EE 262: SYNCHRONOUS MACHINES [Credit: 3]

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UNIT 1-DEFINITION AND FEATURES

Definition:

A synchronous machine is an AC machine whose rotor speed is the same as the angular speed of the revolving/rotating magnetic flux resulting from the interaction of two or more magnetic fields.

Synchronous machines have alternating currents (AC) in the stator windings (called armature) and DC currents in the rotor windings (called field).

Constructional Features

1. Stator:

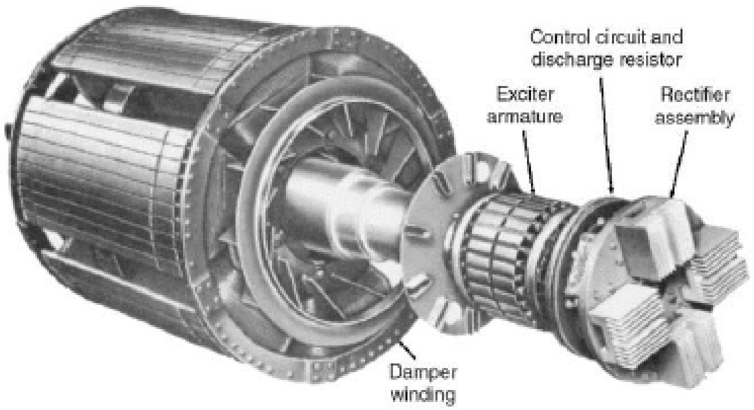
The stator unit is the stationary part of the machine and consists of the

- stator frame or yoke and
- the armature coils.

The **stator frame or yoke** serves the purposes of :

a) providing mechanical support for the poles
b) protection for the machine and
c) carrying the armature flux produced by the poles.

Constructional Features…cont'd



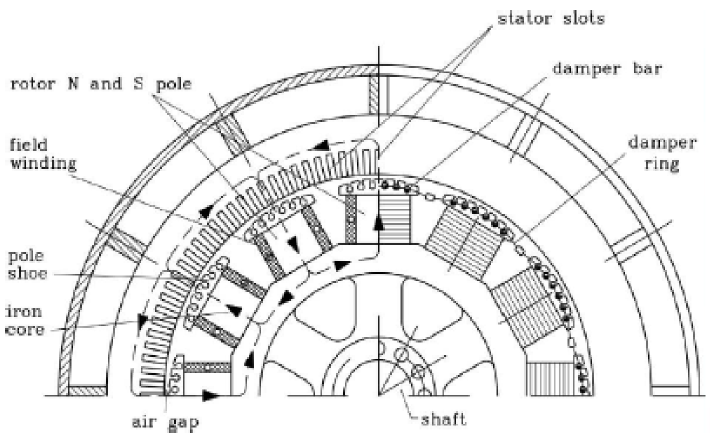
2. Rotor :

The rotor, which is the rotating part of the machine, is located on a shaft running on bearings, and is free to rotate between magnetic poles.

The **rotor core** is cylindrical or drum-shaped, and is built of steel laminations with *slots* to house the **field windings**.

In addition to the DC winding, the rotor carries the so-called **damper windings** (also called **squirrel-cage winding**).

Constructional Features...cont'd



- The damper winding serves the following **functions**:

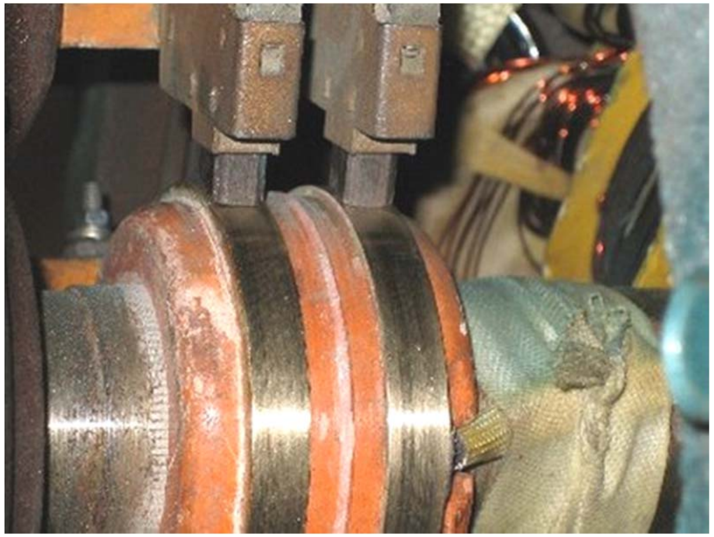
a) produces forces which dampen the oscillation of the rotor, thereby reducing hunting (momentary speed fluctuations)

b) helps to start synchronous motors

c) maintains balanced 3-phase voltage under unbalanced load conditions.

d) improves parallel operation of salient-pole generators driven by internal-combustion engines.

Constructional Features…cont'd



3. Slip-rings or collector rings:

The slip-ring is made of copper segments, and has the same functions in the motor as in a generator.

Its purpose is to facilitate the collection of current from the DC excitation source to the field windings.

4. Brushes and bearings:

These carry current from the external circuit to the commutator.

They are usually made of blocks of carbon or graphite, and are rectangular in shape.

They should slide freely in their holder so as to follow any irregularity in the commutator.

Types of Synchronous Machines:

- Synchronous Generators (or Alternators)
- Synchronous Motors (synchronous motors operating with load attached)
- Synchronous Condensers (synchronous motors operating on no-load)

UNIT 2- SYNCHRONOUS GENERATORS

Types:

a) Salient-Pole Generators (Low-speed Generators)
b) Cylindrical-Rotor Generators (High-speed Generators)

Principle of Operation

Operates on the principle of electromagnetic induction. When the rotor is made to rotate by the turbine of the prime mover, the stator or armature conductors (being stationary) are cut by the rotated DC magnetic flux from the field coils on the rotor.

Hence they have induced emf produced in them. Because the magnetic poles are alternate *N* and *S*, they induce an emf and hence current in the armature conductors, which first flow in one direction and then in the other.

Principle of operation…cont'd.

Hence an alternating emf is induced in the stator windings whose frequency depends on the number of *N* and *S* poles moving past a conductor in one second and whose direction is given by Fleming's Right-Hand Rule.

Stationary Armature

It is more desirable to have a stationary armature with the field poles rotating inside it, as this structure has several advantages;

- Difficulty in insulating slip rings.
- On a rotating armature, arc-overs and short circuits are apt to occur.
- No slip rings are required in a stationary armature.
- Easier to properly insulate a stationary armature

Rotating Magnetic Fields of Synchronous Generators

$$F(\theta,t)=\left\{F_{\max}\cos\theta\cos\omega t\right\}+\left\{F_{\max}\cos(\theta-120^0)\cos(\omega t-120^0)\right\}$$
$$+\left\{F_{\max}\cos(\theta-240^0)\cos(\omega t-240^0)\right\}$$

Distorting Effect of Armature Reaction Flux

- The effect of the armature flux is to distort the main flux distribution in the air gap due to the field flux. This effect is known as **armature reaction.**

- **Counteracting Armature Reaction**

-Increasing the reluctance of the cross-flux path

-compensating or pole-face winding.

Armature Reaction Reactance

- The leakage reactance arising from the armature reaction is called **armature reaction reactance.**

a) CYLINDRICAL-ROTOR SYNCHRONOUS GENERATORS

- Phasor Diagrams

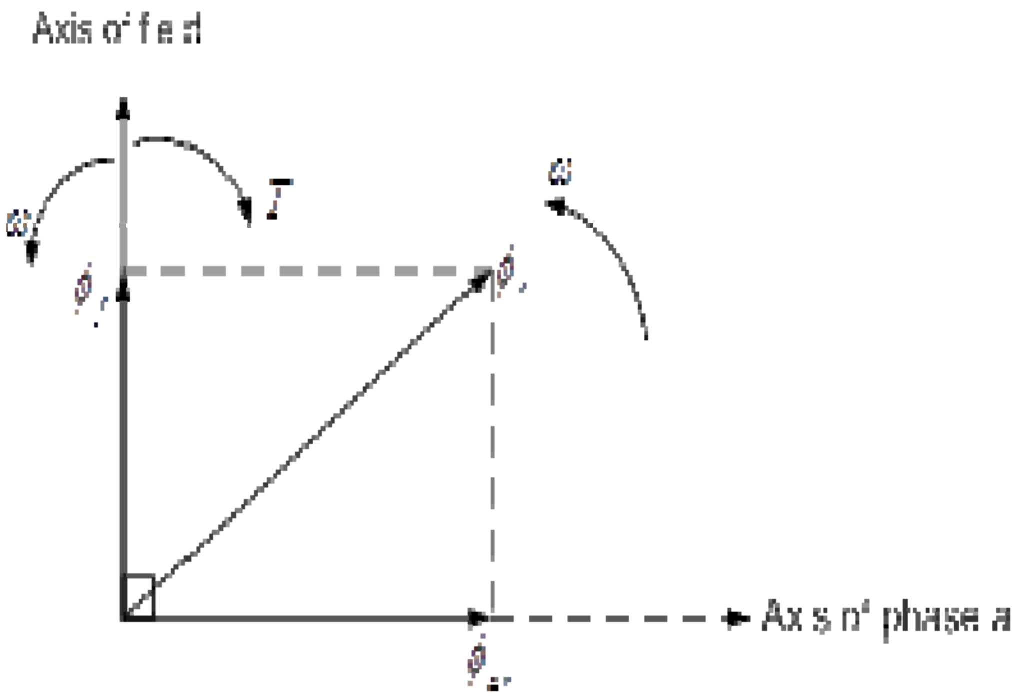


Fig (a)

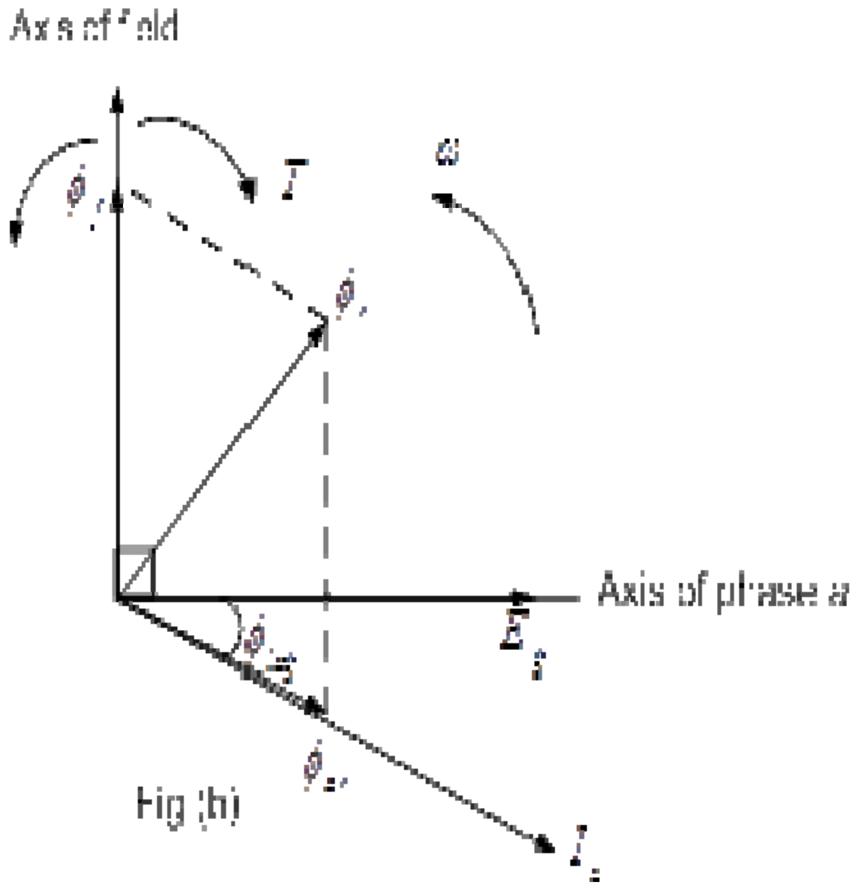
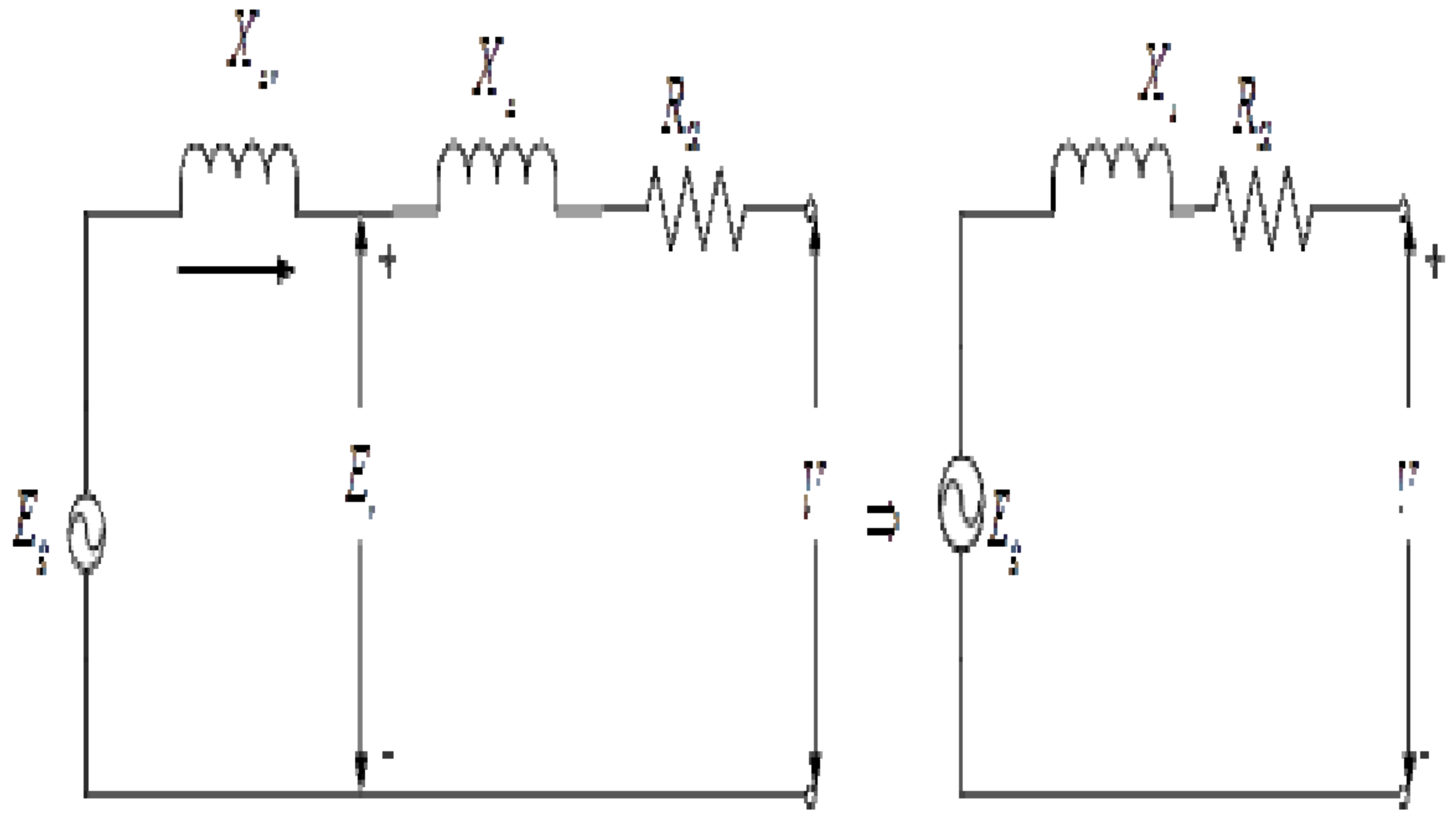


Fig (b)

Equivalent Circuits

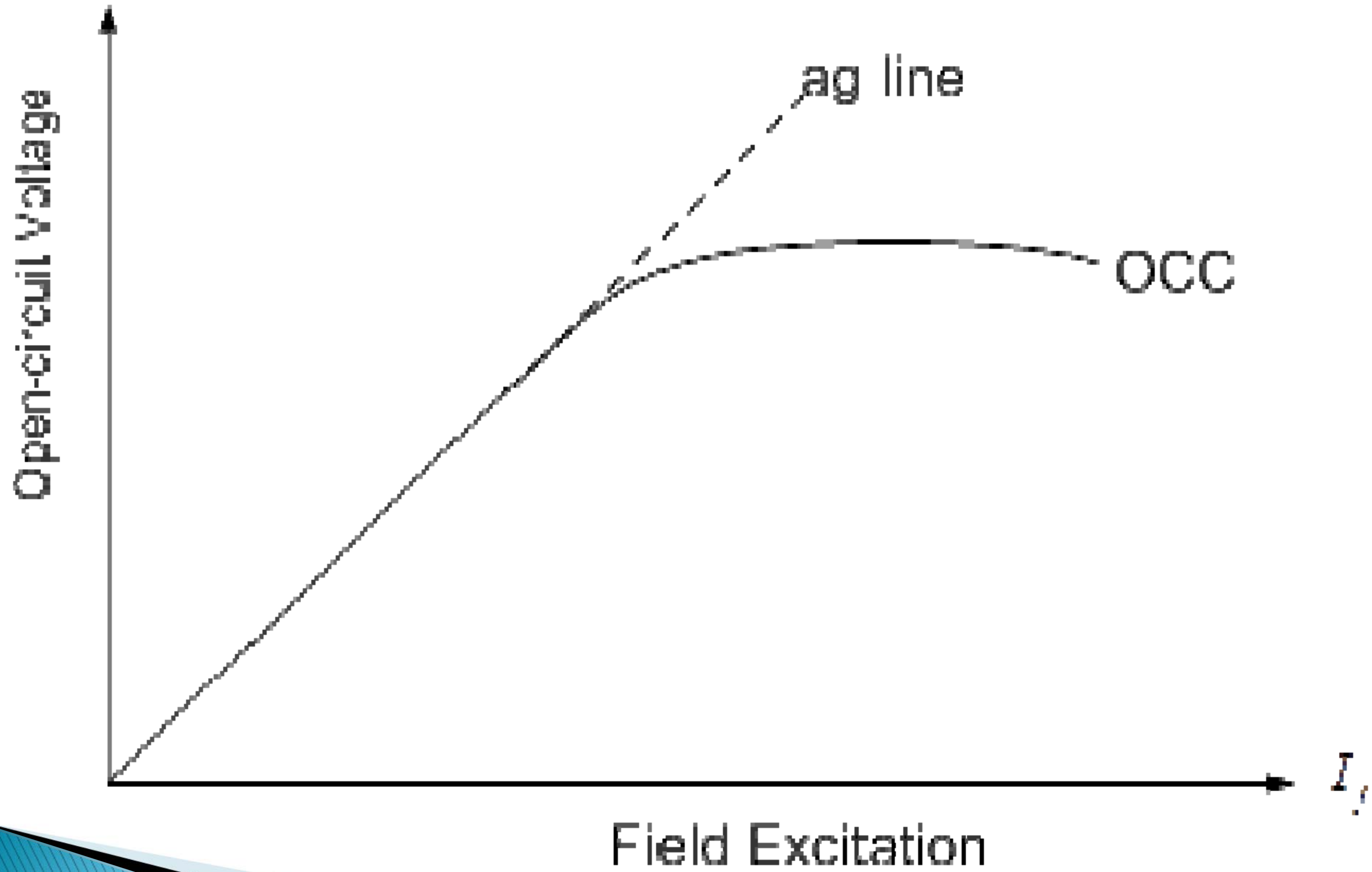


Steady-State Performance Characteristics of the Synchronous Machine

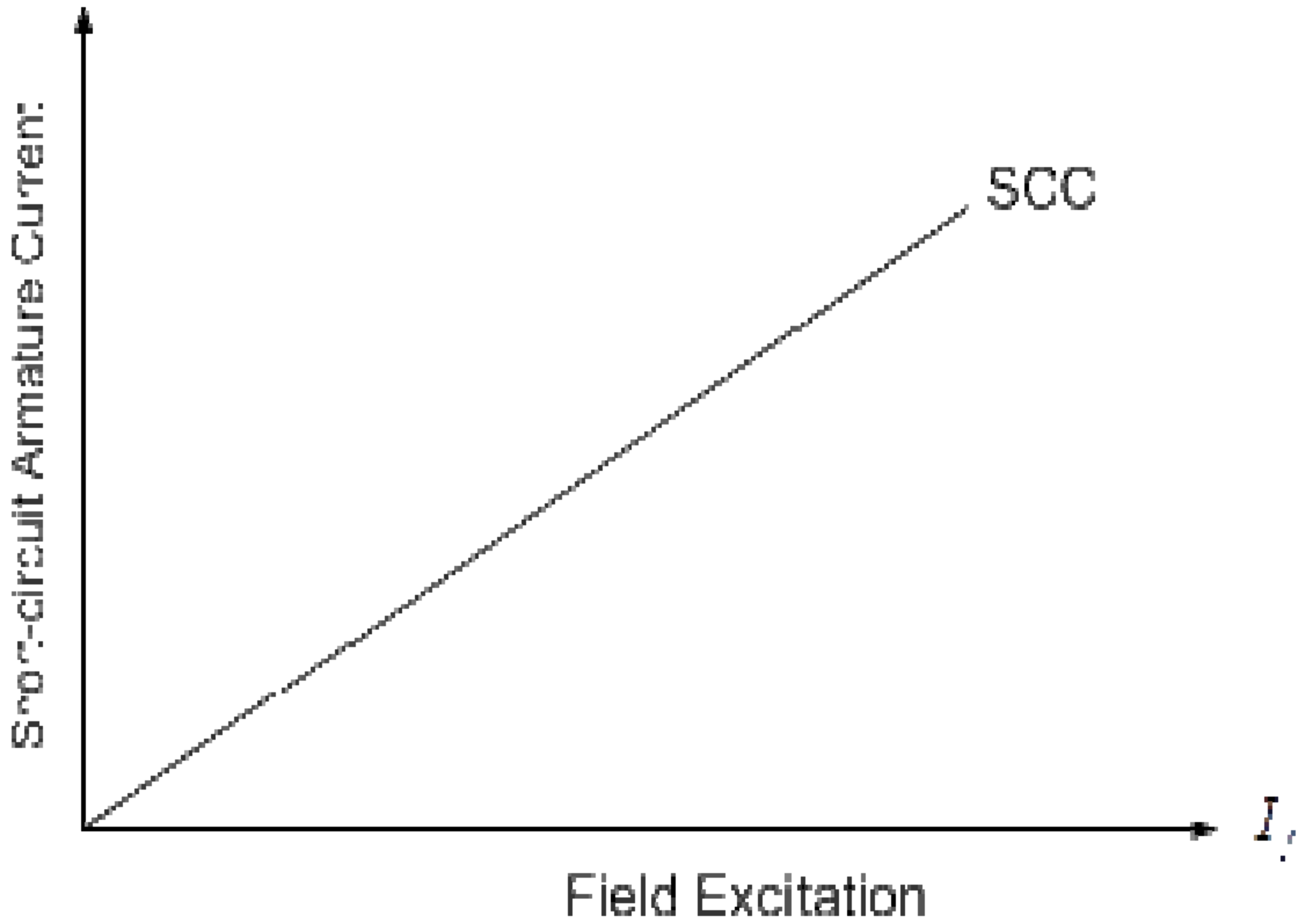
- The tests performed to obtain these characteristics are the *open-circuit* and ***short-circuit tests***.

- These tests yield the open-circuit and short-circuit characteristics.

Open-Circuit Characteristics



Short-Circuit Characteristics



Determination of the armature resistance

- The armature resistance per phase can be measured directly by voltmeter and ammeter method or by using Wheatstone bridge.

Example 1

The following test results were obtained from a 3-phase, 6000 kVA, 6.6 kV star-connected, 2-pole, 50 Hz turbo alternator. With a field current of 125 A, the open circuit voltage is 8000 V at rated speed. With the same excitation and rated speed, the short-circuit current was 800 A. If at the rated full-load, the resistance drop is 3%, determine the following:

i. synchronous impedance
ii. armature resistance
iii. synchronous reactance

Solution 1

The synchronous impedance is calculated using the equation

$$Z_s = \left.\frac{E_{oc}}{I_{sc}}\right|_{\text{for same field current } I_f} = \frac{8000/\sqrt{3}}{800} = \underline{\underline{5.77\,\Omega}}$$

ii. The voltage per phase is

$$E_{oc} = 8000 / \sqrt{3} = \underline{3810 \;\; V}$$

Solution 1…cont'd

Full load current, $I = \dfrac{S_{3\,ph}}{V_L\sqrt{3}} = \dfrac{6000}{6.6\times\sqrt{3}} = \underline{525\ A}$

Resistance drop, , $IR_a = 3\%\times E_{oc} = 0.03\times 3810 = \underline{114.3V}$

iii. Synchronous reactance,

$$R_a = 114.3/525 = \underline{\underline{0.218\,\Omega}}$$

$$X_s = \sqrt{Z_s^{\,2} - R_a^{\,2}} = \sqrt{5.77^2 - 0.218^2} = \underline{\underline{5.74\ \Omega}}$$

Output Power Delivered By Cylindrical-Rotor Synchronous Generator

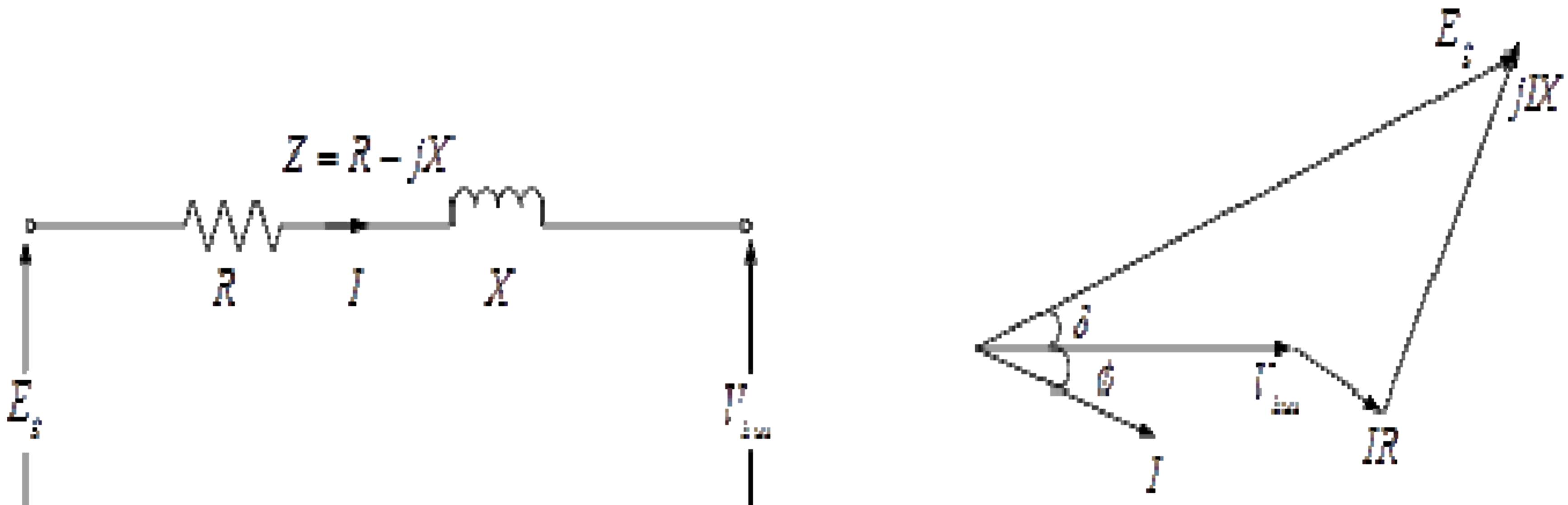


Fig (a) Fig (b)

Fig 11: (a) Circuit Diagram (b) Phasor Diagram

Output Power...cont'd.

The power delivered to the load or bus end is

$$P_2 = V_{bus} I \cos\phi$$

$$I = \frac{E_g - V_{bus}}{Z}$$

In polar forms,

$$I = \frac{E_g \angle \delta - V_{bus} \angle 0}{Z \angle \phi_z} = \frac{E_g}{Z} \angle(\delta - \phi_z) - \frac{V_{bus}}{Z} \angle(-\phi_z)$$

Output Power...cont'd.

- The **real part** of the current is

$$I\cos\phi = \mathrm{Re}al\ part\left[\frac{E_g}{Z}\angle(\delta-\phi_z) \ - \ \frac{V_{bus}}{Z}\angle(-\phi_z)\right]$$

$$= \frac{E_g}{Z}\cos(\delta-\phi_z) - \frac{V_{bus}}{Z}\cos(-\phi_z)$$

- But $\cos(-\phi_z) = \cos(\phi_z) = R/Z$.

Substituting Eqn (23) into (20), we obtain,

Output Power...cont'd.

$$P_2 = V_{bus} I \cos\phi$$

$$= V_{bus} \cdot \left\{ \frac{E_g}{Z} \cos(\delta - \phi_z) - \frac{V_{bus}}{Z} \cos(-\phi_z) \right\}$$

$$= \frac{E_g V_{bus}}{Z} \cos(\delta - \phi_z) - \frac{V_{bus}{}^2 R}{Z^2}$$

$$= \frac{E_g V_{bus}}{Z} \sin(\delta + \alpha_z) - \frac{V_{bus}{}^2 R}{Z^2}$$

Output Power…cont'd.

Where $\alpha_z = \tan^{-1}\dfrac{R}{X} = 90^0 - \phi_z$

And is usually a small angle.

Similarly, $P_1 = \dfrac{E_g V_{bus}}{Z}\sin(\delta - \alpha_z) + \dfrac{V_{bus}{}^2 R}{Z^2}$

With negligible resistance, $P_1 = P_2 = P_{real} = \dfrac{E_g V_{bus}}{X}\sin\delta$

With negligible resistance and constant voltage, maximum power occurs at $\delta = 90^0$,

$$P_{real(\max)} = \frac{E_g V_{bus}}{X}$$

Maximum Power Output From Cylindrical-Rotor Synchronous Generator

The maximum power per phase is given as:

$$P_{\max} = \frac{E_g V}{X_s} \qquad \text{if } R_a \text{ is neglected}$$

$$= \frac{V}{Z_s}\left(E_g - V\cos\alpha\right) \qquad \text{if } R_a \text{ is considered}$$

$$\text{where } \cos\alpha = \frac{R_a}{Z_s}$$

Maximum current and power factor corresponding to maximum power output:

$$I_{\max} = \frac{\sqrt{E_g{}^2 + V^2}}{X_s}$$

$$\cos\theta_{\max} = \frac{E_g}{\sqrt{E_g{}^2 + V^2}}$$

Example 3

- A 3-phase 11 kV 5 MVA star-connected alternator has a synchronous impedance of $(1 + j12)\,\Omega$ per phase. Its excitation is such that the generated line emf is 12 kV. If the alternator is connected to an infinite busbar, determine the maximum output at the given excitation.

Solution 3

The generated phase voltage is $E_g = \frac{12000}{\sqrt{3}} = \underline{6928\ V}$

The terminal voltage per phase is $V = \frac{11000}{\sqrt{3}} = \underline{6351\ V}$

Since the armature resistance is NOT negligible, we need to calculate the internal angle

$$\cos\alpha = \frac{R_a}{Z_s} = \frac{1}{\sqrt{1^2 + 12^2}} = \underline{0.083}$$

solution cont'd

- Hence the maximum power output per phase is

$$P_{\max} = \frac{V}{Z_s}\left(E_g - V\cos\alpha\right)$$

$$= \frac{6351}{\sqrt{1^2 + 12^2}}\left(6928 - 6351 \times 0.083\right)$$

$$= 3375.88\,kW$$

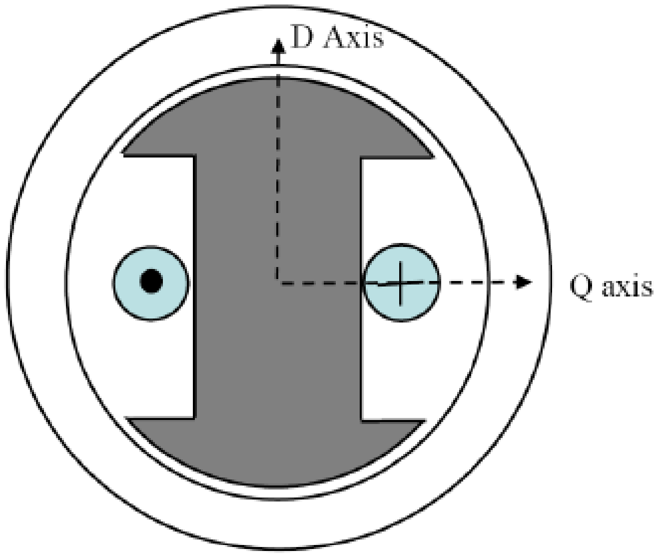
$$\Rightarrow Total\,P_{\max} = 3 \times 3375.88 = \underline{\underline{10127.64\,kW}}$$

Exercises on Maximum Power Output

- Example 1, 2 and 3, Please refer to notes.

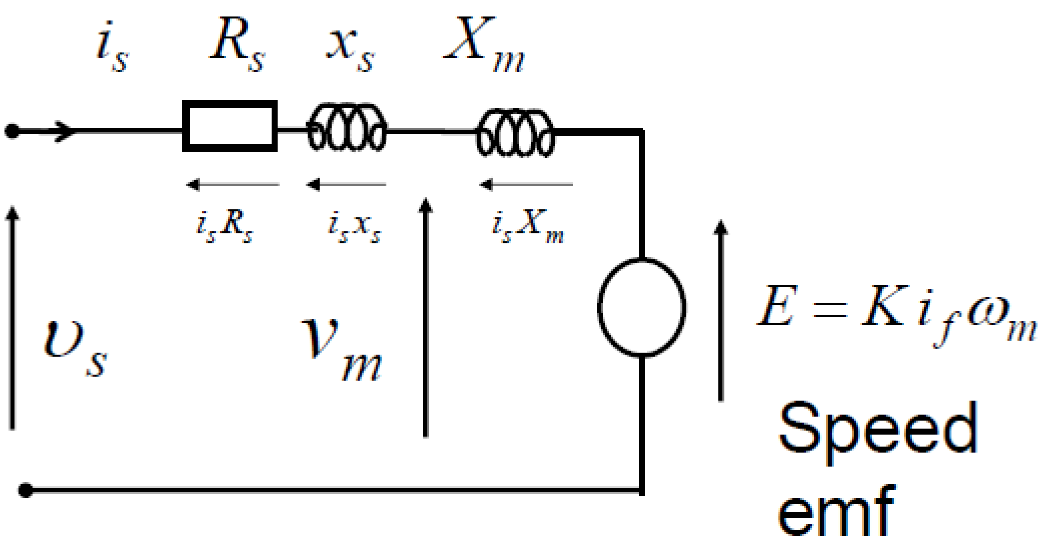
b) SALIENT-POLE GEOMETRY

- A salient rotor has a short air gap section for each pole round which the field winding is wound
- This field winding axis is called the Direct or D-axis
- Perpendicular (Electrically) to the D-axis is the Q-axis
- The Q-axis bisects the long airgap section between the field poles
- When the stator peak mmf is aligned with the D-axis the inductance is greatest. The synchronous reactance is then Xsd
- When the peak stator mmf is aligned with the Q-axis the stator inductance is a minimum. The synchronous reactance is then Xsq



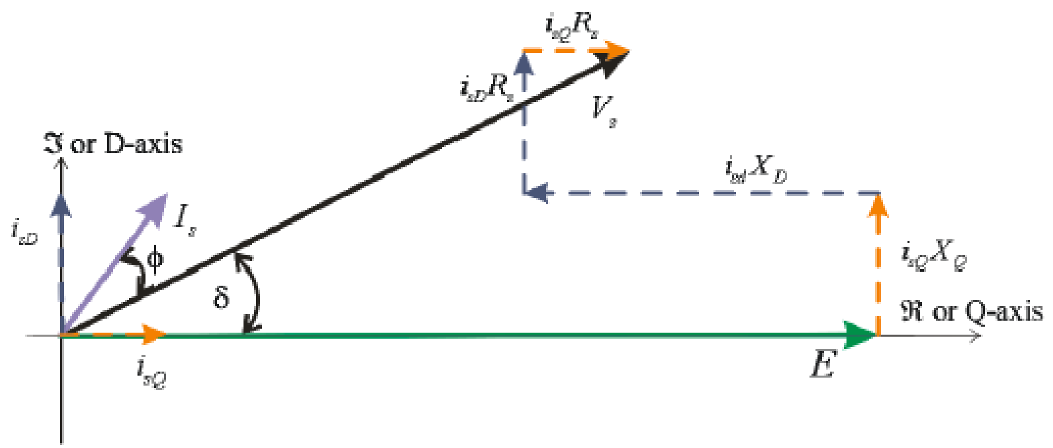
EQUIVALENT CIRCUIT OF SALIENT POLE SYNCHRONOUS MACHINE

- Steady-State per-phase equivalent circuit no longer applies directly
- Which reactance to choose X_{sd} or X_{sq} ?
- Solution is to resolve the flux on the D- and Q-axis separately.



RESOLVING INTO D- AND Q-COMPONENTS

- Resolving the flux on the D- and Q-axis separately.
- D-axis induced voltages will lie in parallel to E
- The current inducing that voltage will be on the Q-axis as in an inductor current lags voltage by 90 deg.
- Similarly any voltage induced by the Q-axis flux will be perpendicular to E and the current inducing the Q axis flux must therefore be parallel to E

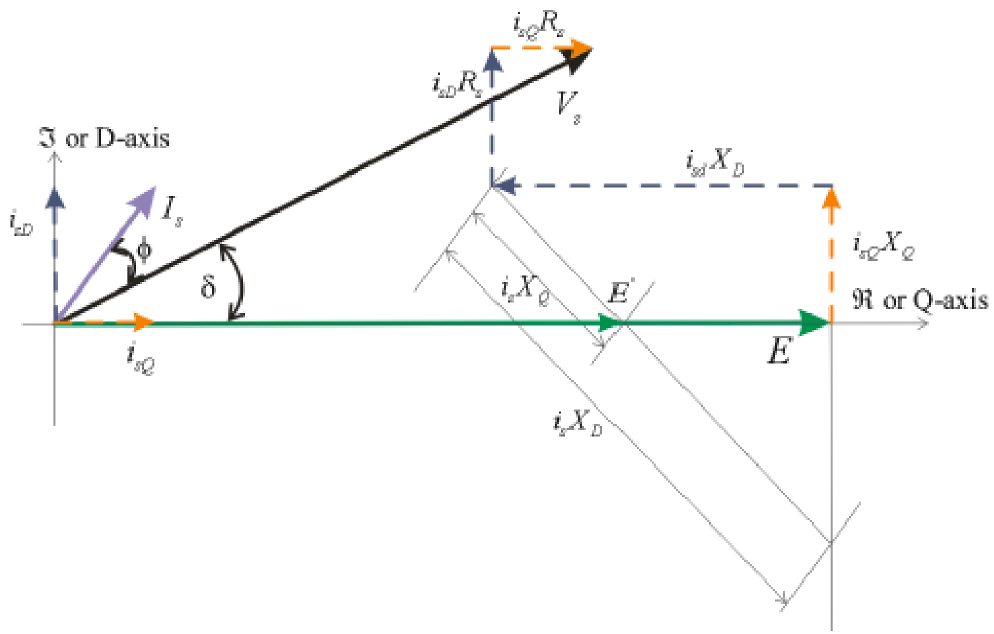


Phasor diagram for a salient pole motor operating at leading power factor showing resolved currents and reactances on the D- and Q- axis

DETERMINING THE OPERATING CONDITIONS

- Knowing the supply voltage and current of the machine and the D- and Q- axis reactances; to resolve the current Is into Isd and Isq we need to first determine the load angle
- From the phasor diagram we can see that the load angle depends on Xsq and the magnitude of E on Xsd

- E' is introduced as the intercept of IsXq and E
- This allows us to determine the load angle
- The following slide shows how this is done

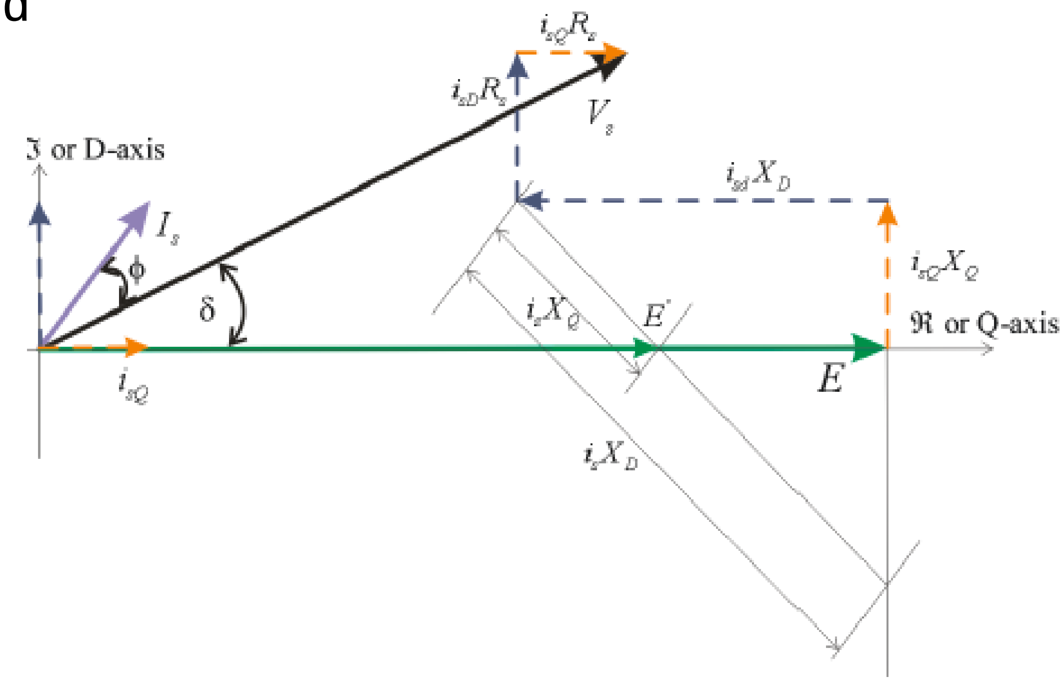


DETERMINING THE OPERATING CONDITIONS

- The d- and q- components of current can now be found and the phasor diagram fully described

- This can all be done by drawing the phasor diagram to scale using a ruler and a protractor

- This can also be done analytically as follows



DETERMINING THE OPERATING CONDITIONS

$v_s = \; i_s e^{j\emptyset}(R_s + jX_{sQ}\,) + E' e^{j\delta}$

$v_s = (i_s \cos(\emptyset)) + j i_s \sin(\emptyset))(R_s + jX_{sQ}\,) + (E' \cos(\delta)) + j\text{E'}\sin(\delta))$

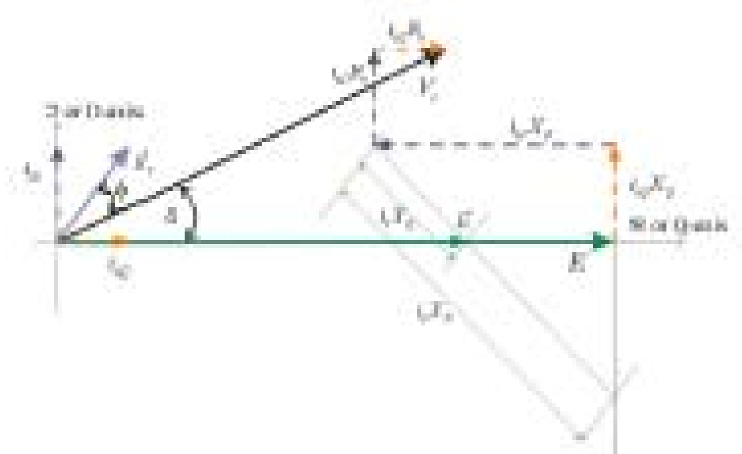
Splitting the above equation into real and imaginary parts, we have:

$$v_s = \; i_s \cos(\emptyset) R_s - \; i_s \sin(\emptyset) X_{sQ} + E' \cos(\delta)$$
$$E' \cos(\delta) = v_s \; - i_s \cos(\emptyset)\, R_s + i_s \sin(\emptyset) X_{sQ}$$

and

$$0 = i_s \cos(\emptyset)\, X_{sQ} + i_s \sin(\emptyset)\, R_s + E' \sin(\delta)$$
$$E' \sin(\delta) = -i_s \cos(\emptyset) X_{sQ} - i_s \sin(\emptyset)\, R_s$$

and



$$\tan(\delta) = \frac{E' \sin(\delta)}{E' \cos(\delta)} = -\frac{i_s \cos(\emptyset)\, X_{sQ} + i_s \sin(\emptyset) R_s}{i_s \cos(\emptyset) X_{sQ} + i_s \sin(\emptyset)\, R_s + E' \sin(\delta)}$$

Hence

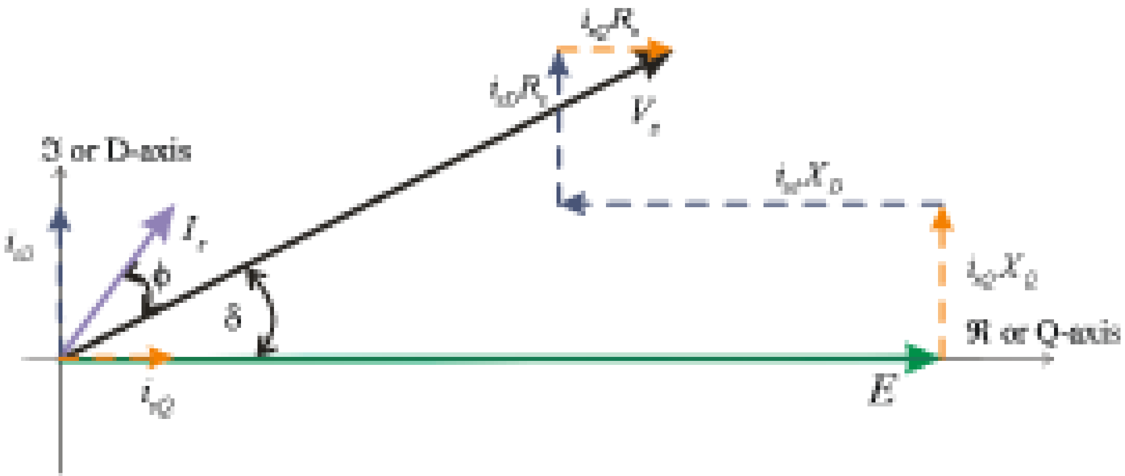
$$\delta = -\tan^{-1}\left(\frac{i_s R_s \sin(\emptyset) + i_s X_{sQ} \cos(\emptyset)}{v_s - i_s R_s \cos(\emptyset) + i_s X_{sQ} \sin(\emptyset)}\right)$$

DETERMINING THE OPERATING CONDITIONS

- Having determined the load angle we can write:

$$i_{sD} = i_s \sin(\emptyset - \delta)$$

$$i_{sQ} = i_s \cos(\emptyset - \delta)$$



- Resolving components onto the D- and Q- axis we have:

D–axis: $0 = v_s \sin(\delta) + i_{sD}R_s + i_{sQ}X_{sQ}$

Q–axis: $E = v_s \cos(\delta) - i_{sQ}R_s + i_{sD}X_{sD}$

EVALUATION OF POWER

- Power per phase: $P = v_s i_s \cos \emptyset$

$$P = v_s \,(I_{sQ} \cos \delta + I_{sD} \sin \delta)$$

- Neglecting resistive drop as in non-salient case:

$$v_s \cos \delta = E - i_{sD} X_D$$

- From D-axis equation: $i_{sD} = \frac{E - v_s \cos \delta}{\omega L_D}$

$$v_s \sin \delta = i_{sQ} X_Q$$

- From Q-axis equation: $i_{sQ} = -\frac{v_s \sin \delta}{\omega L_Q}$

EVALUATION OF POWER

- Substituting and evaluating for 3-phases:

$$P = 3 \cdot v_s \left[-\left(\frac{v_s \sin\delta}{\omega L_Q} \right) \cdot \cos\delta + \left(\frac{E - v_s \cos\delta}{\omega L_D} \right) \cdot \sin\delta \right]$$

$$P = 3 \cdot v_s \left[\frac{E \cdot \sin\delta}{\omega L_D} - \left(\frac{v_s \cos\delta \cdot \sin\delta}{\omega L_D} \right) - \left(\frac{v_s \sin\delta \cdot \cos\delta}{\omega L_Q} \right) \right]$$

$$P = 3 \cdot v_s \left[\frac{E \cdot \sin\delta}{\omega L_D} - \frac{v_s}{\omega} \frac{\sin(2\delta)}{2} \left(\frac{L_Q - L_D}{L_D L_Q} \right) \right]$$

$$P = 3. \left[\frac{v_s E \sin\delta}{\omega L_D} + \frac{v_s^{\ 2}}{\omega} \left(\frac{L_D - L_Q}{L_D \cdot L_Q} \right) \cdot \frac{\sin(2\delta)}{2} \right]$$

POWER LOAD ANGLE RELATIONSHIP

$$Power = 3.\left[\frac{VE\sin\delta}{\omega_e L_d} + \frac{V^2}{\omega_e}\left(\frac{L_d - L_q}{L_d \cdot L_q}\right)\cdot\frac{\sin(2\delta)}{2}\right]$$

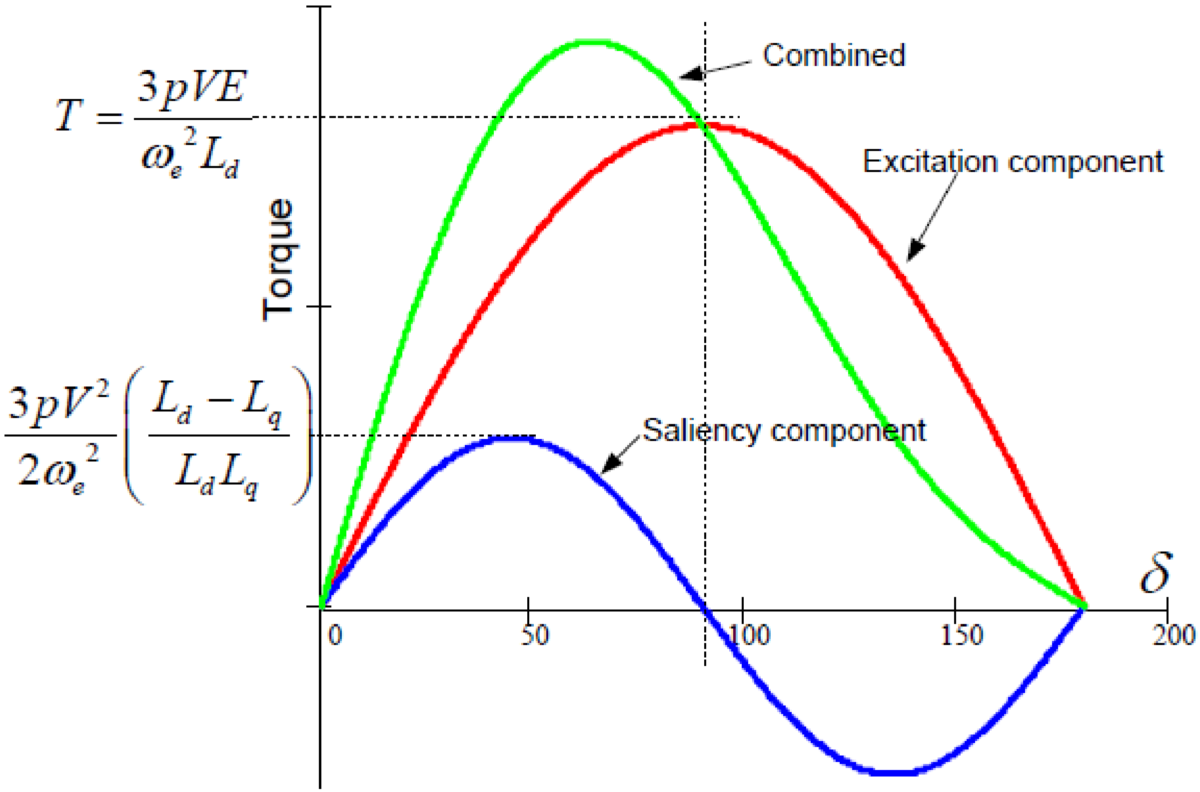
$$Torque = \frac{3\cdot p}{\omega_e^{\ 2}}\left\{\boxed{\frac{VE\sin\delta}{L_d}} + \boxed{V^2\left(\frac{L_d - L_q}{2L_d L_q}\right)\sin 2\delta}\right\}$$

Dependent on field strength

Saliency term – dependant on L_d/L_q

- The first part depends on E and is due to the field interaction with the stator. The second part depends upon V_s only and is due to the saliency interacting with the stator. In other words there is a power transfer and torque when I_f is zero

POWER LOAD ANGLE RELATIONSHIP



For the traditional wound rotor (salient) machine L_d is always greater than L_q.

Example 4

The reactances X_d and X_q of a salient–pole synchronous generator are 1.00 and 0.60 p.u., respectively. The armature resistance is negligible. Compute the excitation voltage when the generator delivers rated kVA at 0.80 pf lagging current, and rated terminal voltage.

Please refer to notes for **solution 4.

Output Power Delivered by Salient-Pole Synchronous Generator

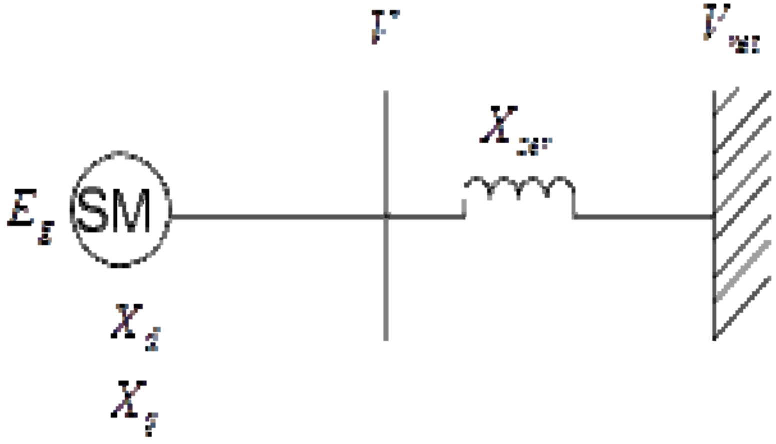


Fig (a)

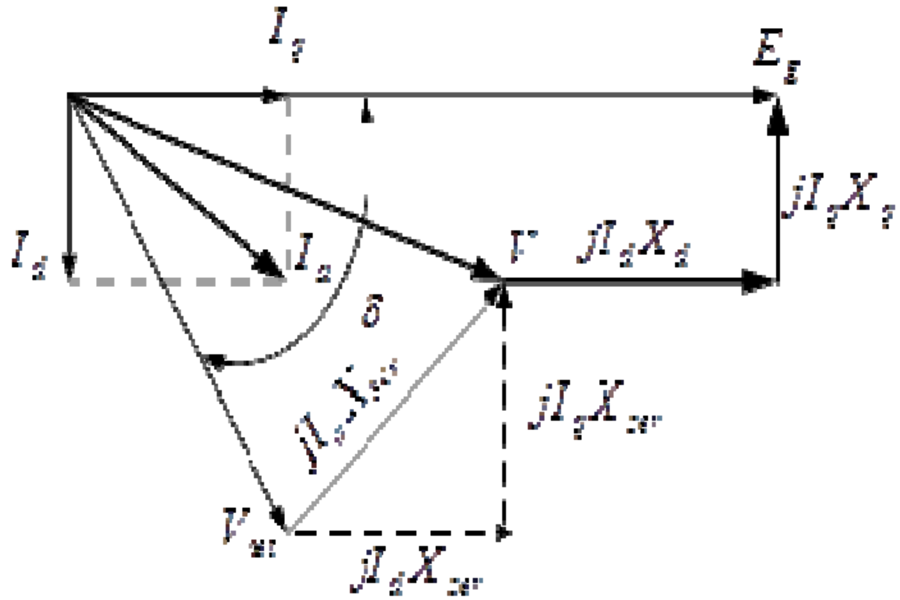


Fig (b)

Salient-Pole Synchronous Machine and Series Impedance
(a) Single-Line Diagram (b) Phasor Diagram

Output Power…cont'd.

Hence

Equation 41

$$P = \frac{E_g V_{net}}{X_{dT}} \sin\delta + V_{net}{}^2 \frac{X_{dT} - X_{qT}}{2 X_{dT} X_{qT}} \sin 2\delta$$

Example 5

Example 6

Voltage regulation

It is a known fact that with a change in load, there is a change in terminal voltage of an alternator.

The *magnitude of this change depends not only on the load but also on the load power factor*.

The voltage regulation is defined as:

$$VR = \frac{E_0 - V}{V} \tag{42}$$

Notes on Eqn (42)

- $(E_0 - V)$ is the **arithmetic difference** and not the vector difference.
- For a **leading** load power factor, the terminal voltage will fall on removing the full-load. Hence, regulation is **negative** in that case.
- The rise in voltage when full-load is thrown off, is not the same as the fall in voltage when full-load is applied.

Determination of Voltage Regulation

Voltage Regulation of a generator depends on:

- armature resistance
- synchronous reactance
- power factor.

In small machines, the voltage regulation is found by **direct loading.**

Voltage Regulation…cont'd.

In large machines, the voltage regulation is found by some **indirect methods**:

i. Synchronous Impedance or EMF Method (due to Behn Eschenberg)
ii. Ampere-Turn or MMF Method (due to Rothert)
iii. Zero Power Factor or Potier Method (as name implies, due to Potier)

Indirect Method 1-Synchronous Impedance or EMF Method

The general data required in this method are the OCC, SCC and the synchronous impedance.

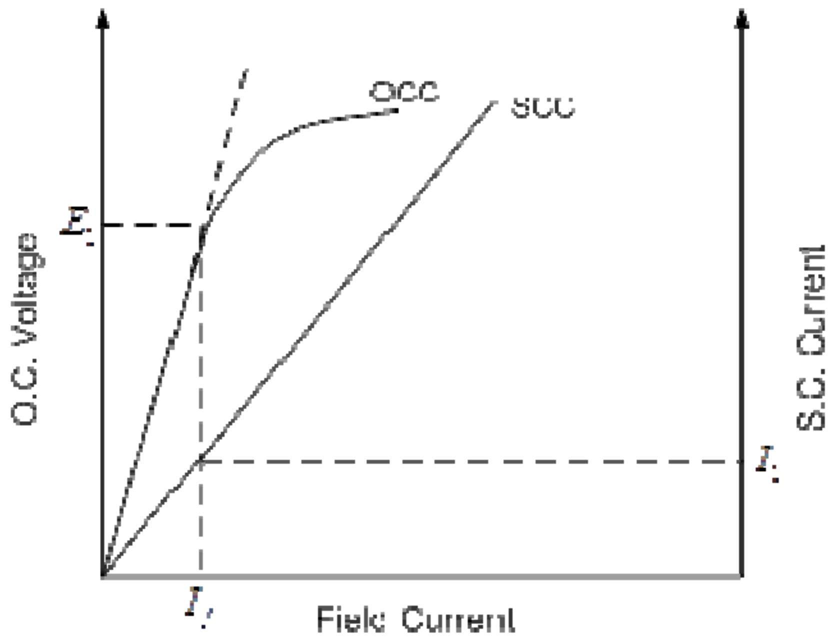


Fig (a)

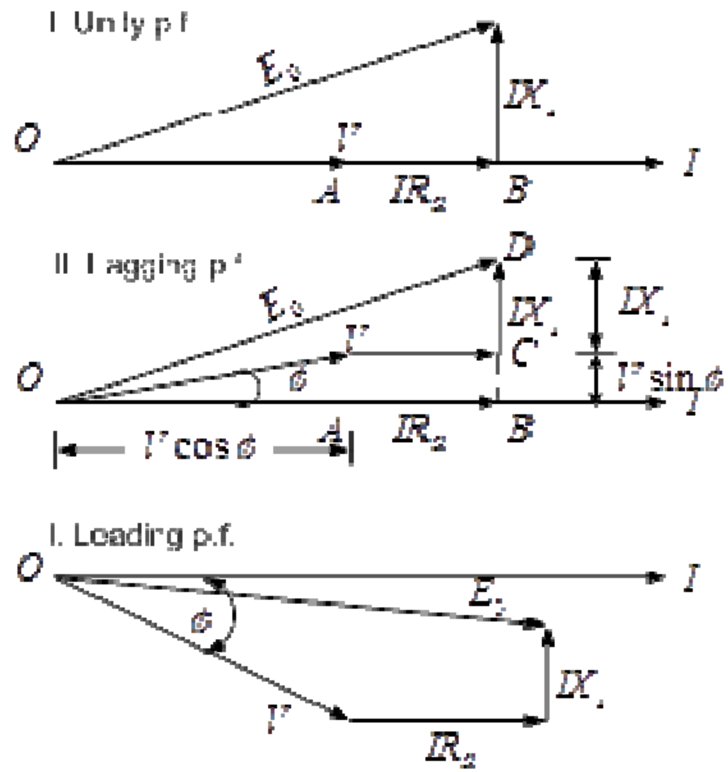


Fig (b)

Example 7
Example 8
Example 9

**Please refer to notes

Steady-State Operating Characteristics of Synchronous Generators

The main characteristics are :

i. Terminal Voltage Characteristics (**curves for a given power factor)**
ii. Compounding Curves (**curves at rated terminal voltage)**
iii. Reactive-Active Power Capability Curves (**curves for a given power factor)**

i. Terminal Voltage Characteristics (V–Ia) Curves For a Given Power Factor

It shows the variation of terminal voltage with load (or armature) current for a given power factor when the generator is driven at constant speed and excited with constant current.

(V-Ia) curves…cont'd.

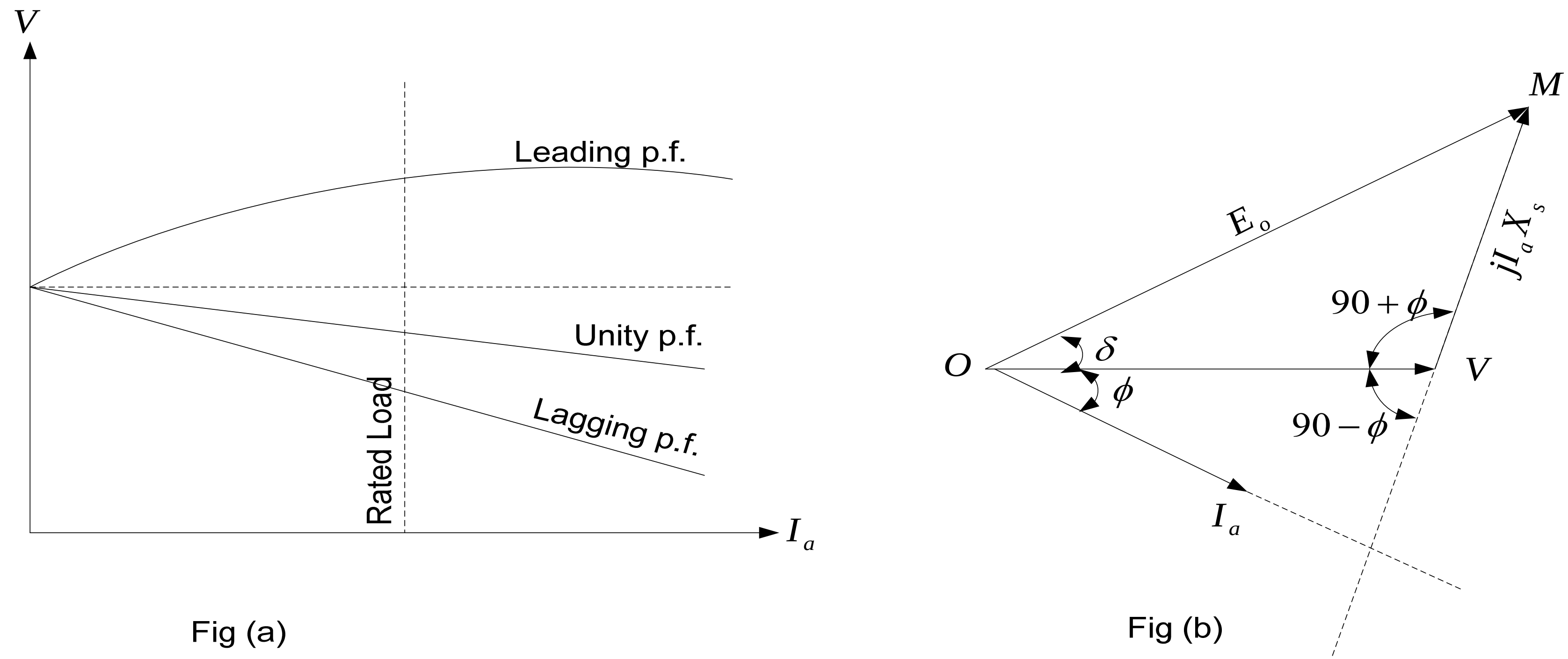


Fig 19: (a) Terminal Voltage Characteristics

(b) Phasor Diagram for Negligible Armature Resistance

Terminal voltage characteristics…cont'd.

- Using the **cosine rule,**
- we obtain $OM^2 = OV^2 + VM^2 - 2 \times OV \times VM \cos \angle OVM$,

from the equation $E_0^2 = V^2 + I^2 X_s^2 - 2 \times V \times IX_s \cos(90 + \phi)$

$$= V^2 + I^2 X_s^2 + 2VIX_s \sin\phi$$

Dividing through by E_0^2

$$1 = \left(\frac{V}{E_0}\right)^2 + I^2\left(\frac{X_s}{E_0}\right)^2 + 2.\left(\frac{V}{E_0}\right).I.\left(\frac{X_s}{E_0}\right).\sin\phi$$

or

$$1 = \left(\frac{V}{E_0}\right)^2 + \left(\frac{I}{I_{sc}}\right)^2 + 2.\left(\frac{V}{E_0}\right).\left(\frac{I}{I_{sc}}\right).\sin\phi$$

Terminal voltage characteristics…cont'd.

Consider the following cases:

- **Case I: Unity Power Factor ($\emptyset = 0$)**

The Equation is now

$$1 = \left(\frac{V}{E_0}\right)^2 + \left(\frac{I}{I_{sc}}\right)^2$$

Terminal voltage characteristics...cont'd.

- Case II: Zero Power Factor *Lagging*

$\phi = 90^0$ and $\sin \phi = 1$

$$1 = \left(\frac{V}{E_0}\right)^2 + \left(\frac{I}{I_{sc}}\right)^2 + 2 \times \left(\frac{V}{E_0}\right) \times \left(\frac{I}{I_{sc}}\right).$$

$$= \left[\left(\frac{V}{E_0}\right) + \left(\frac{I}{I_{sc}}\right)\right]^2$$

or

$$1 = \left(\frac{V}{E_0}\right) + \left(\frac{I}{I_{sc}}\right)$$

$$\Rightarrow \left(\frac{V}{E_0}\right) = 1 - \left(\frac{I}{I_{sc}}\right)$$

Terminal voltage characteristics…cont'd

- Case III: Zero Power Factor *Leading*

$\phi = -90^0$ and $\sin\phi = -1$.

$$1 = \left(\frac{V}{E_0}\right) - \left(\frac{I}{I_{sc}}\right)$$

Compounding Curves

The curve that shows the field current required to maintain rated terminal voltage as the constant-power-factor-load is varied is known as a compounding curve.

Compounding Curves…cont'd.

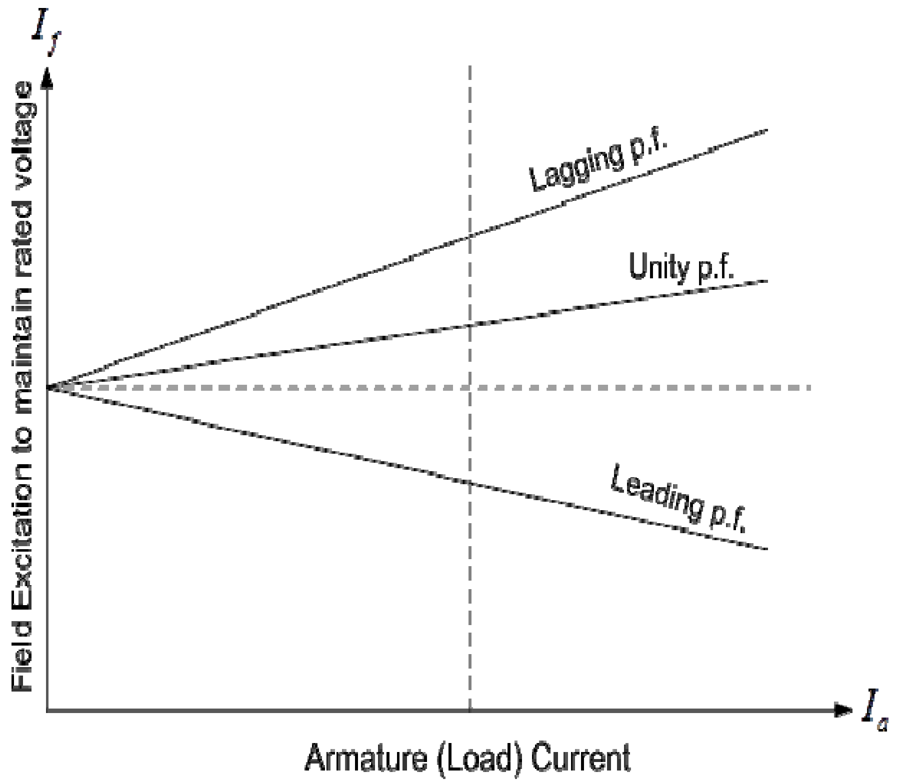


Fig 20: Generator Compounding Curves

Compounding Curves…cont'd.

1. If the field current is held constant while the load varies, the terminal voltage will vary.
2. All unity- and lagging-pf loads will require an increase of excitation with increase of load current
3. Low leading-pf loads will require a decrease of excitation with increase of load current.

Reactive-Active Power Capability Curves (Q -P Curves for a given pf)

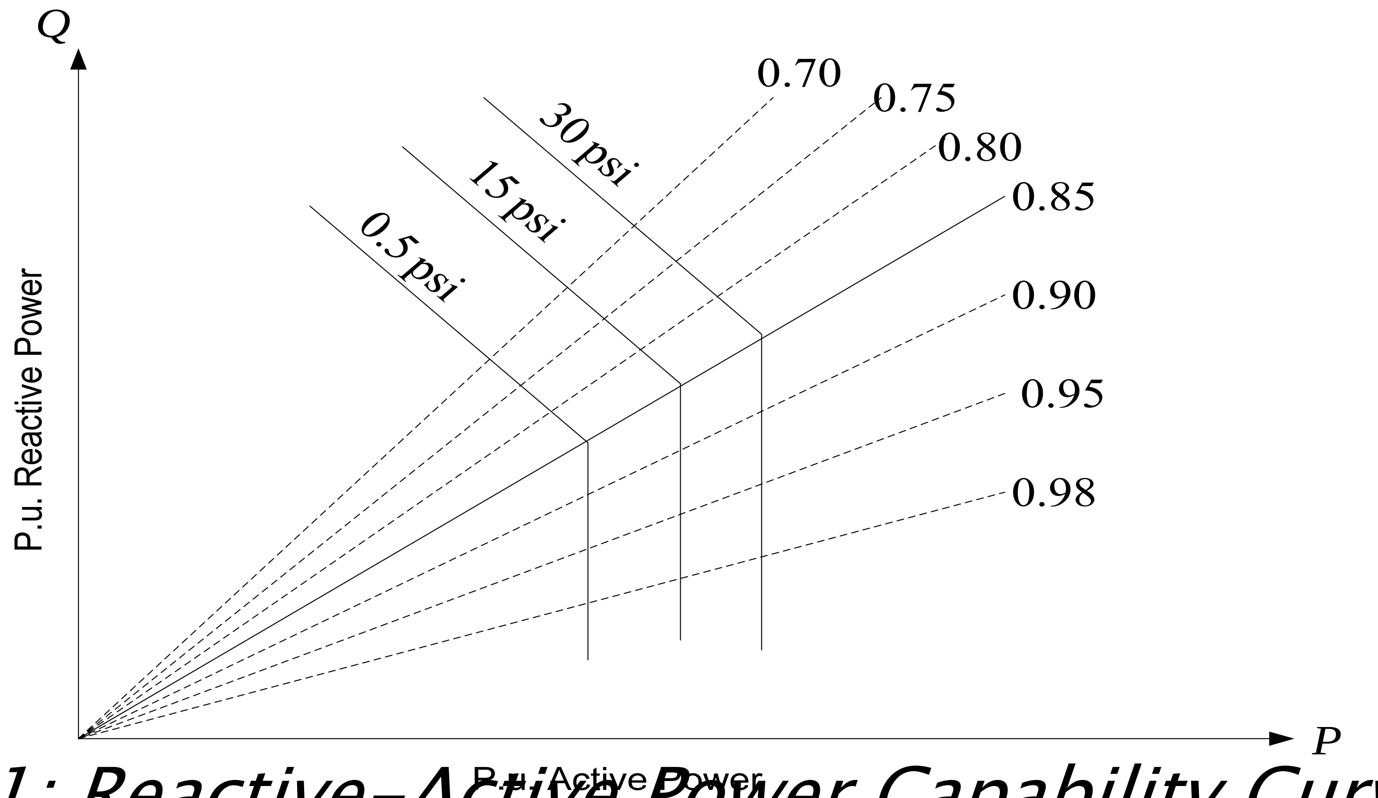


Fig 21: Reactive-Active Power Capability Curves of a Turbo-generator

Exercises on Voltage Regulation

- Exercise 4

- Exercise 5

UNIT 3-PARALLELING OF GENERATORS FOR LOAD SHARING

- **Reasons**

1) Local or regional power demand may exceed the power of a **single** available generator.

2) Parallel generators allow one or more units to be shut down for scheduled or emergency maintenance without having to interrupt power supply to the load.

Paralleling of Generators…cont'd.

3) Generators operate at reduced efficiency at light or part load. And so, shutting down one or more generators allows the remaining load to be supplied by fewer machines that are efficiently loaded.

4) Load growth can be handled by added machines without disturbing the original installation.

Paralleling of Generators…cont'd

5) Available machine prime movers and generators can be matched for economic or optimal utilization in terms of economy and flexibility of use.

Requirements for Generator Paralleling

1) The terminal voltages must be the same at the paralleling or interconnection or tie point or junction, even though not the same at the generators.

2)The phase sequences or rotations for three-phase generators must be the same at the paralleling point.

3) The line frequencies must be identical or approximately equal at the paralleling point.

Requirements for Generator Paralleling …cont'd.

4) With reference to the load, the voltage of the incoming generator must be *in phase* with that of the running machine

5) The incoming generator must generate a *voltage wave* of approximately the *same shape* as that of the running generator.

Synchronization

At the time of synchronization, *all* the conditions for paralleling two or more generators must be met;

1. effective *terminal voltage* of the incoming generator *must be exactly equal to that of the others, or of the busbar connecting them*.
2. *frequencies should be the same*, although it is more desirable that the frequencies at the instant of paralleling be almost, but not quite, identical.
3. *phase sequence or rotation* of the running and incoming generators *must be the same*.
4. individual phase voltages which are to be connected to each other must be in exact phase opposition. This is the same as saying that the terminals of DC generators must be connected positive to positive (+ to +) and negative to negative (– to –).

Synchronization… cont'd

- The requirements of 1, 2 and 3 above are satisfied as follows:

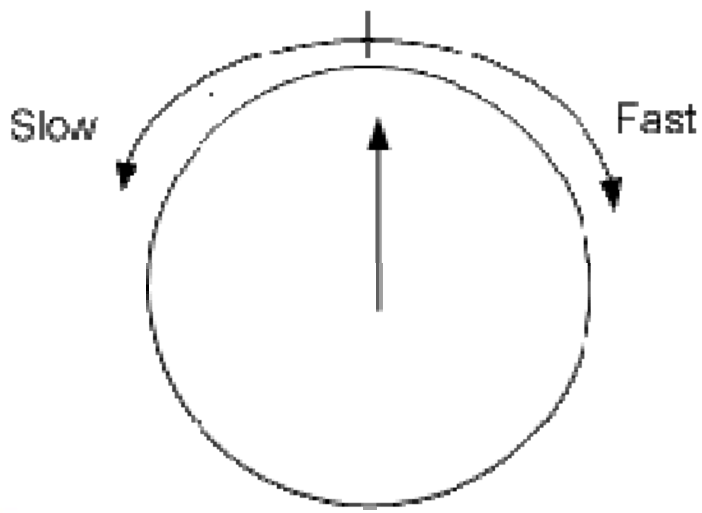
i. The incoming generator *terminal voltage is made equal to the bus line voltage* to which the running machine(s) have already been connected, *by manipulating the DC field excitation*. The effective terminal voltage magnitude can be checked by means of voltmeters.

ii. The frequency, $f = N_s \cdot P/120$, which depends directly on the speed, is adjusted by changing the speed of the prime mover (driving machine).

iii. A *synchronizing device or equipment*, called ***synchroscope***, is used in modern day times to satisfy the condition of *equal phase sequence or rotation*.

Synchroscope Method for Synchronization

- In practice, in large central power station installations, generators are synchronized by means of an indicating instrument called the ***synchroscope***.



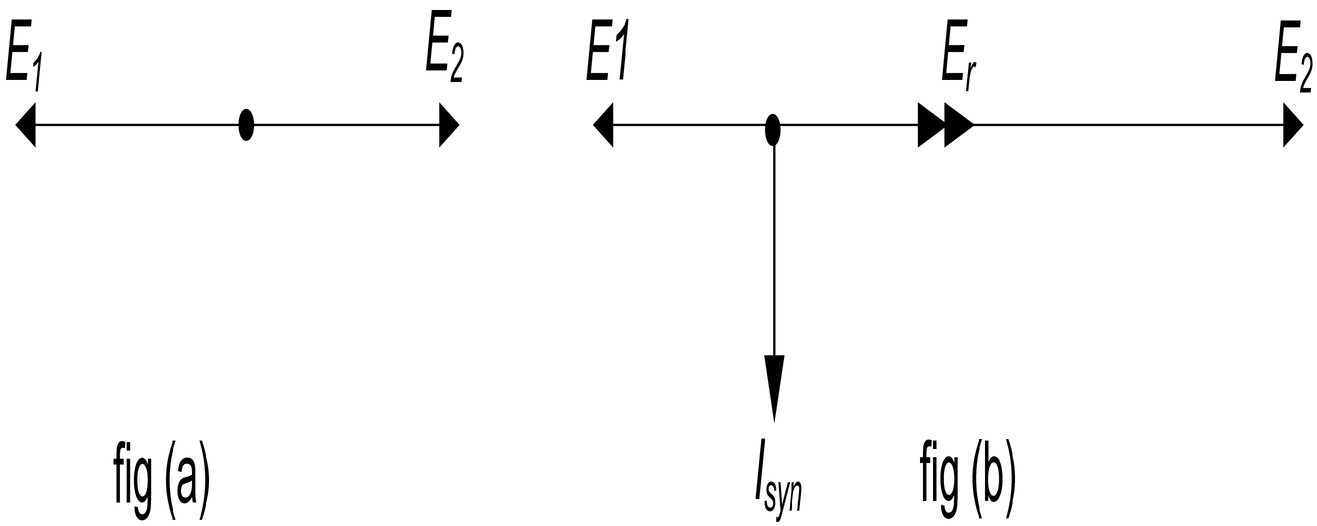
Load Sharing or Allocation

- Any two or more generators that have been synchronized together can be made to **share** the active-power and reactive-power load by appropriate adjustments of the prime-mover throttles and field rheostats respectively.
- In discussing load distribution among two paralleled generators, we shall be looking at the:

1. effect of change in field excitation
2. effect of change in mechanical driving torque of the prime mover

1. Effect of Change in Excitation – Reactive Load Sharing

- Concept of Synchronizing Current



$$I_{syn} = \frac{E_r}{Z} \cong \frac{E_r}{X_s} \text{ (lagging behind } E_r \text{ by } 90^0\text{).}$$

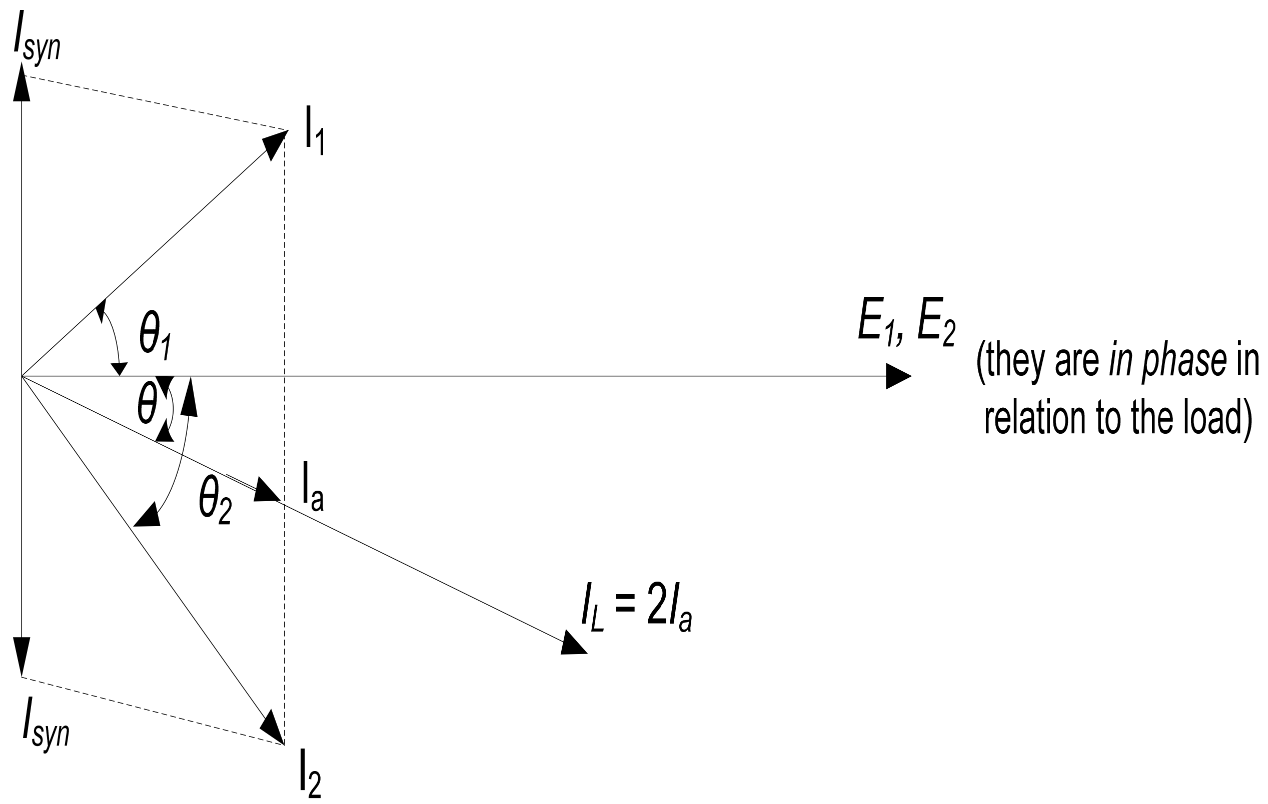
The circulating synchronizing current produces two effects simultaneously:

i. It produces *demagnetizing effect* (because of its lagging) on Generator 2 and decreases the flux in Generator 2, resulting thereby in a reduction in E_2.
ii. But it produces a *magnetizing effect* (because of its leading) on Generator 1 and increases the flux in Generator 1, resulting thereby in an increase in E_1.
iii. However, the active power supplied by each of the generators is not materially affected.

2. Effect of Change in Field Excitation for Paralleled Generators

- Consider two already synchronized generators each supplying current to an external load.
- If the field excitation of one generator is changed, a reactive circulating current (synchronizing current) results, that changes the reactive kVA-output and hence the power factor at which each of the generator is producing. See Fig 24 in next slide.

- *Change in field excitation…cont'd.*



- *Fig 24: Effect of Change in Excitation for Two Paralleled Generators*

Change in field excitation…cont’d.

- The vectors and are shown ***in-phase because they are represented relative to the load***. The synchronous current circulating through Generator 1 is leading , and that through Generator 2 is lagging .

- Effect of Change in Field Excitation for Paralleled Generators…cont'd.

If two generators in parallel supply **equal current** and have the **same power factor**, and the field excitation of one of them is changed, a reactive circulating current (synchronizing current) is established.

- The following points must be noted:

i. If ***excitation is changed, only the power factor*** at which the load is delivered ***by the respective generators*** is changed.

points to note…cont'd.

ii. By keeping the input of the prime mover of a generator constant, any change in field excitation merely changes the reactive-kVA component of the output and the terminal voltage, but not the active-kW output.

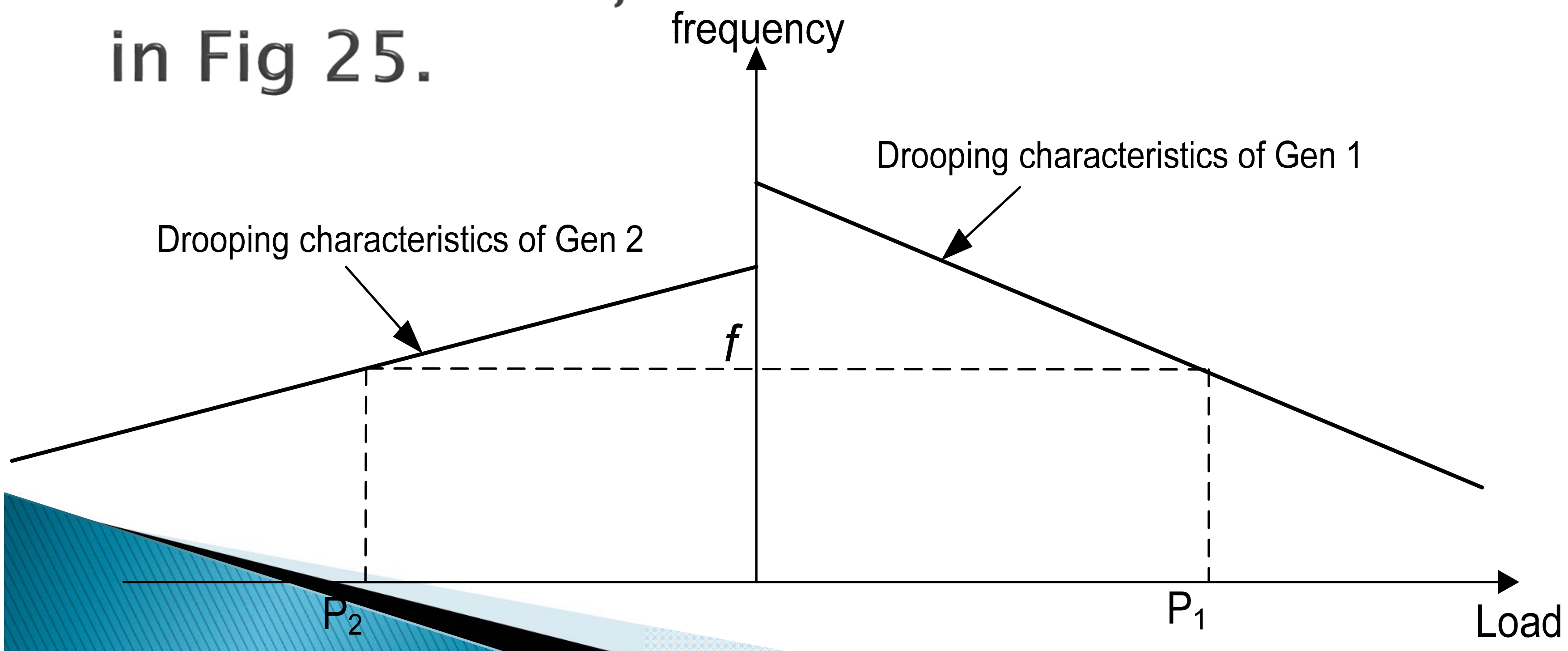
iii. A generator cannot, therefore be made to take an active load merely by increasing its field excitation.

3. Effect of Change in Prime Mover Input – Active Load Sharing

- The load taken up by a generator directly depends on its driving mechanical torque
- Generators in parallel tend to remain synchronized. If the speed of one is increased, it immediately supplies more load and slows down, and the other supplies less load and speeds up, so that the speeds of the alternators again become equal.
- By increasing the input to its prime mover, a generator can be made to take a greater share of the load, though at different power factor

Active Load sharing ...cont'd.

The exact sharing of *active power* between synchronous generators is determined by their speed-load or frequency-load characteristics, which take the form shown in Fig 25.



Active Load sharing ...cont'd.

- For steady state operation, the frequencies of the two machines must be equal. Hence,

$$\omega = \omega_{01} - P_1 \tan\delta_1 = \omega_{02} - P_2 \tan\delta_2$$

- The slope, $\tan\delta$, is termed the ***drooping*** of the characteristics.

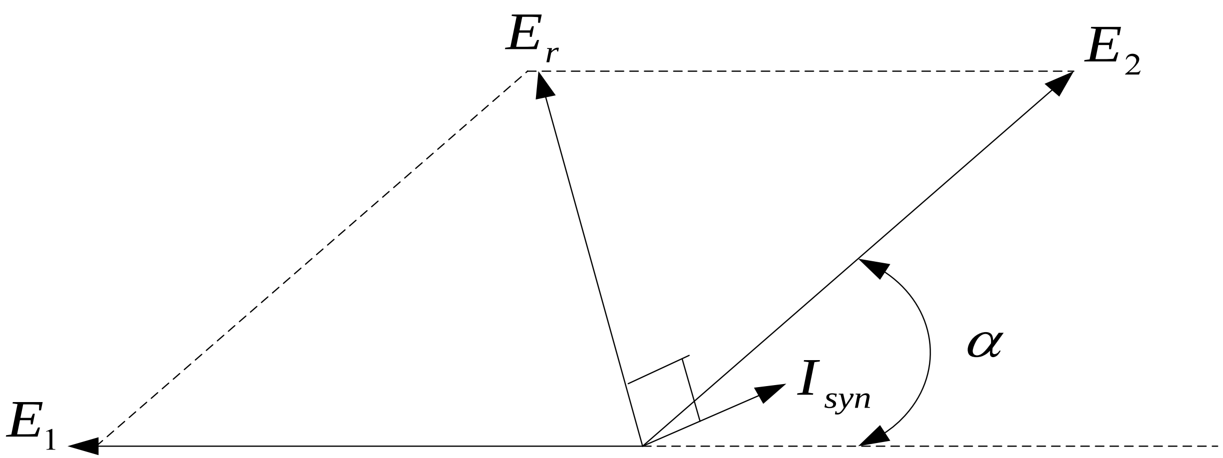
- Changing the speed-load characteristic changes the load sharing, and this involves an alteration to the governor setting.

Examples and Exercises

- Example 10
- Example 11
- Exercises on Parallel Operation of Alternators

Synchronizing Power and Torque – Effect of Increasing the Driving Mechanical Torque

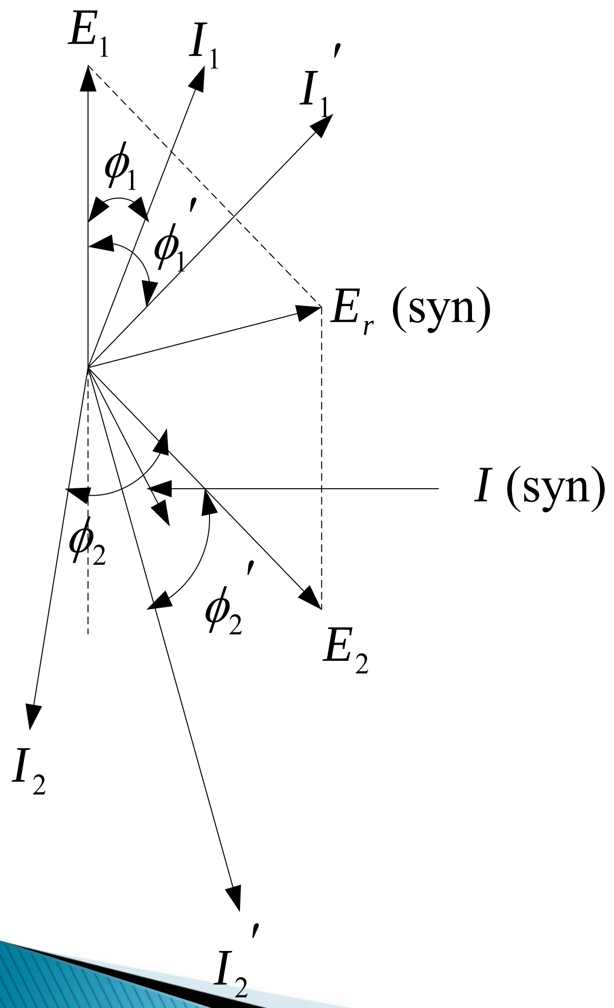
Should the ***torque driving incoming alternator 2 be increased***, by adjusting the throttle opening of the prime mover to admit more steam or water or fuel as the case may be, *the alternator 2 would increase in speed* ***for only a small fraction of a revolution until its induced voltage*** E_2 ***has pulled slightly ahead in phase relation*** α. See Fig 26.



Effect of *Increasing* Prime Mover Power Input to One of Two Alternators Supplying Currents and Different Power Factors

- *If the power input to the prime mover of Machine 2 is increased*, then its emf vector will swing ahead by a certain angle as shown in Fig 27.

Increasing prime mover input…cont'd.



$$\overrightarrow{I_2'} = \overrightarrow{I_2} + \overrightarrow{I_{syn}}$$

$$\overrightarrow{I_1'} = \overrightarrow{I_1} + \overrightarrow{I_{syn}}$$

Synchronizing Power

- If additional power input or torque is supplied to say machine 2 causing it to accelerate, its induced voltage will advance by a small angle δ ahead that of machine 1, and machine 2 will take a greater part of the load as depicted in the following diagram.

Synchronising power…cont’d.

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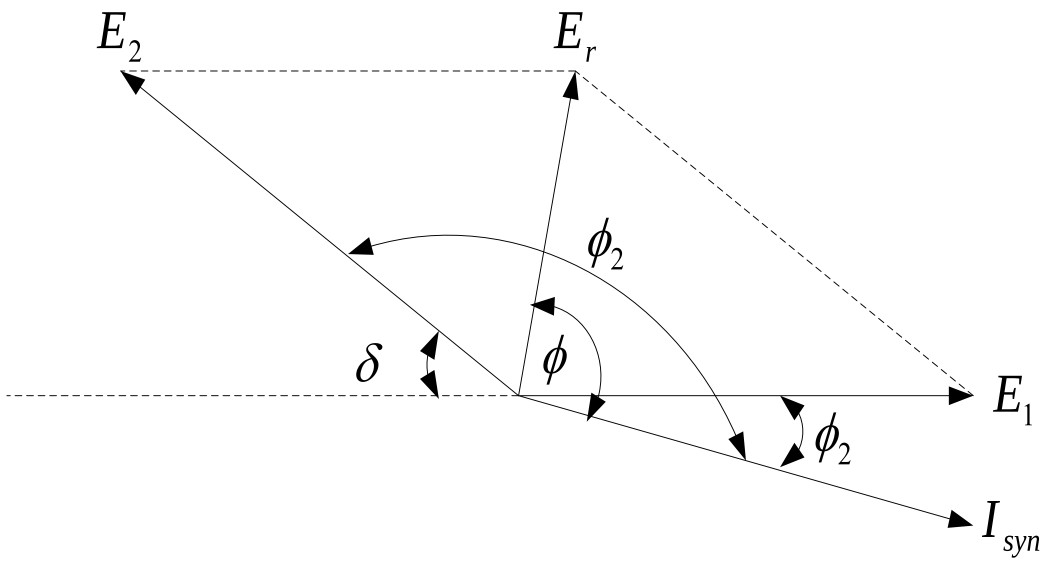


Synchronising power...cont'd.

$$E_r = 2E\cos\left(\frac{180^0 - \delta}{2}\right) = 2E\cos\left(90 - \frac{\delta}{2}\right) = 2E\sin\frac{\delta}{2}$$

$$\delta \text{ is very small, and so for small } \delta, \quad \sin\frac{\delta}{2} \cong \frac{\delta}{2}. \qquad (55)$$

Thus

$$E_r \cong 2E \cdot \frac{\delta}{2} = E\delta$$

The synchronizing current is

$$I_{syn} = \frac{E_r}{Z} \cong \frac{E \cdot \delta}{Z}$$

Active Load sharing ...cont'd.

Power supplied by Alternator 1 is: $E_1 I_{syn} \cos\phi_1$

Power supplied by (accelerated) Alternator 2 is: $E_2 I_{syn} \cos\phi_2$

The ***power supplied by the accelerated alternator*** is called ***synchronizing power***, and is given by the expression P_{syn} as

$$P_{syn} = E_2 I_{syn} \cos\phi_2 = E \cdot \frac{E \cdot \delta}{X_s} \cdot \cos\phi_2$$

Since ϕ_2 is close to 180 degrees, $\cos\phi_2 \cong -1$. Hence (58)

$$P_{syn} = \frac{\delta \cdot E^2}{X_s}$$

- The ***total*** synchronizing power for ***3-phases*** is

$$P_{syn(3\phi)} = \frac{3\delta \cdot E^2}{X_s}$$

- The synchronizing power is produced because the armature impedance is highly inductive.
- The synchronizing power is produced even when their emfs are not equal.
- Alternators in parallel tend to remain synchronized. If the speed of one is increased, it immediately supplies more load and slows down, and the other supplies less load and speeds up, so that the speeds of the alternators again become equal.

Synchronizing Torque

can be caused by:

- a change to the mechanical input from the prime mover or
- a change of armature current due to circuit conditions or
- a change of excitation.

Synchronizing Torque…cont'd.

The synchronizing torque is maximum for no load ($\delta = 0$) and reduces as the machine is more heavily loaded. For a load angle $\delta = \pi/2$ it is zero. $P_{syn} = \dfrac{\partial P}{\partial \delta}$ is the synchronizing power/radian and T_{syn} the torque/radian.

Synchronizing Torque…cont'd

If T_{syn} is the synchronizing torque in $N-m$, the total synchronizing power is related to the synchronizing torque as:

$$P_{syn(3\phi)} = \frac{T_{syn} \cdot 2\pi N_s}{60} = \frac{3\delta \cdot E^2}{X_s}$$

$$\Rightarrow T_{syn} = \frac{P_{syn(3\phi)}}{\omega_s} = \frac{P_{syn(3\phi)}}{\left(2\pi N_s / 60\right)}$$

$$= \frac{3\delta E^2 \cdot 60}{X_s \cdot 2\pi N_s}$$

Examples

- Example 12
- Example 13
- Example 14

Relationship Between Mechanical (Rotor) Angular Displacement α_{mech} and Electrical Displacement δ.

- The number of electrical degrees equals times the number of mechanical degrees in any machine, where is the number of poles.

$$\delta_{elec} = \frac{P}{2} \alpha_{mech}$$

Hunting of Alternators

- When two alternators are operating in parallel, *any instantaneous reduction in the angular velocity of one machine*, due to variations in the load, causes:

i. A change in load division between them and
ii. A synchronizing current to circulate

- Hunting generally occurs in alternators driven by reciprocating engines, because the driving torque of reciprocating engines is not uniform in a revolution of the flywheel.
- The torque output will *pulsate* if the prime mover of one of the alternators is a reciprocating engine.

Hunting of Alternators…cont'd.

- Turbo-generators seldom hunt, because the prime mover supplies a uniform driving torque.
- It is customary to specify, for alternators to be operated in parallel, the allowable torque-angle variation.
- Machines driven by internal combustion engines must have large flywheels or heavy damping windings to prevent excessive oscillations.

Reducing Hunting in Alternators

- Dampening of the oscillations by use of a *heavy squirrel-cage dampening winding* placed on the field poles
- Changing the *natural* period of vibration of the machine by changing the flywheel (a *heavier flywheel* usually gives a more dampening effect).
- Dampening the governor, if the oscillations are started by the action of the governor.

Exercises on Synchronizing Power and Torque

- Exercise 7

- Exercise 8

UNIT 4—
THREE-PHASE SYNCHRONOUS MOTORS

- The synchronous motor is one type of three-phase AC motor, which operates at a constant speed from no-load to full-load.

Constructional Features and Principles of Operation of Synchronous Motors

- *Laminated stator core* with three-phase stator (*armature*) windings.
- *Rotating DC field* windings on the rotor, complete with slips rings,
- Brushes and brush holders,
- Two-end shields to house the bearings that support the shaft.

Principle of Operation of Synchronous Motors

- In a three-phase synchronous motor, a polyphase current is supplied to the stator winding, and it produces a ***revolving magnetic field or flux*** travelling at synchronous speed or , as in an induction motor.
- A direct current is supplied to the rotor winding, and it produces a ***fixed polarity*** at each pole of the rotor.

Principle of Operation…cont'd.

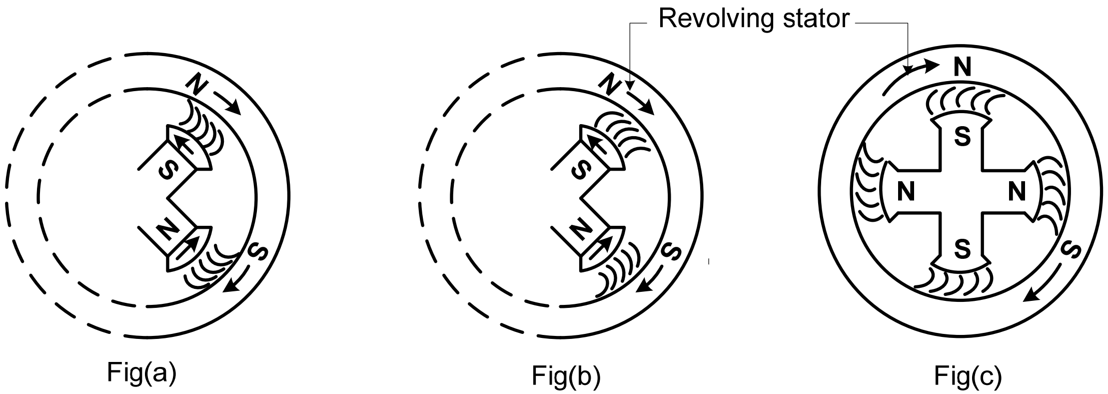


Fig 28: Principle of Operation of Locking Synchronous Motors into Synchronism with the Revolving Stator Magnetic Field

Why Synchronous Motors Are Not Self-Starting

- The revolving stator magnetic field tends to pull the rotor poles first in one direction and then in the other direction, and as a result, **the starting torque is zero.**

- The **synchronous motor is thus inherently not self-starting**, unless some starting mechanisms or techniques are employed.

Starting of Synchronous Motors – Use of *Damper Windings* as Squirrel-Cage Induction Motor

- It is practically impossible to start a synchronous motor with its DC field energized, as the net starting torque is zero.

- A *squirrel-cage winding* is generally placed on the rotor poles of a synchronous motor to make the machine self-starting.

Necessary Precaution When Starting Synchronous Motor – Use of *External Starting Resistance*

- *The rotor winding has a large number of turns and therefore an **extremely high voltage is induced in the many turns of the field winding, which will appear between its terminals**.*

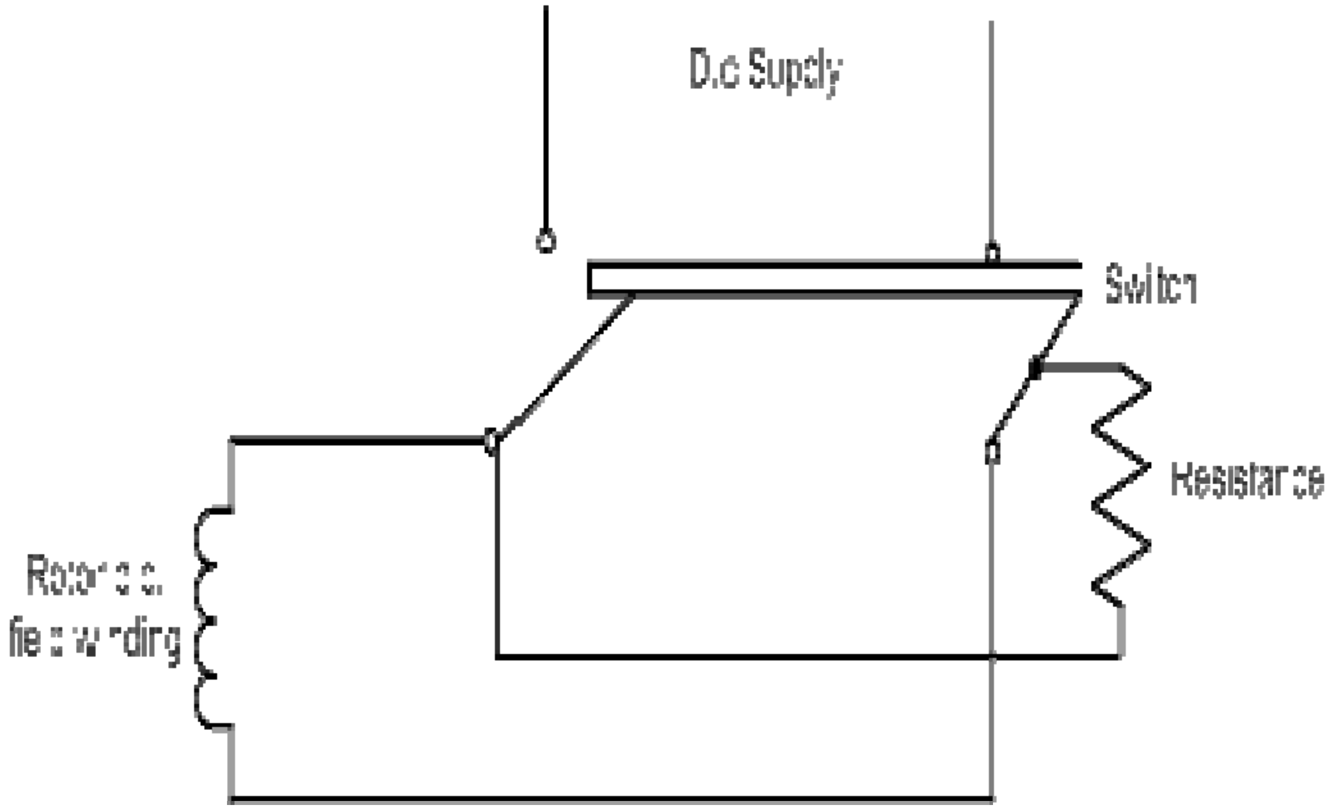
- *A high-peak terminal voltage also appears when the rotor circuit of a machine in operation is opened.*

Precautions…cont'd.

- These high voltages will puncture the insulation, unless the winding is highly insulated.

- In practice, to contain this phenomenon, the DC *field winding is short-circuited during the starting period through a very low resistance* connected to the switch of the rotor circuit.

Precautions…cont'd.



- *Fig 29: Precautionary Measure Taken During The Starting of Synchronous Motor*

Synchronous Capacitors

- *Synchronous capacitors* are actually synchronous motors that are operating on *no-load (without a connected mechanical load)* for the purpose of power factor correction or improving the voltage regulation of a transmission line.

Advantages of Synchronous Condensers over Capacitors

- The ease with which the power factor can be controlled by either producing or absorbing reactive power.
- Their performance can be regulated continuously and smoothly over a wide range.
- They are more practical than capacitors.
- The speed of the synchronous motor is constant and independent of load.

Disadvantages of Synchronous Condensers compared with Capacitors

- Some arrangement must be provided for starting and synchronizing the motor
- A DC supply is necessary for the rotor excitation.
- Synchronous motors contribute to the current flowing into a short-circuit fault on the system, and may call for additional expenditure in switchgear.
- They are more expensive that static capacitors.

Effect of Loading on the Synchronous Motor

- When the mechanical load on a DC or AC motor is increased, the speed, *N*, falls. Consequently, in accordance with the relation

$$E_b = E_g = \frac{\Phi Z N P}{60b}$$

- This fall in speed in turn decreases the back or counter emf E_b(equal to the generated voltage E_g), so that the source is able to supply more current (for a DC motor) to meet the increased load demands.

Torque Angle at No-Load

- At *no-load*, the stator and rotor *pole centres are directly in line* with each other.

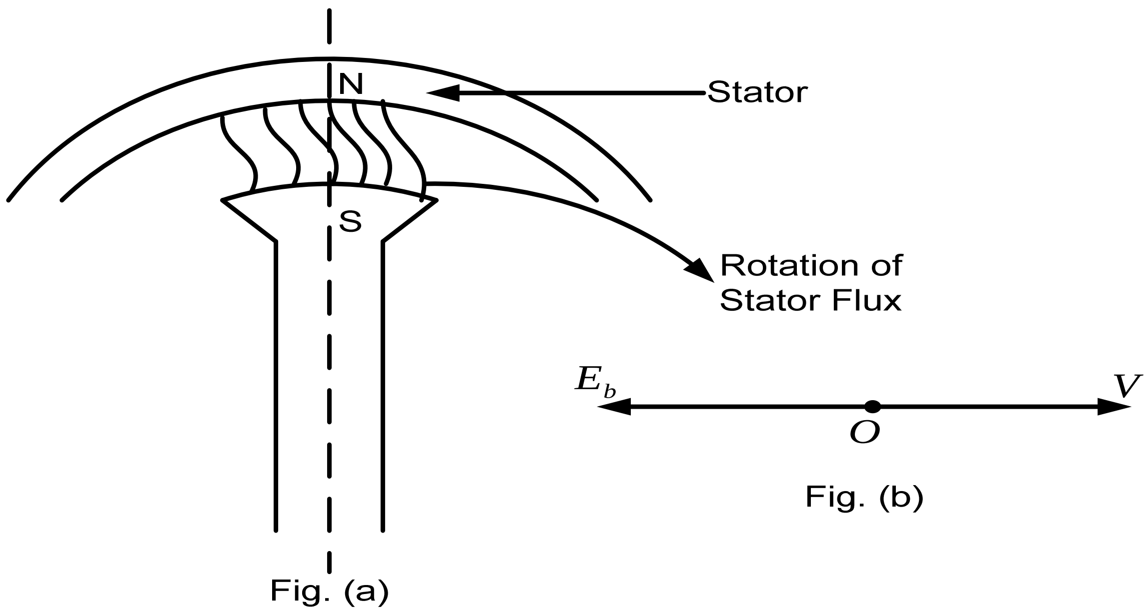


Fig 30: (a) Torque Angle at No-Load (b) No-Load Condition Vector Diagram

Torque Angle at Rated Load

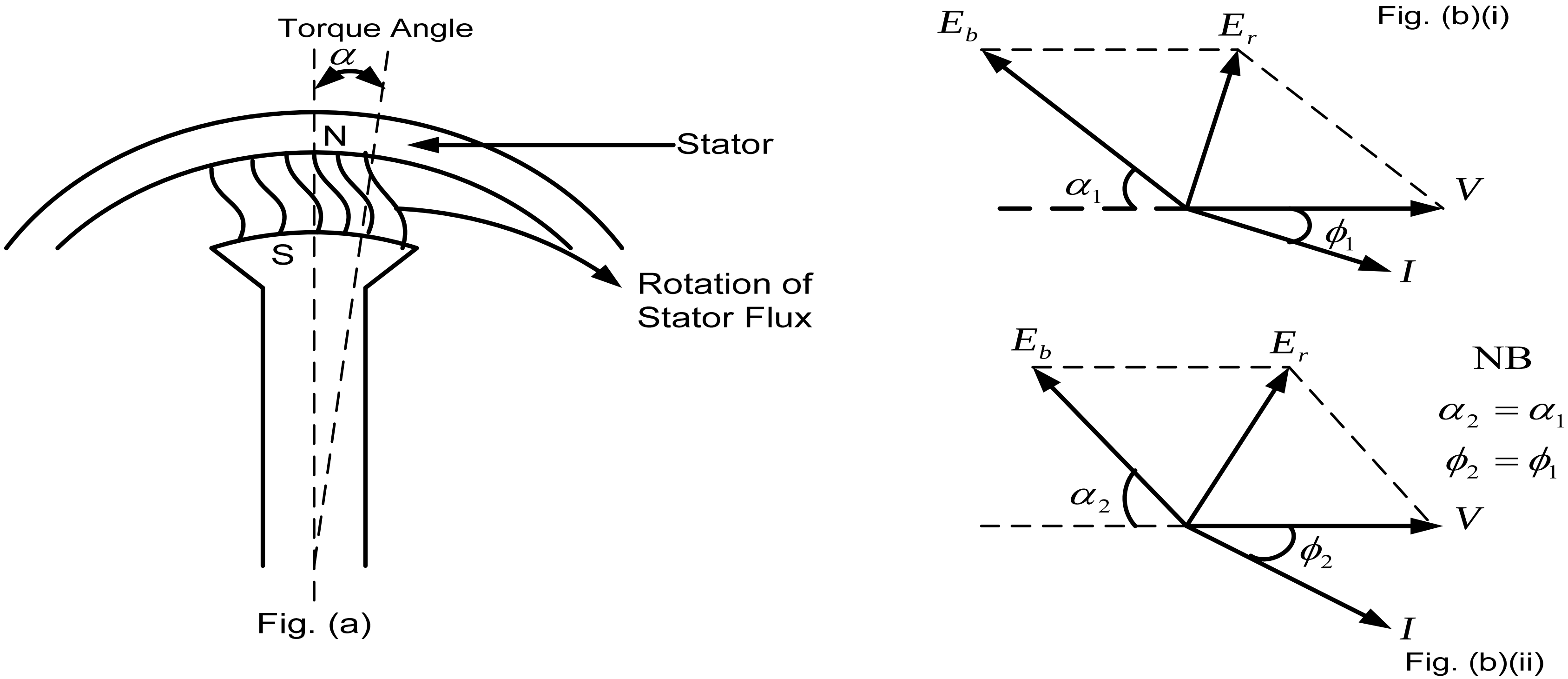


Fig 31: (a) Torque Angle at Rated Load (b) Rated Load Condition Vector Diagrams

Torque Angle…cont'd.

- The torque angle increases with the increase in load.
- For increasing load with a constant value of generated or back emf , the phase angle ϕ increases in lagging direction.

Operating Characteristics of Synchronous Motors

- Electrical utility companies usually charge industries for operating at low power factors below a specified level, say, 0.9.
- Utility companies attempt to correct the power factor of their systems.
- 2 methods can be used:

i. Power-factor corrective capacitors
ii. Three-phase synchronous motors

V-Curves or *Compounding Curves* of the Synchronous Motor (Effect of Rotor Field Excitation on Armature Current and Power Factor *for Constant Mechanical Load*)

- Three operational conditions may exist, depending on the amount of excitation applied to the rotor:

i. Under-excitation – operation at lagging power factor (inductive effect)
ii. Normal excitation – operation at unity power factor (resistive effect)
iii. Over-excitation – operation at leading power factor (capacitive effect)

Case 1: Under-Excitation $E_b < V$ (*Lagging* Power factor)

- Since the speed is constant, the induced voltage *decreases*.

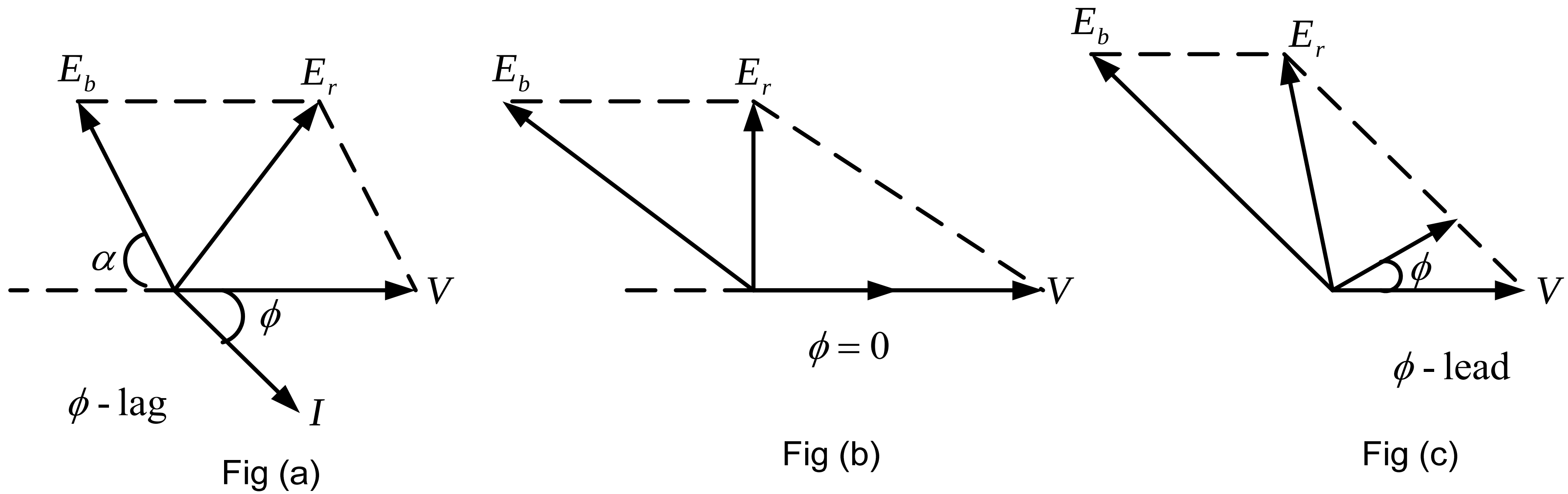


Fig 32: Effect of Varying DC Excitation on Armature Current for Constant Shaft Load (a) Under-Excitation (b) Normal Excitation (c) Over-Excitation

Case 2: Normal Excitation $E_b = V$ (*Unity* Power factor)

- For a given load at unity power factor, the resultant voltage and therefore the stator current are minima.

Case 3: Over-Excitation $E_b > V$ (*Leading* Power factor)

- If the field excitation is still further increased, the induced voltage is increased, the current increases and ***leads*** the applied voltage.

- Hence for a given load, the power factor is governed by the dc field excitation. A weak field excitation produces a lagging current and a strong field produces a leading current.

Characteristic curves

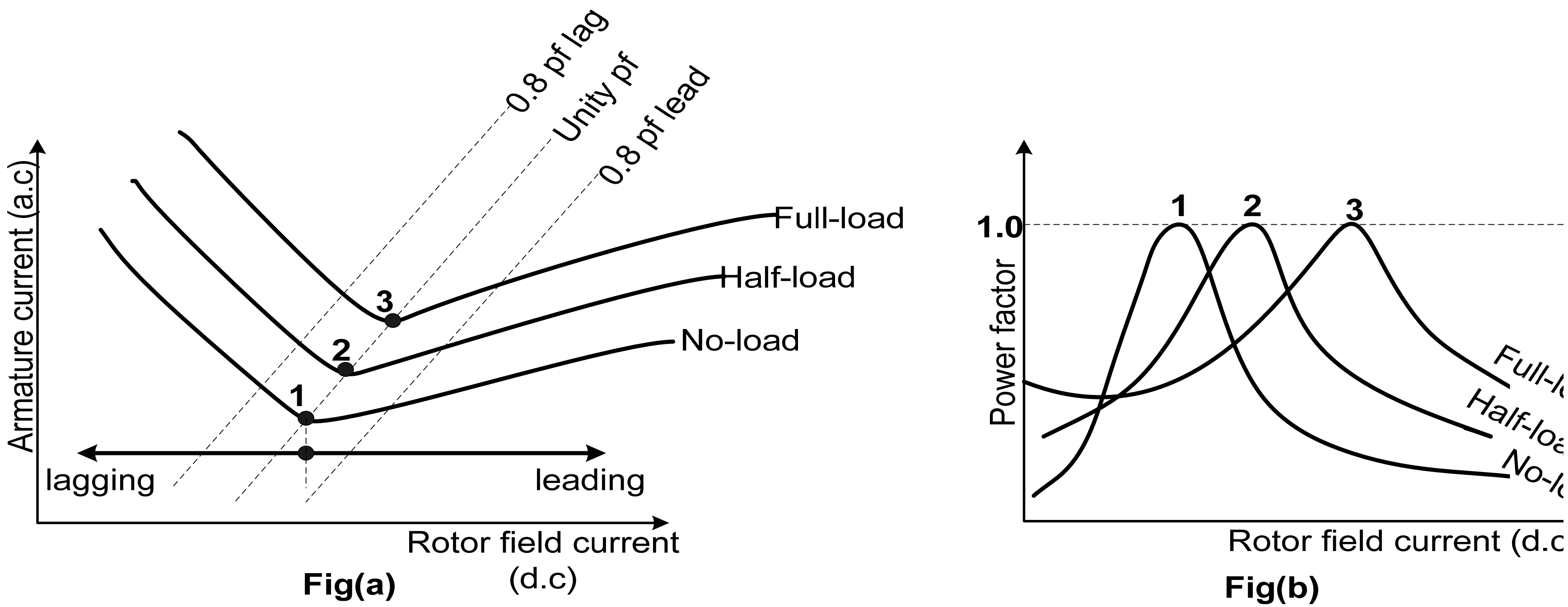


Fig 33: Characteristic V-Curves of a Three-Phase Synchronous Motor

(a) Stator Current versus Rotor Current at a Particular Load

(b) Power Factor versus Rotor Current at a Particular Load

Observations about V-curves of Synchronous Motor

- Note the variation of stator current drawn by the synchronous motor as rotor dc excitation current varies
- The situations shown on the graph of Fig 33 (a) above indicate no-load, half-load and full-load conditions with power factors equal to unity, 0.8 leading and 0.8 lagging.
- The graph of Fig 33 (b) shows variation of power factor with changes in rotor dc excitation under three different load conditions (no-load, half-load and full-load).

observations…cont'd.

- Observe that for a given load or output power, the stator current is minimum when the power factor equals unity.
- The dashed lines are loci of constant power factor (0.8 leading, unity and 0.8 lagging).
- Points to the right of the unity power factor compounding curve correspond to over-excitation and leading current input
- Points to the left of the unity power factor compounding curve correspond to under-excitation and lagging current input
- The synchronous motor compounding curves, as in Fig 33 (a) above, are very similar to the generator compounding curve.

Circuit and Phasor Diagram for Over-Excitation and Leading Pf

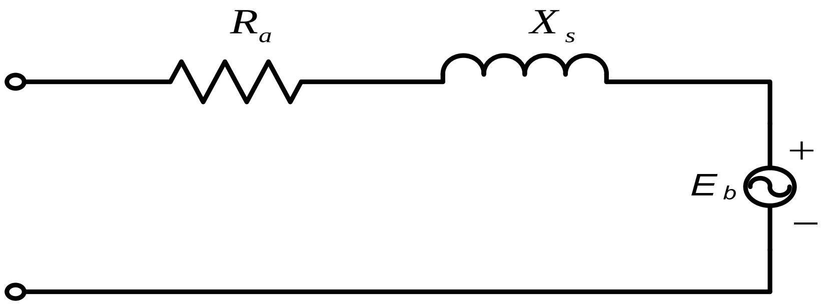


Fig (a)

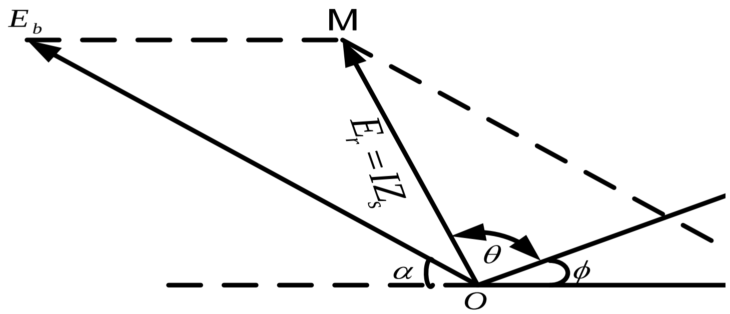


Fig (b)

Fig 34: (a) Equivalent Circuit (b) Phasor Diagram of Synchronous Motor for Over-Excitation and Leading Power Factor ϕ

Generated emf per Phase in Synchronous Motor

$$E_b = \sqrt{V^2 + E_r^2 - 2 \times V \times E_r \cos(\theta \pm \phi)}$$
$$= \sqrt{V^2 + (IZ_s)^2 - 2 \times V \times IZ_s \cos(\theta \pm \phi)}$$

+ sign : leading pf

- sign : lagging pf

$\phi = 0$: unity pf

Mechanical Power per Phase Developed By Synchronous Motor

The mechanical power developed *per phase* in the rotor is

$$P_{mech} = \frac{E_b V}{Z_s}\cos(\theta - \alpha) - \frac{E_b^2}{Z_s}\cos\theta$$

Maximum Mechanical Power Developed in Synchronous Motor

The value of maximum power is then obtained for $\theta = \alpha$ as

$$P_{mech\,\max} = \frac{E_b V}{Z_s} - \frac{E_b{}^2}{Z_s}\cos\alpha$$

$$= \frac{E_b V}{Z_s} - \frac{E_b{}^2}{Z_s}\cos\theta$$

Notes on maximum power developed:

1. The *maximum power and hence torque* (speed is constant at synchronous value) *depends on* V *and* E_b, *i.e., excitation*.
2. The maximum value of θ and hence α is 90^0. For all values of V and E_b, this limiting value of α is the same, but maximum torque will be proportional to the maximum power developed as given in Eqn (68).

Mechanical torque

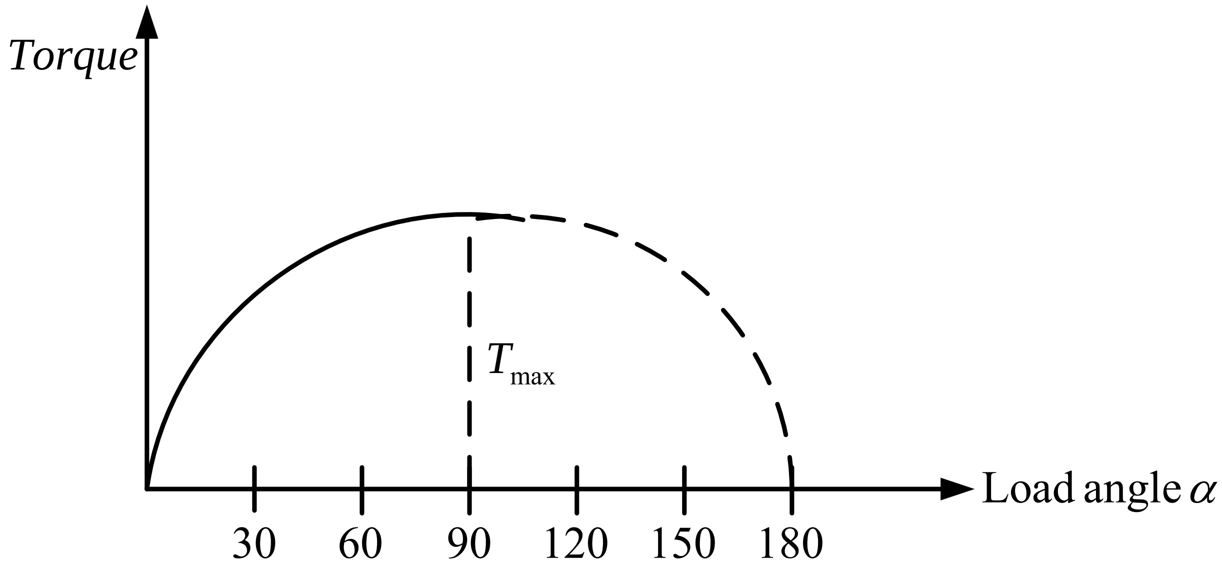


Fig 35: Mechanical Torque of Synchronous Motor as Function of Load Angle α

Mechanical power…cont'd.

Mechanical Power Developed in Rotor of Synchronous Motor for Negligible Armature Resistance $R_a \cong 0$ **:**

If armature resistance R_a is neglected, then

$$Z_s \approx X_s \quad \text{and} \;\; \theta = \tan^{-1}\frac{X_s}{(R_a = 0)} = 90^0 \tag{69}$$

Hence for negligible armature resistance $R_a \cong 0$, the mechanical power expression of Eqn (83) reduces to

$$\begin{aligned} P_{mech} &= \frac{E_b V}{X_s}\cos(90^0 - \alpha) \\ &= \frac{E_b V}{X_s}\sin\alpha \;\; \text{(for negligible armature resistance)} \end{aligned} \tag{70}$$

Maximum Power from Synchronous Motor

Generally, the maximum torque from a synchronous motor is

$$P_{mech\max} = \frac{E_b V}{X_s} \qquad \text{armature resistance neglected}$$

$$= \frac{E_b}{Z_s}\left(V - E_b \cos\theta\right) \qquad \text{armature resistance considered} \qquad (71)$$

$$\text{where } \cos\theta = \frac{R_a}{Z_s}$$

This corresponds to the *"pull-out"* torque

$$T_{\max} = \frac{P_{mech\max}}{\omega_s} = \frac{P_{mech\max}}{2\pi(f/p)} \qquad (72)$$

where f is the frequency and p is the *pole pairs*.

Circuit and Phasor Diagram for *Normal Excitation* and *Unity pf* in Synchronous Motor

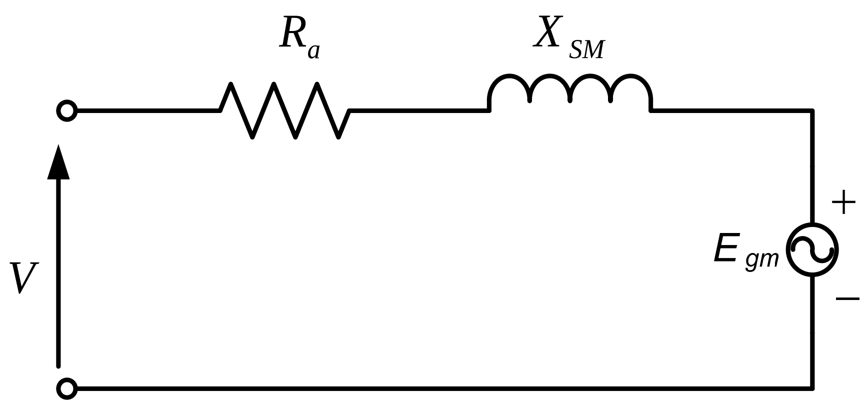


Fig (a)

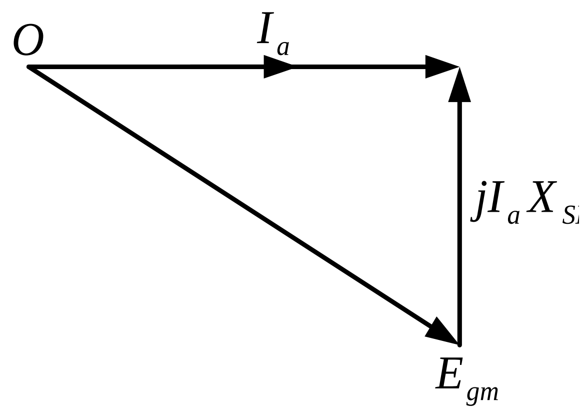


Fig (b)

Fig 36: (a) Equivalent Circuit (b) Phasor Diagram of Synchronous Motor at Normal Excitation and Unity Power Factor

From the phasor diagram at full-load,

$$E_b = \sqrt{V^2 + (IZ_s)^2}$$

Examples and Exercises

- Examples 15-19

- Exercises on Synchronous Motors

Exercise 9
Exercise 10
Exercise 11
Exercise 12

THE END