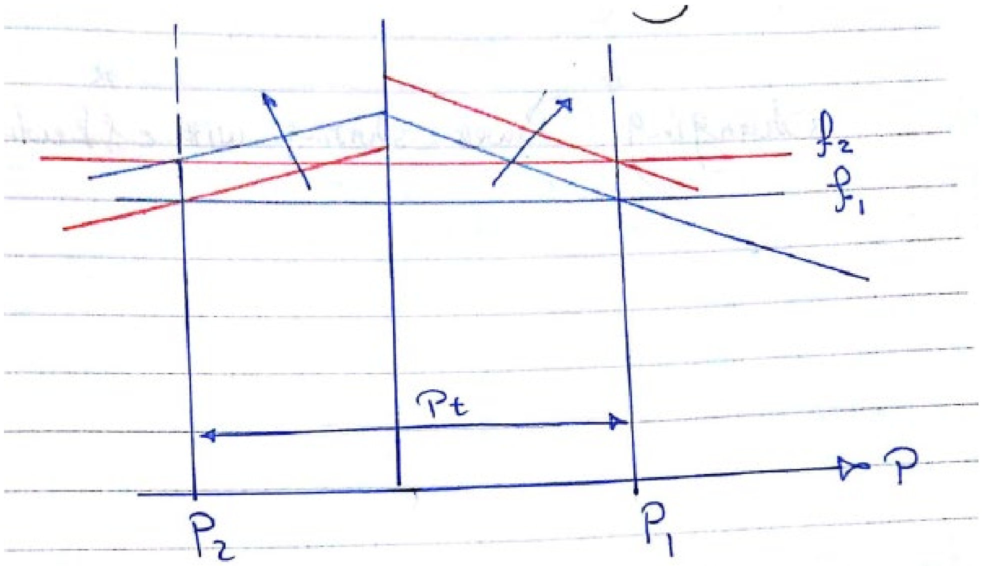


Similar for same Vt, by increase V2 and decrease V1

$$Q_{tot} = Q_1 + Q_2 = Q_1' + Q_2'$$

10.5.4 Shifting frequency without affecting sharing (same Ptot)

Increase f1 and f2 at the same time by same amount



Similar to increase Vt, by increase V2 and increase V1

You can easily change system frequency without having same load sharing ,
increase f1 only or f2 only or f1 and f2

10.5.5 Change Pt

$$P_t \uparrow \Rightarrow f \downarrow$$

$$P_t \downarrow \Rightarrow f \uparrow$$

SUMMARIZE:

1. The system is constrained in that the total power supplied by the two generators together must equal the amount consumed by the load. Neitherfys nor VT is constrained to be constant.

2. To adjust the real power sharing between generators without changing fys' simultaneously increase the governor set points on one generator while decreasing

the governor set points on the other. The machine whose governor set point was increased will assume more of the load.

3. To adjust fys without changing the real power sharing, simultaneously increase or decrease both generators' governor set points.

4. To adjust the reactive power sharing between generators without changing VT , simultaneously increase the field current on one generator while decreasing the field current on the other. The machine whose field current was increased will assume more of the reactive load.

5. To adjust Vr without changing the reactive power sharing, simultaneously increase or decrease both generators' field currents.

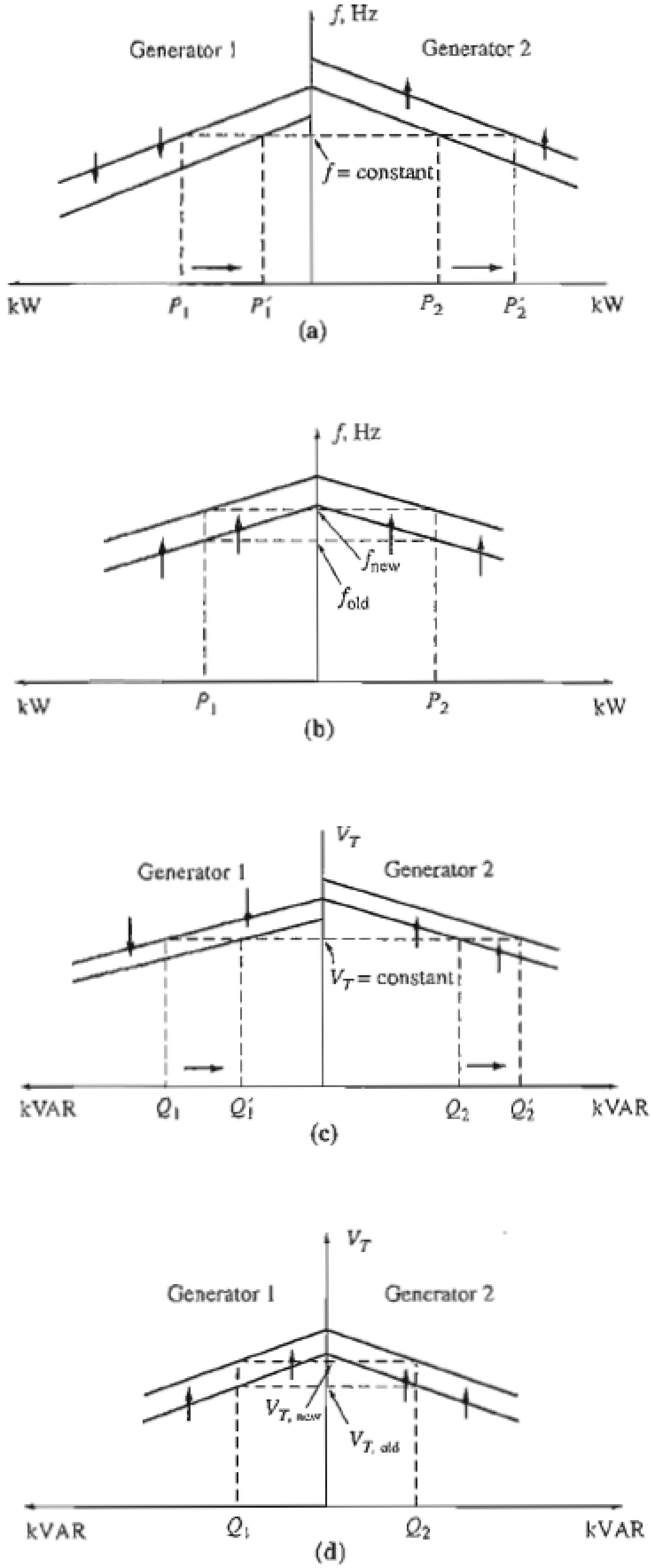
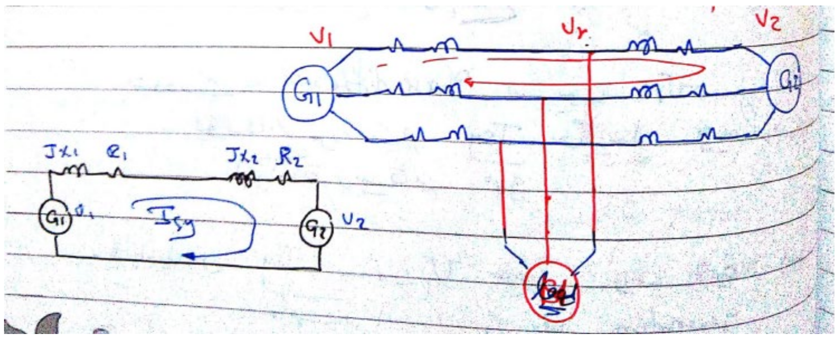

f, Hz
Generator 1
Generator 2
f = constant
kW
P_1
P_1'
P_2
P_2'
kW
(a)
f, Hz
f_{new}
f_{old}
kW
P_1
P_2
kW
(b)
V_T
Generator 1
Generator 2
V_T = constant
kVAR
Q_1
Q_1'
Q_2
Q_2'
kVAR
(c)
V_T
Generator 1
Generator 2
$V_{T, new}$
$V_{T, old}$
kVAR
Q_1
Q_2
kVAR
(d)

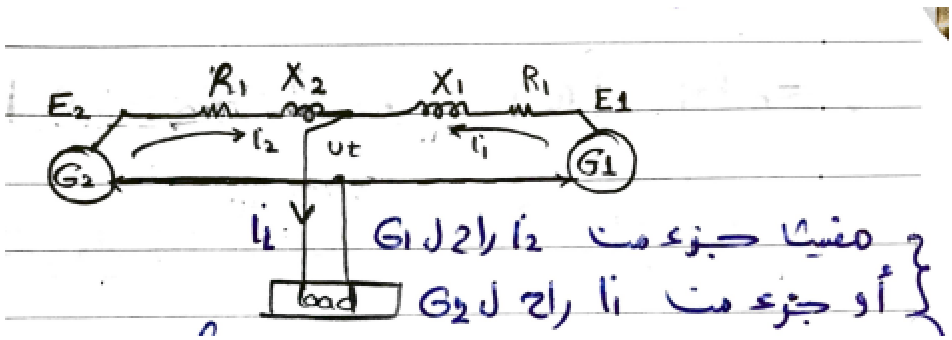
FIGURE 4–40

11 SYNC FROM DISTURBANCE

When disturbance occurs

How does the system gain back it's synchronism



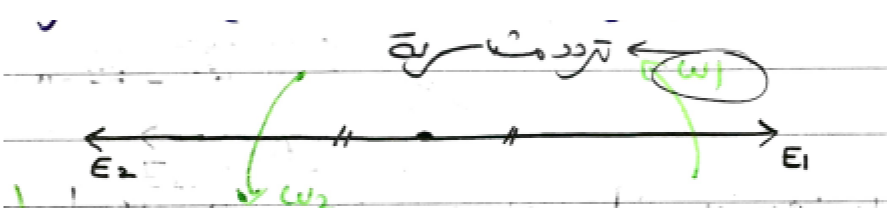


11.1 Synchronized system

For sync. Has E_1 and E_2

1-same mag,

2- same speed (freq))



So there will be no current from G1 to G2 or vice versa

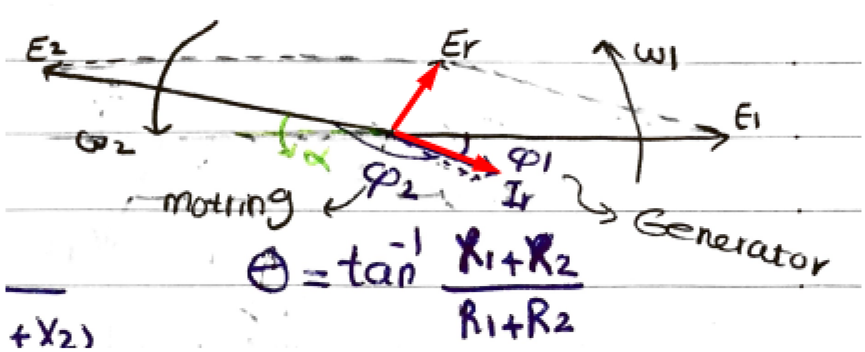
All current are sent to the load

There is no Circulating current as:

$$I_r = \frac{E_1 - E_2}{(R_1 + R_2) + j(X_1 + X_2)} \; (circulating\ current)$$

11.2 Fuel Disturbance

Now assume fuel increased or decreased in one of them, then frequency (speed) of one will increase and the other will decrease



$$I_r = \frac{(\overline{E_1} + \overline{E_2})}{(R_1 + R_2) + j(X_1 + X_2)} = \frac{E_r}{(R_1 + R_2) + j(X_1 + X_2)}$$

And shifted by

$$\theta = \frac{X_1 + X_2}{R_1 + R_2}$$

M1 (with acute angle) : GENERATOR

M2 (with wide angle) : MOTOR

So , M2 speed will increase , and load on M1

Which makes there speed be the same again , regain **SYNCHRONISM**

So we call

$$I_r\ (synchronizing\ current)$$
$$produces\ Sync\ Power \rightarrow Synch\ T$$

note لو كان الـ G ← speeds up

فالـ E2 هيزل لتحت

و نفس الكلام لـ G1 , G2

$$P_{sy} = P_1' - P_1$$

$$P_{sy} = \frac{3E_f V_t}{X_s} \sin\delta - \frac{3E_f V_t}{X_s} \sin(\delta + \alpha)$$

Say E the same

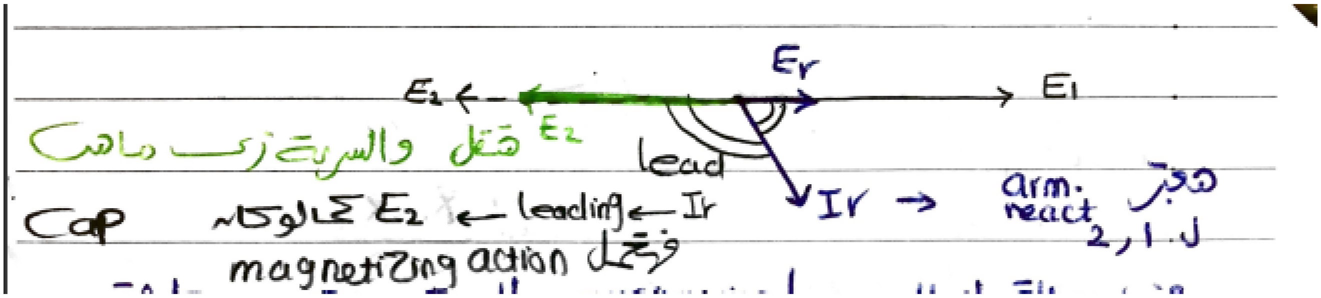
$$P_{sy} = \frac{3E_f V_t}{X_s} [\sin\delta - \sin(\delta + \alpha)]$$

For small α

$$P_{sy} = \frac{3E_f V_t}{X_s} \alpha \cos\delta$$

11.3 Excitation Disturbance

One generator (G2) Excitation decreases



Its length will decrease at same speed

This current (represent as Armature reaction for both Machines)

$$E_r = E_1 - E_2$$

This Ir wil

Acute angle -> Lag -> cause DEMAGNETIZATION action to M1

Wide angle -> Lead -> cause MAGNETIZING action to M2

Cause $E_2 \uparrow$ $and\ E_1 \downarrow$

Until they are $E_1 = E_2$ and synchronism is regained to the system

DESIGN OF SYNCHRONOUS MACHINE

12 DESIGN OF ALTERNATOR

12.1 Power Equation

$$S_n = m\, E_{ph} I_{ph} * 10^{-3}$$

$$E_{ph} = 4.44\, f\, \phi\, T_{ph}\, K_w$$

$$f = \frac{P n_s}{2}$$

$$\therefore S_n = m * \left(4.44\, f\, \phi\, T_{ph}\, K_w\right)\left(I_{ph}\right) * 10^{-3}.$$

$$S_n = 1.11 * k_w * (P\phi) * \left(2mT_{ph}I_{ph}\right) * n_s * 10^{-3}$$

$$I_c = I_{ph}$$

$$\boxed{I_c = a_{parallel}\, I_{ph}}$$

$$\overbrace{Z_a}^{\text{total armature conductor}} = 2\, m\, T_{ph} = 2 * 3 * T_{ph}$$

$$total\ elecctric\ loading = I_c Z_a = 2\, mT_{ph} I_c = \overbrace{ac}^{\text{specific electric loading}} * \pi D$$

$$total\ magnetic\ loading\ = P\phi = \overbrace{B_{av}}^{\text{specific magentic loading}}\ \pi DL$$

$$S_n = 1.11 * k_w * (P\phi)(I_c Z_a) * n_s * 10^{-3}$$
$$S_n = 1.11 * k_w * (\pi DL * B_{av})(\pi D * ac) * n_s * 10^{-3}$$
$$S_n = (11\, B_{av}\, ac\, k_w * 10^{-3}\,) * D^2 L\, n_s$$
$$S_n = C_o\, D^2 L\, n_s$$

$$C_o = \ 11\, B_{av}\, ac\, k_w * 10^{-3}$$

12.1.1 Peripheral Velocity/Speed

$$V_a = \pi D\, n_s$$

$$\therefore \quad D = \frac{V_a}{\pi n_s}$$

$$S_n = (11\, B_{av}\, ac\, k_w * 10^{-3}\,) \left(\frac{V_a}{\pi n_s}\right)^2 \; L\, n_s$$

$$S_n = (1.11\, B_a\, ac\, k_w * 10^{-3}) * \frac{V_a^2}{n_s}\, L$$

12.2 Choice of (Bav) Average gap flux density

Factors affecting the choice of Bav :

Iron Loss	$P_{iron} \propto B_{av}^2$
Voltage	$V \propto \dfrac{1}{B_{av}}$
Stability	There's some Bav which if the machine can't provide it won't operate as wished and will get to the saturation before providing enough torque to withstand load change

<u>Values of Bav for **conventionally cooled generator**</u>

$$B_{av} = 0.52 : 0.65\ \frac{wb}{m^2} \qquad\qquad for\ salient\ pole\ machined$$

$$B_{av} = 0.54 : 0.65\ \frac{wb}{m^2} \qquad\qquad for\ turbo\ alternators\ (cylindrical)$$

12.3 Choice of (ac) ampere conductor per meter

Factor affecting choicr of ac

Copper-Losses and Temperature rise	$P_{cu} \propto ac$
Voltage	$V \propto \dfrac{1}{ac}$
Synchronous reactance	$X_s \propto ac$
Stray Losses	$P_{stray} \propto \ ac$

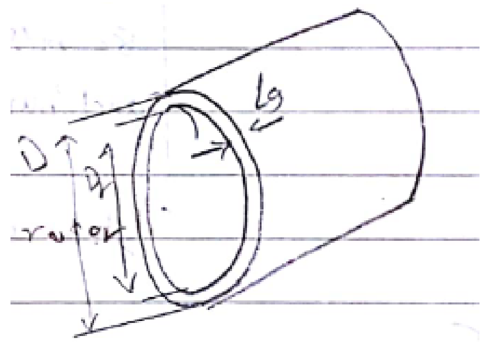
<u>Value of ac</u>

$$ac = 20000 : 40000\ \frac{wb}{m^2} \qquad\qquad for\ salient\ pole\ machined$$

$$ac = 50000 : 75000\ \frac{wb}{m^2} \qquad\qquad for\ turbo\ alternators\ (cylindrical)$$

12.4 Design of salient-pole machine

$$\overbrace{D}^{\text{Stator Diameter}} \cong \overbrace{D_r}^{\text{Rotor Diameter}}$$



Choice of D depend on

1- Poles Type (Rect , Round)
2- Permissible Peripheral Velocity (Va)

12.4.1 Poles Types

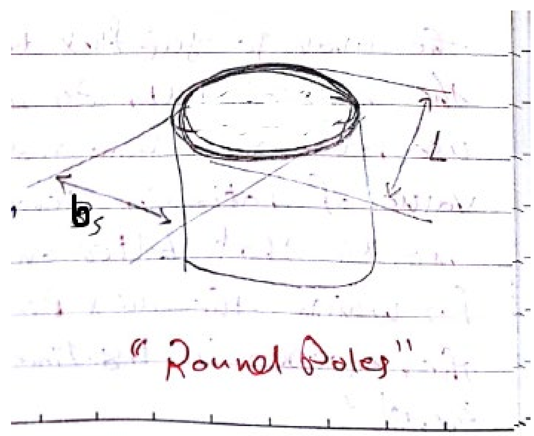
1- Round Poles (Square)
2- Rectangular Poles

12.4.1.1 Round Poles

With square pole shoes

for round $b_s = L$

$$\frac{pole\ arc}{pole\ pitch} = \frac{b_s}{\tau_p} = 0.6 : 0.7$$

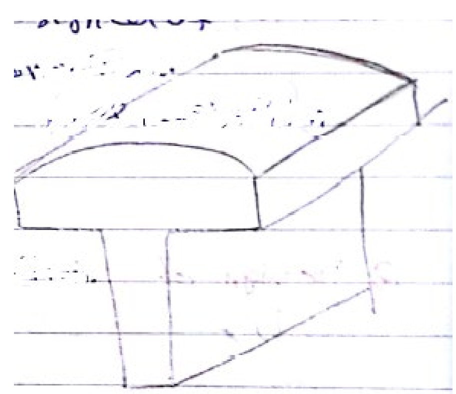


12.4.1.2 Rectangular Poles

$$\frac{b_s}{\tau_p} = \frac{L}{\tau_p} = 1 : 5$$

$$but\ for\ economical\ \frac{b_s}{\tau_p} = 1:3$$

12.5 Permissible Peripheral Speed (Va)



—1 Rectangular Pole

50 m/s	For **Bolted** on poles construction
80 m/s	For **dovetailed** and hummer head construction

12.6 Length of air-gap (at center of pole)

$$B_{av} = 0.01 : 0.015 \frac{wb}{m^2} \qquad for\ salient\ pole\ machined$$

$$B_{av} = 0.02 : 0.025 \frac{wb}{m^2} \qquad for\ turbo\ alternators\ (cylindrical)$$

12.6.1 Shape of pole phase

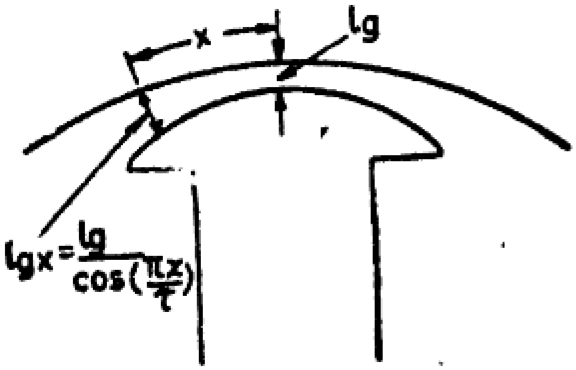


Fig. 12·24. Shape of pole face for sinusoidal flux distribution.

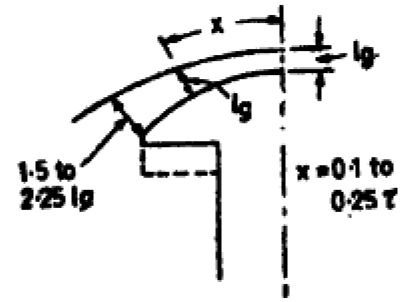


Fig. 12·25 Commonly used pole face profile.

$$\boldsymbol{L_{gx} = L_g * \frac{1}{\cos\left(\frac{\pi x}{\tau_p}\right)}}$$

$$Longest\ L_{g_{longest}}\ (at\ point\ a)(to\ provide\ sin.distribution) is\ \ (1.5 : 2.25) * L_g$$

$$\frac{L_g}{\tau_p} = 0.02 : 0.025$$

12.6.2 X range

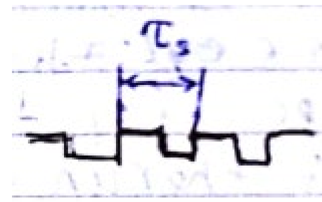
For exact sin. Flux distribution Length of airgap at a distance (x) from centre

$$x = \quad (0.1 : 0.25\ ) * \tau_p$$

13 ARMATURE DESIGN

13.1 Number of slots (S)

Value of slot pitch τ_s depends on Voltage of the machine



τ_s	$\leq 25\ mm$	Low Voltage Machine
τ_s	$\leq 40\ mm$	6kV & Low Voltage Machine
τ_s	$\leq 60\ mm$	Up to 15 kV

$$\tau_s = \frac{\pi D}{s}$$

$$\therefore S = \frac{\pi D}{\tau_s}$$

13.2 Number of stator slots/ph/pole (q)

$$q = \frac{S}{mp}$$

The number of slots per-phase per-pole is usually between

$$2 \leq q \leq 4$$

13.3 Number of Turns/Phase

$$T_{ph} = \frac{E_{ph}}{4.44\, f \phi_p k_w} * a_{parallel\ paths}$$

13.4 Conductor X-Section

$$I_{ph} = \frac{kVA * 10^3}{3E_{ph}} = I_c * a\ \ (A)$$

$$a_s = \frac{I_{ph}}{J_s}\ \ (mm^2)$$

$$J_s : current\ density\ for\ conductors\ (A/mm^2)$$

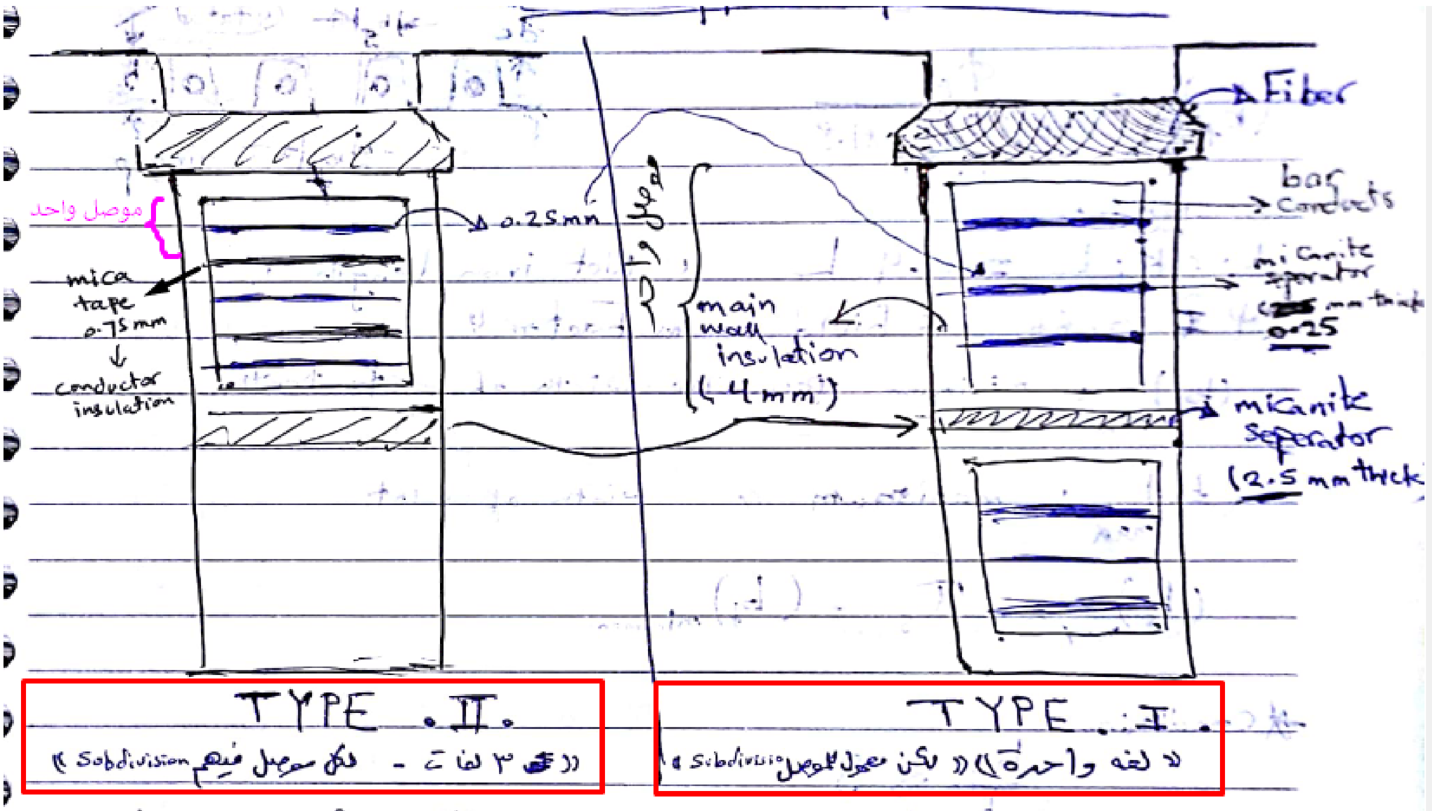
13.5 Insulation

13.5.1 TYPE I

If conductor XSection (a_s) is large

It will be **subdivided** into many parts to reduce conductors eddy current losses

The subdivision can be achieved by laying a number of **bar cupper strips flat wise**



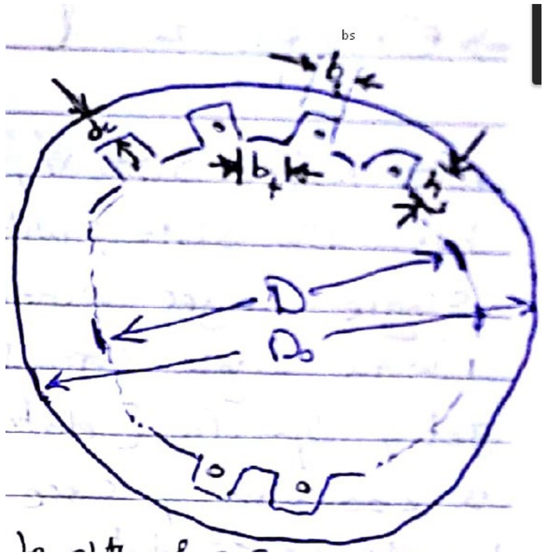
13.5.2 TYPE II

In case of multi-turns coils each turn has to be carefully insulated, and it's a usual practice to design the **inter-turn insulating to with stand line-line voltage V_{LL}**

This is done by tapping each turn by mica-tape for 11kV

(We insulate each turn by it self)

13.6 Slot Dimensions



The flux density on teeth at no load shouldn't exceed

$$B_{teeth_o} \leq 1.7 : 1.8 \quad \frac{wb}{m^2}$$

Minimum permissible width of teeth

$$(b_t)_{Min} = \frac{\phi_p}{\psi \left(\frac{S}{P}\right) L_i * 1.8}$$

$$L_i = \overbrace{k_i}^{\text{stacking factor}} * L = 0.9L$$

$$\psi \cong 0.66 \left((Field\ Form\ Factor)\right)$$

Maximum permissible width of slot

$$(b_s)_{Max} = \tau_s - (b_t)_{Min}$$

<u>CONDITION</u>

$$\frac{h_s}{b_s} \leq \ 3$$

13.7 Length of mean turn

$$(in\ cm)\ \ L_{mt} = 2L + 2.5\ \tau_p + 20\ cm$$

13.8 Stator Core

$$d_C = \frac{\phi}{2 * L_i * B_c}$$

$$B_c : Flux\ density\ in\ tooth$$

$$1 \le B_c \le 1.2$$

Note :

$$B_{av} = \frac{2}{\pi}\, B_g = \frac{\phi}{\tau_p L}$$

$$ac = \frac{2 * 3 * I_{ph} \tau_p}{\pi D}$$

$$E_{ph} = 4.44\, f\, \left(\frac{T_{ph}}{a_{parallel}}\right) \phi\, k_w$$

13.9 Outer Diameter

$$D_o = D + 2(h_s + d_c)$$

Here Example 3,4

13.10 Estimation of air-gap Length

No-load field mmf per pole (AT_{fo})

Armature mmf (AT_a)

$$(AT)_a = \frac{2.7 * k_w * I_{ph} * T_{ph}}{P}$$

$$(AT)_{f_o} = (AT)_a * SCR = \left(\frac{2.7 * k_w * I_{ph} * T_{ph}}{P}\right) * SCR$$

$$SCR\ (short\ circuit\ ratio) = \quad 1.15\ :\ \ 1.2$$

Mmf required for air gap = 80% of No-load field mmf per pole

$$(AT)_g = 0.8\,(AT)_{fo}$$

$$0.8 \times 10^6\, B_g K_g L_g = 0.8 * 2.7 * \frac{k_w I_{ph} T_{ph}}{P} * SCR$$

$$air\ gap\ contraction\ factor\ (uniform\,?, salient\,?)$$
$$K_g = 1.15\ :\ \ 1.2$$

Exampl · 12 11. A 500 kVA, 3 3 kV, 50 Hz, 600 r p m 3 phase salient pole alternator has 180 turns per phase. Estimate the length of air gap if the average flux density is 0 54 Wb/m² ; the ratio pole arc to pole pitch, 0 65 ; the short circuit ratio, 1·2 ; the gap contraction factor, 1·15, and the winding factor, 0·955 The mmf required for gap is 80 percent of no load field mmf and the winding foctor, 0 955

Solution. Synchronous speed $n_s = 600/60 = 10$ r.p.s. ∴ Poles $= 2 \times 50/10 = 10$.

Current per phase $I_{ph} = \dfrac{500 \times 1000}{\sqrt{3} \times 3300} = 87 \cdot 4$ A.

Armature mmf per pole $AT_a = \dfrac{2 \cdot 7 \times 87 \cdot 4 \times 180 \times 0 \cdot 955}{10} = 40 \cdot 62$ A

No load field mmf per pole $AT_{f0} = SCR \times AT_a = 1 \cdot 2 \times 4062 = 4875$ A.

Field from factor $K_f = \psi = 0.66$.

Maximum flux density in air gap $B_g = \dfrac{B_{av}}{K_f} = \dfrac{0.54}{0.66} = 0 \cdot 818$ Wb/m².

Mmf for air gap $= 800{,}000\, B_g K_g l_g = 0.8\, AT_{f0}$ (given) $= 0.8 \times 4875$.

∴ Lentgh of air gap $l_g = \dfrac{0.8 \times 4875}{800{,}000 \times 0.818 \times 1 \cdot 15}$ m $= 5 \cdot 2$ mm.

$$\frac{pole\ arc}{pole\ pitch} = \frac{b_s}{\tau_s} = \psi = k_f = K_g = 0.66$$

$$A_p = \tau_p L = \frac{\pi D L}{P}$$

$$B_{av} = \frac{\phi}{\tau_p L}$$

$$B_g = \frac{B_{av}}{k_f}$$

$$0.8 \times 10^6\, B_g K_g L_g = 0.8 * 2.7 * \frac{k_w I_{ph} T_{ph}}{P} * SCR$$

$$L_g = \frac{0.8 * 2.7 * \frac{k_w I_{ph} T_{ph}}{P} * SCR}{0.8 \times 10^6\, B_g K_g}$$

12·10. Short circuit ratio. The short circuit ratio (SCR) of a synchronous machine is defined as the ratio of field current required to produce rated voltage on open circuit to field current required to circulate rated current at short circuit. Fig. 12·23 shows the open circuit and short circuit characteristics of a synchronous machine. According to the definition,

$$\text{SCR}=\frac{OF_o}{OF_s}=\frac{CF_o}{bF_s}=\frac{CF_o}{aF_o}=\frac{1}{aF_o/CF_o}$$

$$=\frac{1}{\dfrac{\text{per unit voltage on open circuit}}{\text{corresponding per unit current on short circuit}}}$$

$$=\frac{1}{X_d} \qquad \ldots(12\cdot6)$$

14 PROBLEM SOLUTION STEPS

1- $n_S=\frac{n_m}{60}$
2- $assume\ k_w=0.955\ ,\frac{L}{\tau_p}=given\ (2)$
3- $n_m=\frac{120f}{P}\quad or\ n_s=\frac{2f}{P}$
4- $C_o=\ 11\,B_{av}\,ac\,k_w*10^{-3}$
5- $S_n=C_o\,D^2L\,n_s\quad or\ \ S_n=(1.11\,B_a\,ac\,k_w*10^{-3})*\frac{V_a^2}{n_s}\ L$
6- $D^2L=\ (\ )$
7- $get\ L=\left(\frac{(given)\pi D}{P}\right)$
8- Solve 2 equations and get D , L

9- $get\ E_{ph}=\frac{V}{\sqrt{3}}$
10- $get\ f\ \ from\ 3$
11- $\phi_p=B_{av}*\tau_pL=B_{av}\frac{\pi D}{P}\ L=B_{av}*\frac{L^2}{(given)}$
12- $T_{ph}=\frac{E_{ph}}{4.44\,\phi_p\,f\,k_w}*a_{parallel}$
13- $Z_a=2*3*T_{ph}$

14- $\tau_s=\frac{\pi D}{s}\quad (assume\ it\ or\ given\ by\ voltage\ range\ )(2.5)$
15- $S=(\quad)$
16- $q=\frac{S}{mP}=\ \ must\ be\ integer$
17- $S'=(\ )\ \ that\ makes\ q\ integer$
18- $Z_s=\frac{Z_a}{S}$

19- $I_{ph} = I_c = \frac{kVA*10^3}{3E_{ph}}$ $\left\{ I_c = \frac{1}{a} I_{ph} \right\}$

20- $a_c = \frac{I_{ph}}{J}$

Checks

21- $V_a = \pi D n_s \{* 1.8\ if\ said\} < V_{given}$

22- $0.01 \le \frac{L_g}{\tau_p} \le 0.015$

$$\frac{pole\ arc}{pole\ pitch} = \frac{b_s}{\tau_p} = \psi = k_f = K_g = 0.66$$

$$A_p = \tau_p L = \frac{\pi D L}{P}$$

$$B_{av} = \frac{\phi}{\tau_p L}$$

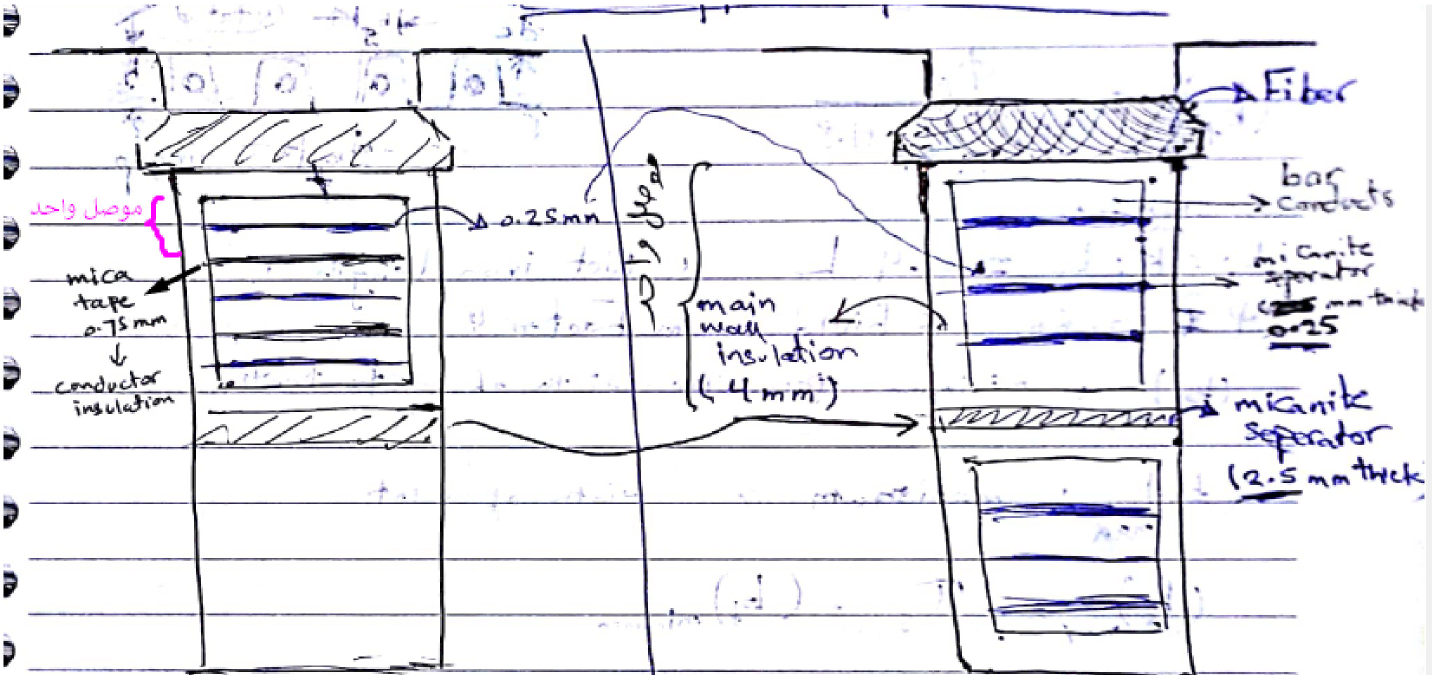
$$B_g = \frac{B_{av}}{k_f}$$

$$0.8 \times 10^6\ B_g K_g L_g = 0.8 * 2.7 * \frac{k_w I_{ph} T_{ph}}{P} * SCR$$

$$L_g = \frac{0.8 * 2.7 * \frac{k_w I_{ph} T_{ph}}{P} * SCR}{0.8 \times 10^6\ B_g K_g}$$

23- Draw **Stator Slot Diagram**

Slots divided by 2 up and down (up divided by 2) ex (28 then 14 up then 7 coil)



TYPE II.
« Subdivision لكل موصل فيهم - ٣ لفات »

TYPE I.
« لفه واحدة » لكن معزول الموصل Subdivision »

Stator slot diagram