# Lecture Notes
# ELE-A6

**Ramadan El-Shatshat**

**Synchronous Machine**

# Classification of AC Rotating Machines

- **Synchronous Machines:**
- **Synchronous Generators:** A primary source of electrical energy.

- **Synchronous Motors:** Used as motors as well as power factor compensators (synchronous condensers).

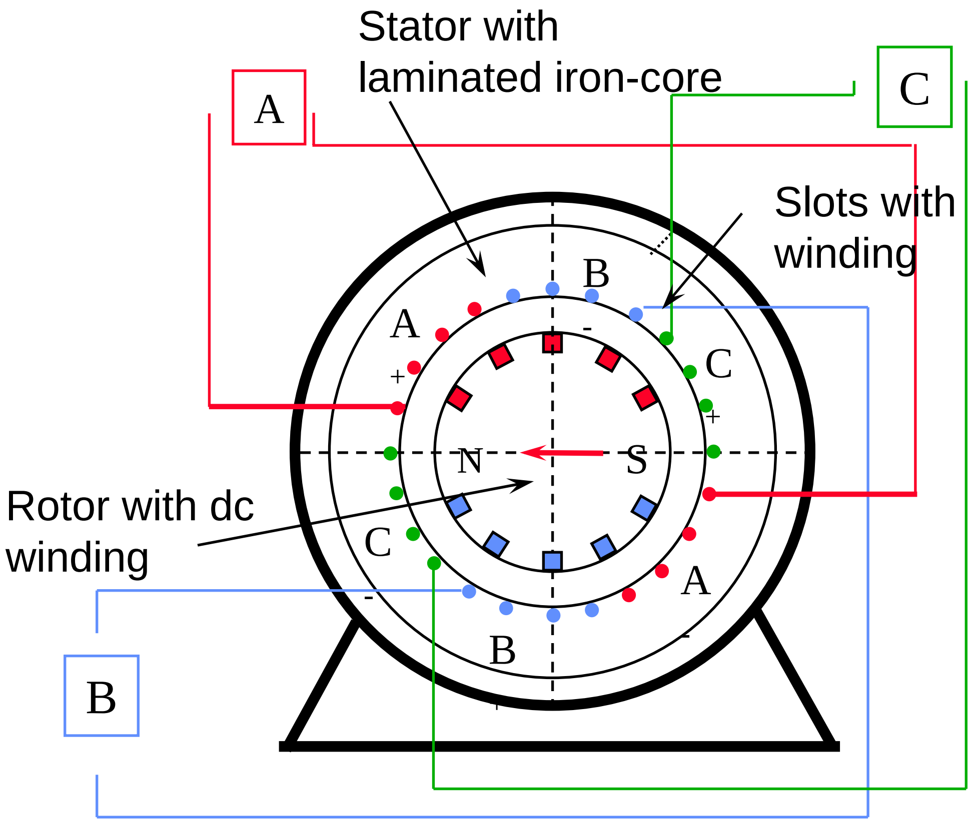
- **Asynchronous (Induction) Machines:**
- **Induction Motors:** Most widely used electrical motors in both domestic and industrial applications.
-
- **Induction Generators:** Due to lack of a separate field excitation, these machines are rarely used as generators.

# SYNCHRONOUS MACHINES

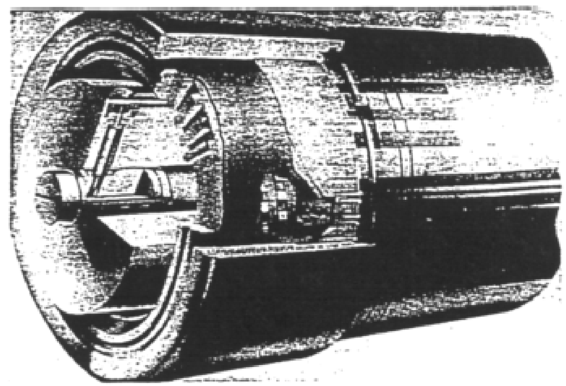
**Round Rotor Machine**

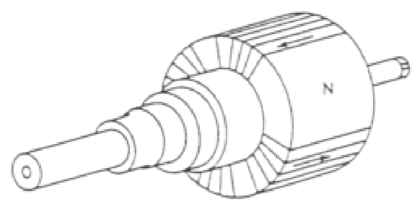
- **The stator is a ring shaped laminated iron-core with slots.**
- **Three phase windings are placed in the slots.**
- **Round solid iron rotor with slots.**
- **A single winding is placed in the slots. Dc current is supplied through slip rings.**

**Concept (two poles)**

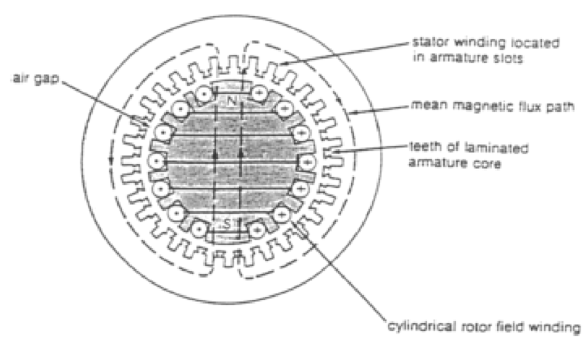


# Round Rotor Machine






Side view



# SYNCHRONOUS MACHINES

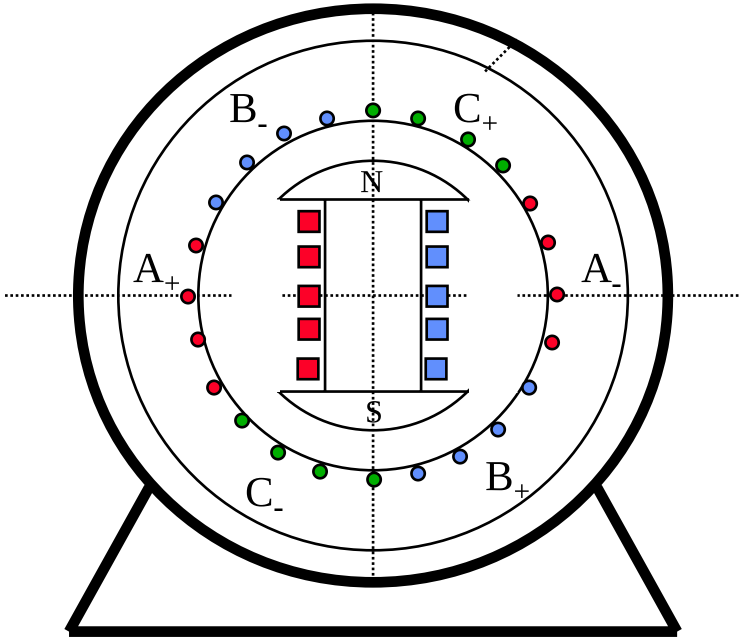
**<u>Salient Rotor Machine</u>**

- The stator has a laminated iron-core with slots and three phase windings placed in the slots.

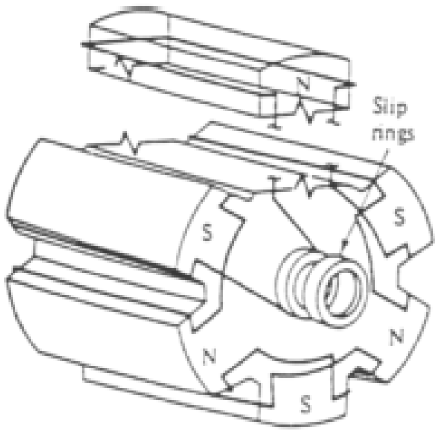
- The rotor has salient poles excited by dc current.

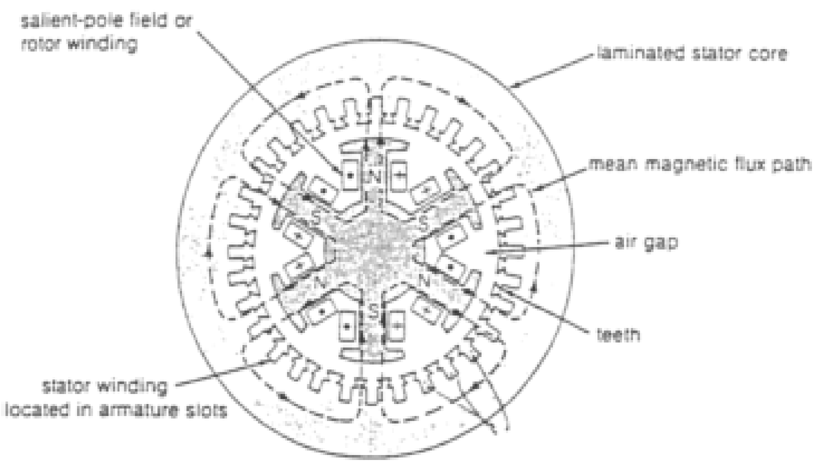
- DC current is supplied to the rotor through slip-rings and brushes.

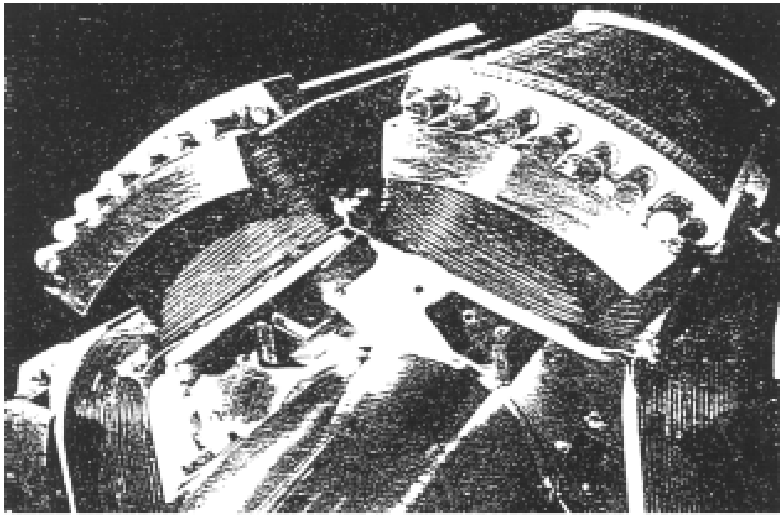
- **<u>Concept (two poles)</u>**

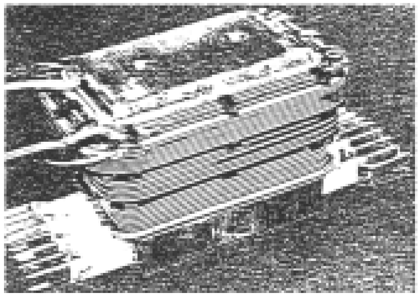


# Salient Rotor Machine



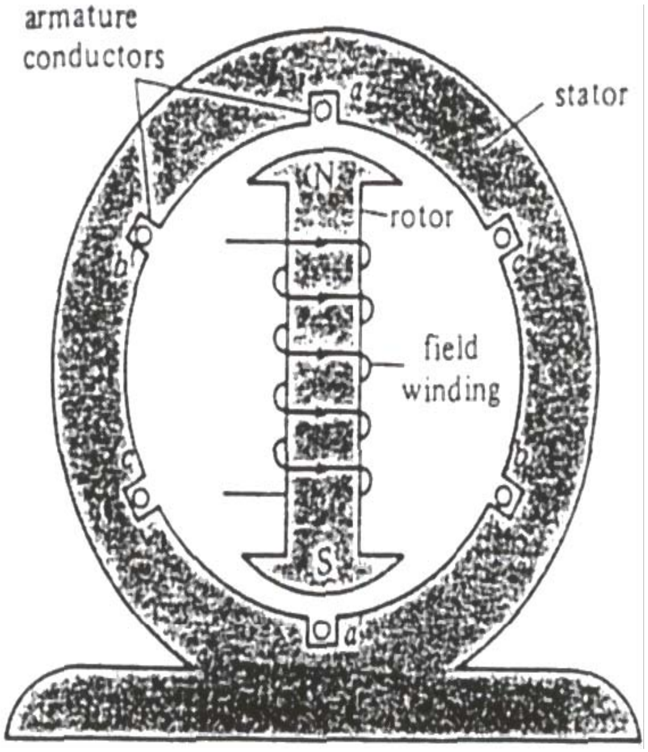





# SYNCHRONOUS GENERATOR

- **Principle of Operation**

1) From an external source, the field winding is supplied with a DC current -> excitation.
2) Rotor (field) winding is mechanically turned (rotated) at synchronous speed.
3) The rotating magnetic field produced by the field current induces voltages in the outer stator (armature) winding. The frequency of these voltages is in synchronism with the rotor speed.



# SYNCHRONOUS MACHINES

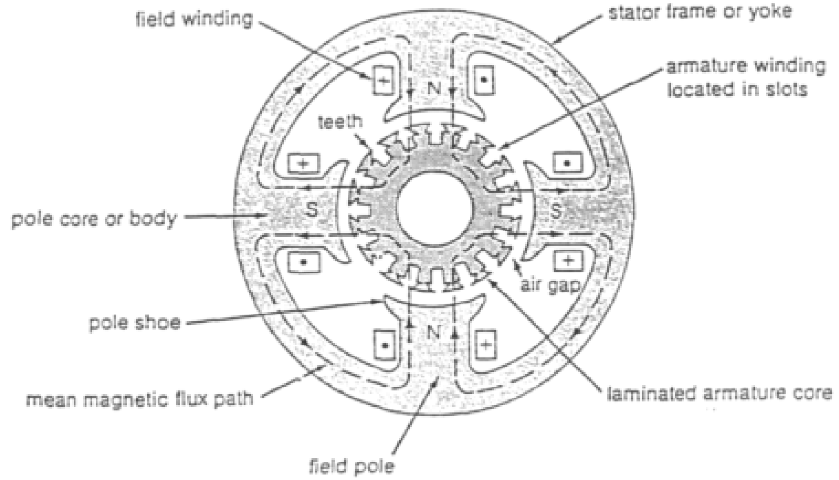
**Operation concept**

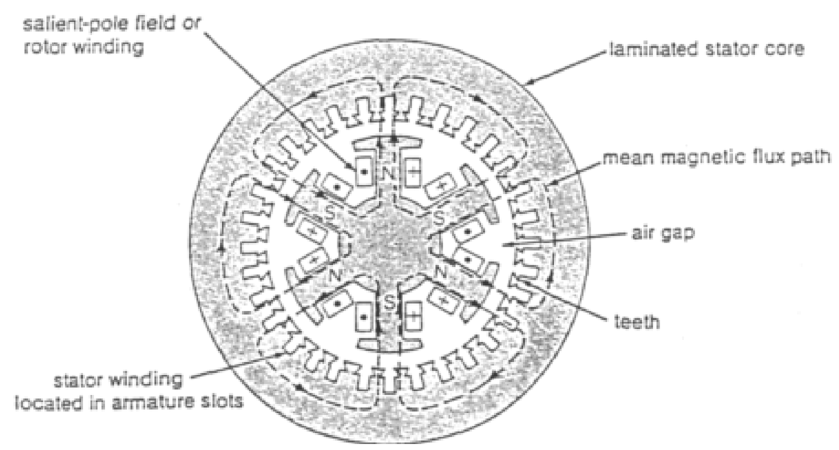
- The frequency - speed relation is $\mathbf{f = (p / 120)\ n = p\ n / 120}$
  **p** is the number of poles.
- Typical rotor speeds are 3600 rpm for 2-pole, 1800 rpm for 4 pole and 450 rpm for 16 poles.
- The rms. value of the induced voltages is:

$$E_A = 4.44\ N\ BA\ f\ ,\ (BA = \phi)$$

- where:
  N = number of turns, B= flux density, A = cross sectional area of the magnetic circuit, f = frequency, and $\phi$ = flux per pole

# Comparisons Between DC and Synchronous Machines



# Synchronous Generators Equivalent Circuit (round rotor)

1) DC current in the field winding produces the main flux, $\phi_f$.

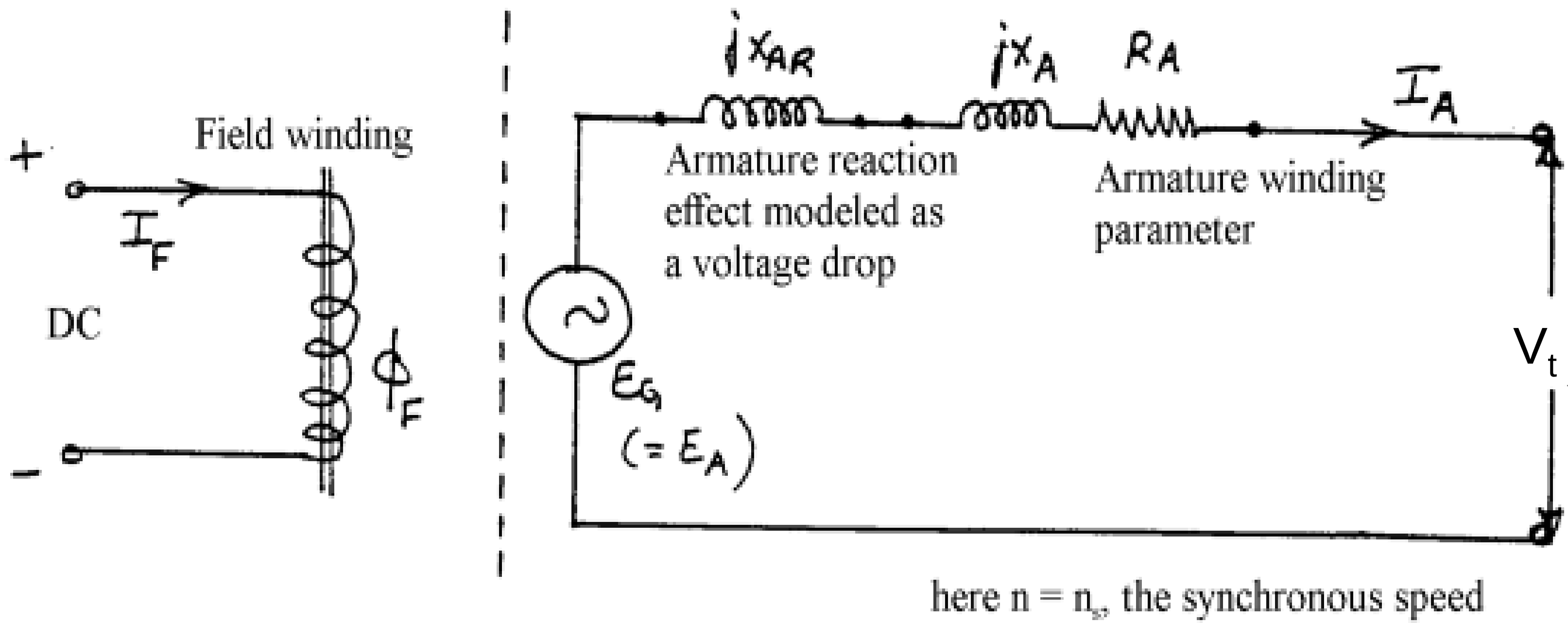
2) $\phi_f$ induces an emf, $E_G$, in the armature winding.

3) Depending on the load condition, the armature current $I_A$ is established. In the following discussions, it is assumed to be a lagging power factor.

*4)* $I_A$ produces its own flux due to armature reaction, $E_{AR}$ is the induced emf by $\phi_{AR}$.

5) The resulting phasor, $E_{resultant} = E_G + E_{AR}$ is the "true" induced emf that is available.

# Synchronous Generators Equivalent Circuit (round rotor)



# Synchronous Generators Equivalent Circuit (round rotor)

**Phasor Diagrams:**

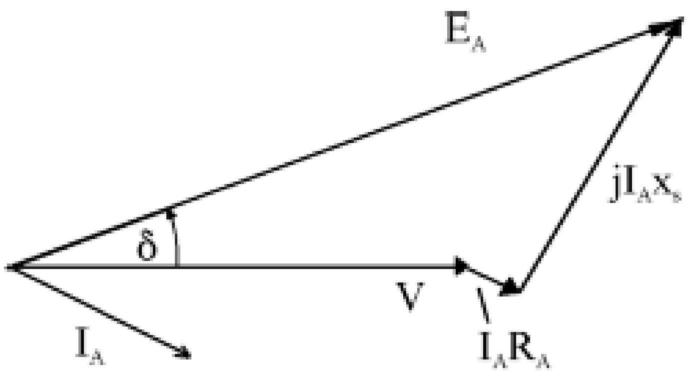
$$V_t = E_A - I_A jX_A - I_A jX_{AR} - I_A R_A = E_A - jX_s I_A - I_A R_A$$

$$V_t = E_A - I_A\left(R_A + jX_s\right)$$

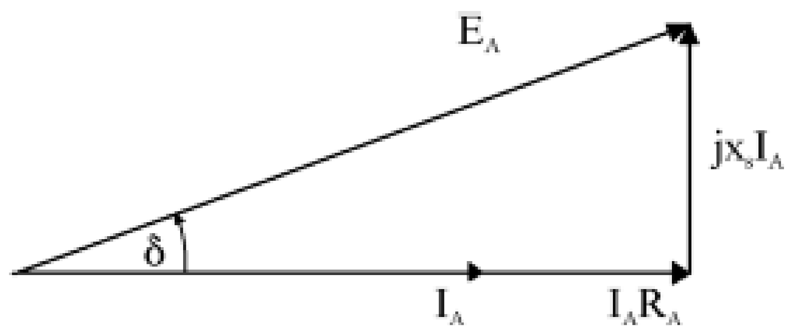
where, ($X_{AR}$ + $X_A$) = synchronous reactance, $X_s$.

# Synchronous Generators Equivalent Circuit (round rotor)

**Inductive Load**




**Resistive Load**




$\delta$ = power angle

# Power Supplied by a Synchronous Generator

$$S = P + jQ = 3V_t I_A^{\ *}$$

$$S = 3V_t\angle 0\left(\frac{E_a\angle(-\delta) - V_t\angle 0}{-jX_s}\right)$$

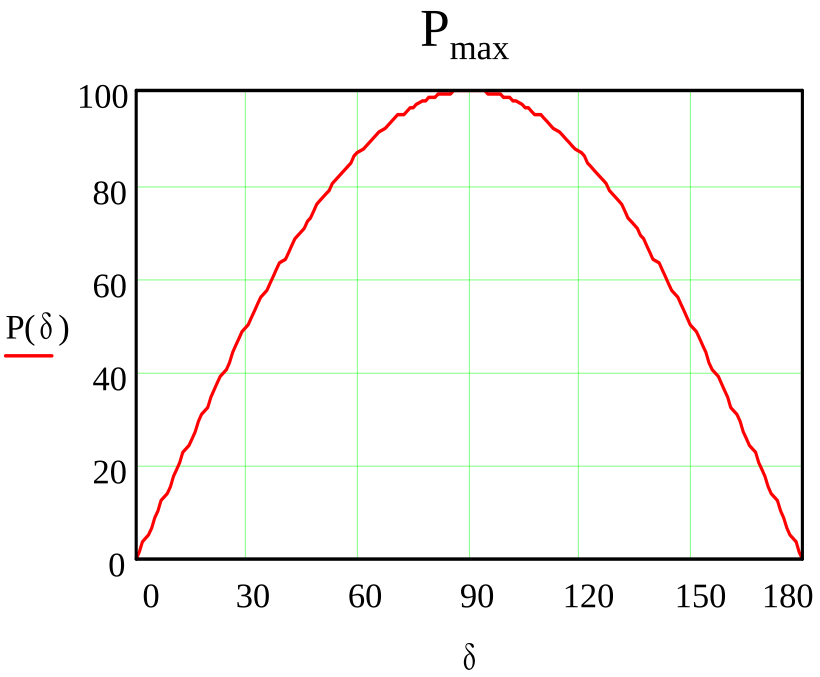
$$P = 3\frac{E_a V_t}{X_s}\sin(\delta)$$

# SYNCHRONOUS MACHINES

## Power angle Characteristics

- The P(δ) curve shows that the increase of power increases the angle between the induced voltage and the terminal voltage.
- The power is maximum when δ =90º
- The further increase of input power forces the generator out of synchronism. This generates large current and mechanical forces.
- The maximum power is the static stability limit of the system.
- Safe operation requires a 15-20% power reserve.

## Round Rotor Machine



# Example 1

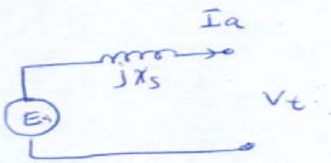
- A 25 kVA, 230 V three phase, four pole, 60 Hz, Y-connected synchronous generator has a synchronous reactance of 1.5 Ω/phase and a negligible resistance. The generator is connected to an open circuit of constant voltage (230 V) and frequency (60 Hz), find:

a) The generated EMF ($E_G$) when the machine is delivering rated kVA at 0.8 power factor lagging.

b) If the field current If is increased by 20 % without changing the power input find the stator current $I_a$.

(a) $V_t = \frac{230}{\sqrt{3}}\angle 0 = 132.8\angle 0$

$I_a = \frac{25,000}{230\sqrt{3}}\angle -\cos^{-1}(0.8) = 62.8\angle -36.9^\circ$ A.




$E_a = V_t + I_a(\cancel{R_a} + jX_s)$

$= 132.8\angle 0 + 62.8\angle -36.9\,(j1.5)$

$= 203.8\angle 21.7 \Rightarrow \delta = 21.7$

$E_a(L\text{-}L) = 353$ V

(b) Since $I_f$ increased by 20% $\Rightarrow E_a$ will increase by same % $\Rightarrow E_a' = 1.2E_a = (1.2)(203.8) = 244.6$ V

Since the input power from prime mover remains unchanged $\Rightarrow P' = P$

$\Rightarrow 3\left(\frac{E_a' V_t}{X_s}\right)\sin\delta' = 3\left(\frac{E_a V_t}{X_s}\right)\sin\delta$

$\Rightarrow \delta' = 17.9$

$I_a = \frac{E_a - V_t}{jX_s} = \frac{244.6\angle 17.9 - 132\angle 0}{j1.5}$

$= 83.4\angle -53$

$\Rightarrow Pf = \cos(53) = 0.6$ lagging.

(8)

$\Rightarrow Q = 3 V_t I_a \sin\theta = 3(132.8)(83.4)\sin 53$

$= 26.5$ KVAR.

(c) $E_a = 203.8$ ( $I_f$ is as part a)

$P_{max}$ occurs when $\delta = 90$

$\Rightarrow P_{max} = \dfrac{3 E_a V_t}{I_a} = 54.13$ KW.

$I_a = \dfrac{203.8\angle 90 - 132.8\angle 0}{j1.5} = 162.2\angle 33.1$

$\Rightarrow P.f = \cos(\theta - 33.1) = 0.84$ leading.

$Q = 3 V_t I_a \sin\theta = 3(132.8)(162.2)\sin(0 - 33.1)$

$= -35.3$ KVAR.

# Voltage Regulation

- As the load on the generator increases, the terminal voltage drops. *But,* the terminal voltage, must be maintained constant, and hence the excitation on the machine is varied, or input power to the generator is varied. That means, $E_G$ has to be adjusted to keep the terminal voltage $V_t$ constant.
- Voltage Regulation, V. R. = $\frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$

# Example 2

Calculate the percent voltage regulation for a three phase, Y-connected, 20 MVA ,13.8 kV synchronous generator operating at full load and 0.8 power factor lagging. The synchronous reactance is 8 ohm per phase and the armature resistance can be neglected.

$$V_t = \frac{13.8 \times 10^3}{\sqrt{3}} = 7967\angle 0 \text{ (line to neutral)}$$

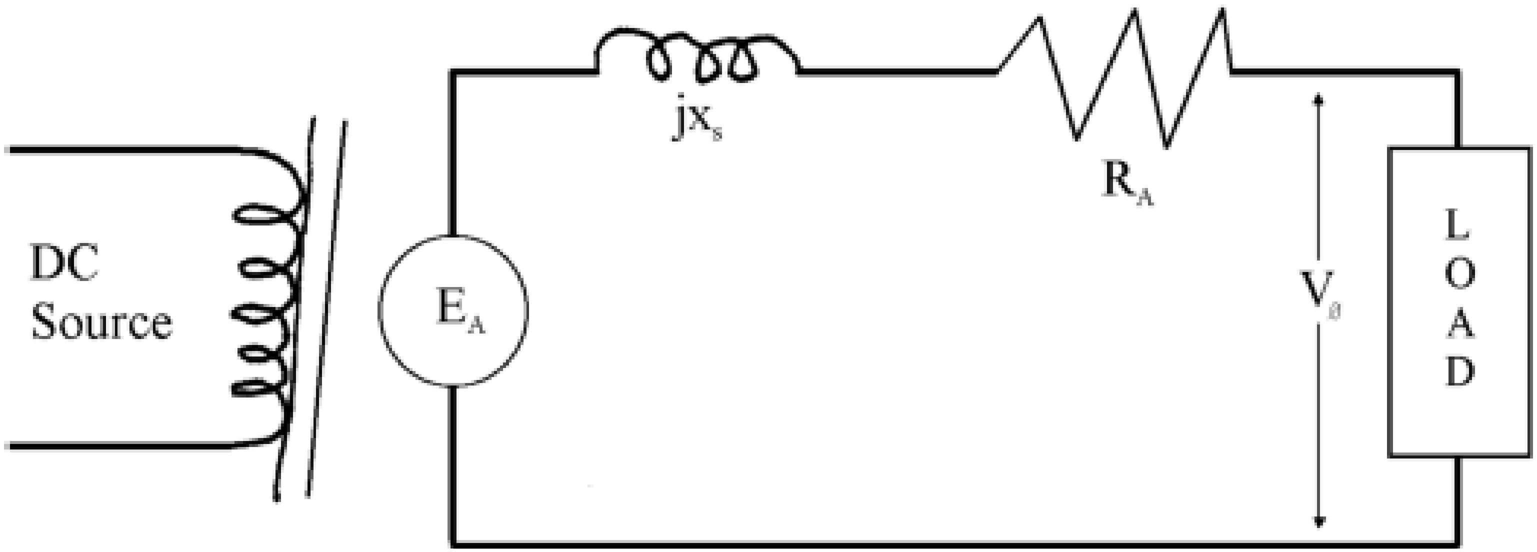
$$I_a = \frac{S}{\sqrt{3}V}\angle -\cos(0.8) = \frac{20 \times 10^3}{\sqrt{3}13.8}\angle -\cos(0.8) = 836.7\angle -36.9$$

$$E_a = V_t + I_a(R_a + jX_s) = 13{,}125\angle 24.1$$

$\text{At no load, } \mathrm{V_{nl}} = E_a, \text{ so the voltatge regulation will be:}$

$$VR = \frac{E_a - V_t}{V_t} = \frac{13{,}125 - 7967}{7967} = 64.7\%$$

# Measuring the Equivalent Circuit Parameters



# Measuring the Equivalent Circuit Parameters

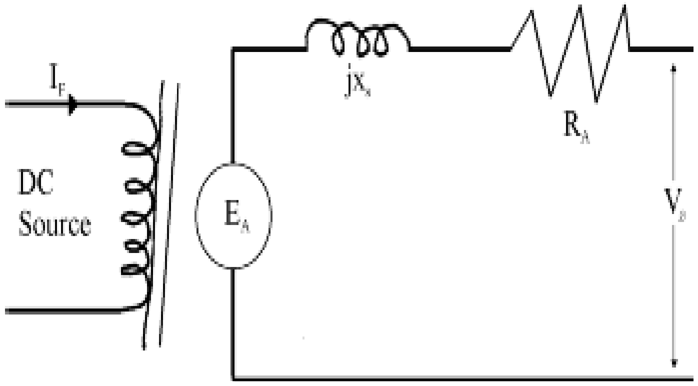
**Measurement of $R_A$:**

The winding resistance is measured by applying a DC voltage across the generator terminals under “stand-still” conditions. An equivalent value of the $R_A$ can then be calculated using the measured DC value.

# Measuring the Equivalent Circuit Parameters

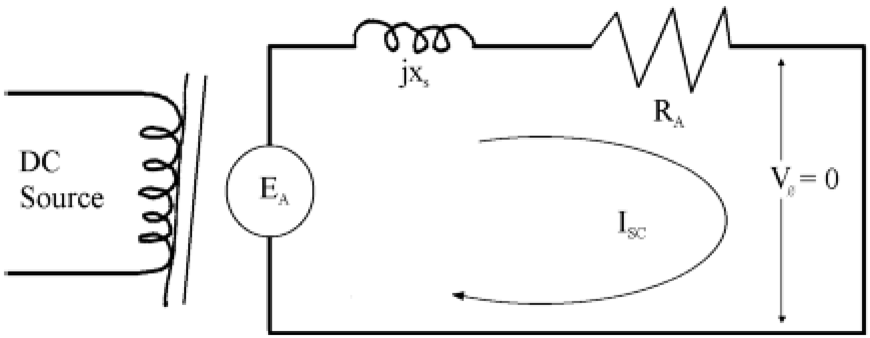
**Measurement of $X_s$:**

- (i) Open circuit test:
- With the generator terminals open;
  - Bring the generator to its rated speed.
  - Increase the field current, $I_F$, gradually from zero.
  - Measure the open circuit terminal voltage, $V_{t(L\text{-}L.)}$
  - Plot $V_{t(L\text{-}L.)}$ as a function of $I_F$. -> (OCC) Open Circuit Characteristic



# Measuring the Equivalent Circuit Parameters

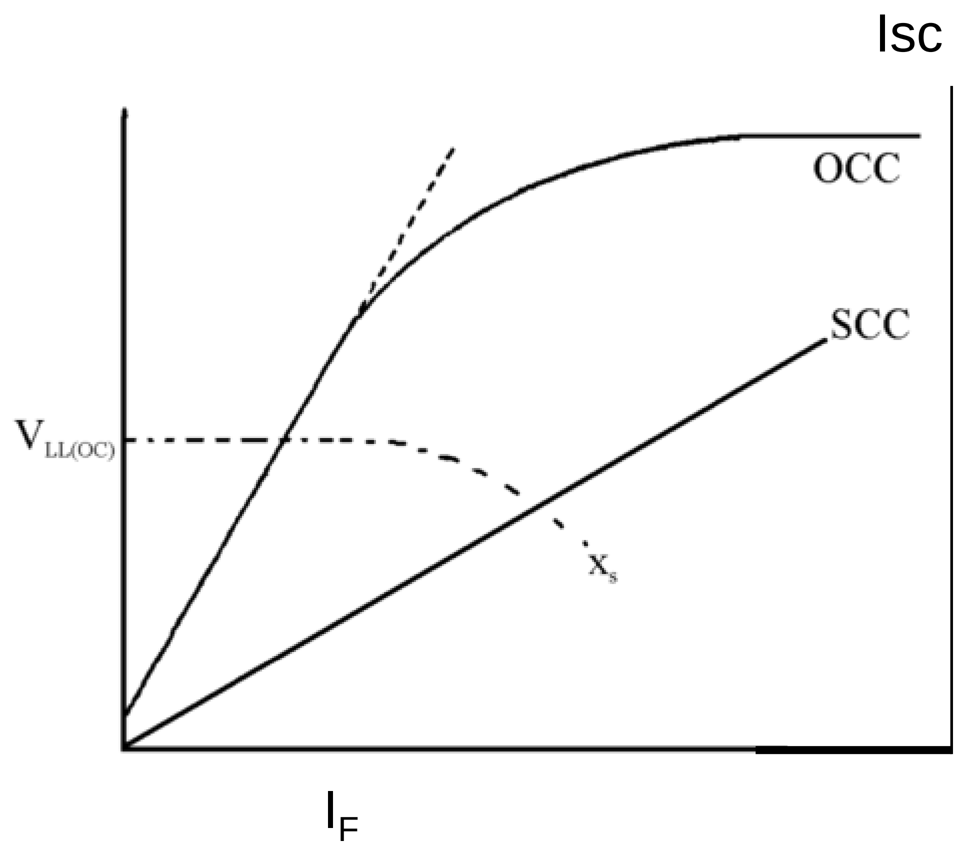
**Measurement of $X_s$:**




- (ii) short circuit test:
- Bring the generator up to its rated speed.

- .Increase $I_F$ gradually from zero and record $I_{SC}$.Plot $I_F$ vs $I_{SC}$ on the original graph from test i.
- .This is the SCC Short Circuit Characteristic.

# Measuring the Equivalent Circuit Parameters




**Measurement of $X_s$:**

$$Z_s = \sqrt{R_A{}^2 + X_s{}^2} = \left.\frac{E_{A_{OC}}}{I_{A_{SC}}}\right|_{constant\ I_F}$$

**In many cases $R_s$ can be ignored.**

# Parallel Operation of Synchronous Generators

- Generators are rarely used in isolated situations. More commonly, generators are used in parallel, often massively in parallel, such as in the power grid. The following steps must be adhered to:
- when adding a generator to an existing power grid:

1) RMS line voltages of the two generators must be the same.

2) Phase sequence must be the same.

3) Phase angles of the corresponding phases must be the same.

4) Frequency must be the same.

# SYNCHRONOUS Motors

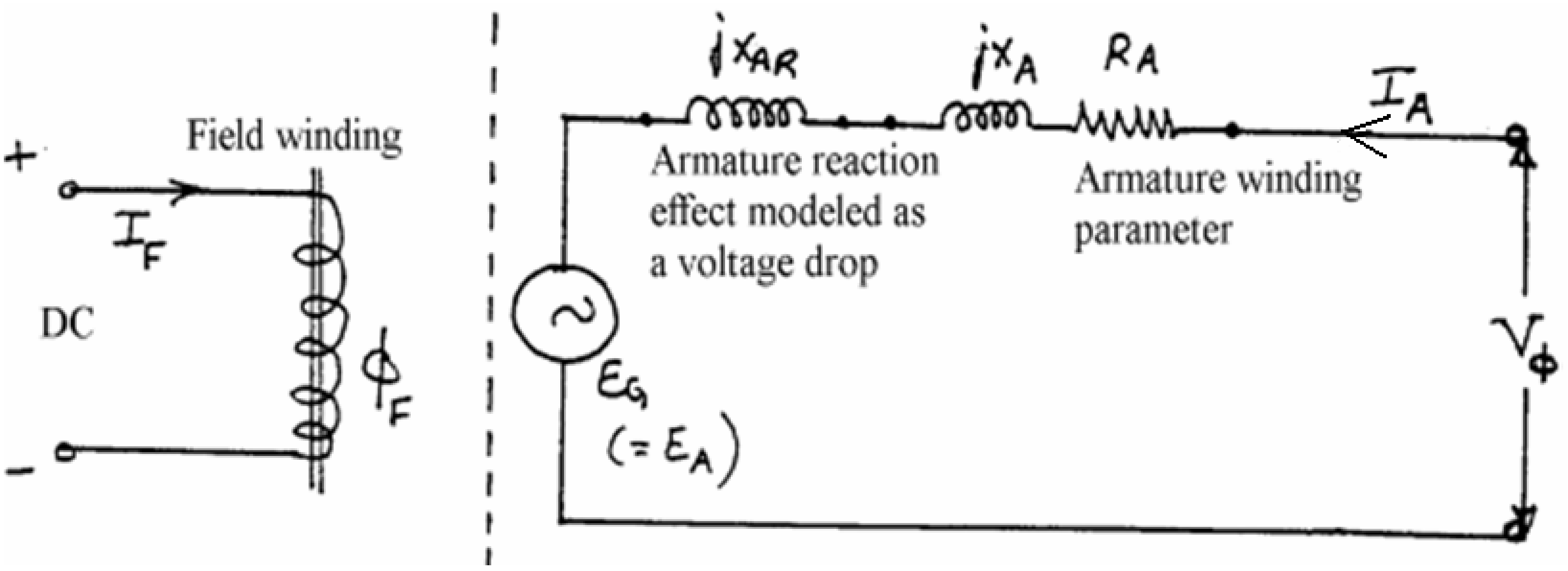
**•Principle of Operation**

- 1) From an external DC source, the field winding is supplied with a DC current -> excitation.
- 2) Outer stator winding is supplied with a three phase voltage which produces a rotating magnetic field.
- 3) The rotor's magnetic field produced by the field current (hence the rotor) will tend to line-up with the rotating magnetic field produced by the stator's 3-phase currents. However, synchronous motors are not "self-starting" motors. A mechanism is needed to put the rotor in synchronism with the RMF.

# Synchronous Motor Equivalent Circuit

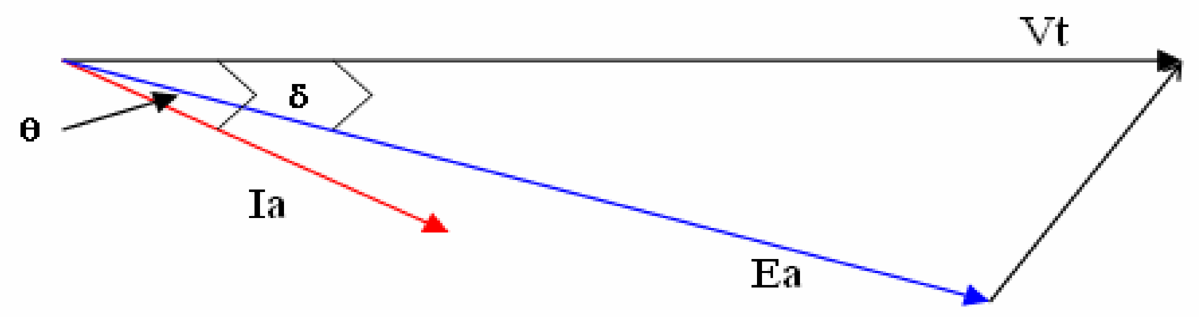
**Phasor Diagrams:**

$$V_t = E_a + jX_s I_a + R_a I_a$$



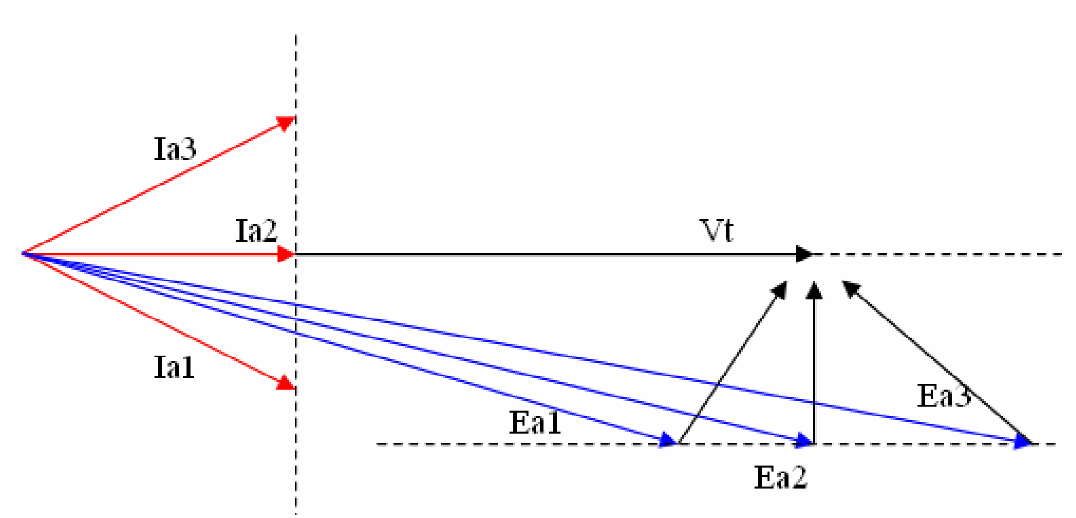
# Synchronous Motor Equivalent Circuit

**Where θ is the angle between Vt and Ia and δ is the angle between Vt and Ea**



# Effect of field current changes

- When If increases, Ea will increase.
- Since there is no change in the output power and Vt, both Ia*cos(θ) and Ea*sin(δ) will be constant.
- As a result, the power factor will change as we change the field current



## Q1

Determine the synchronous reactance, $X_s$. Recall that the synchronous reactance can be determined from the OCC and SCC using the following ratio:

$$X_s = \frac{V_t}{I_{sc}}$$

where $V_t$ is the rated line-to-neutral voltage and $I_{sc}$ is the short-circuit current using the same excitation current that was required to produce rated $V_t$.

Assume that the machine is being used as a generator connected to the infinite grid, and that the induced voltage is related to the field current by

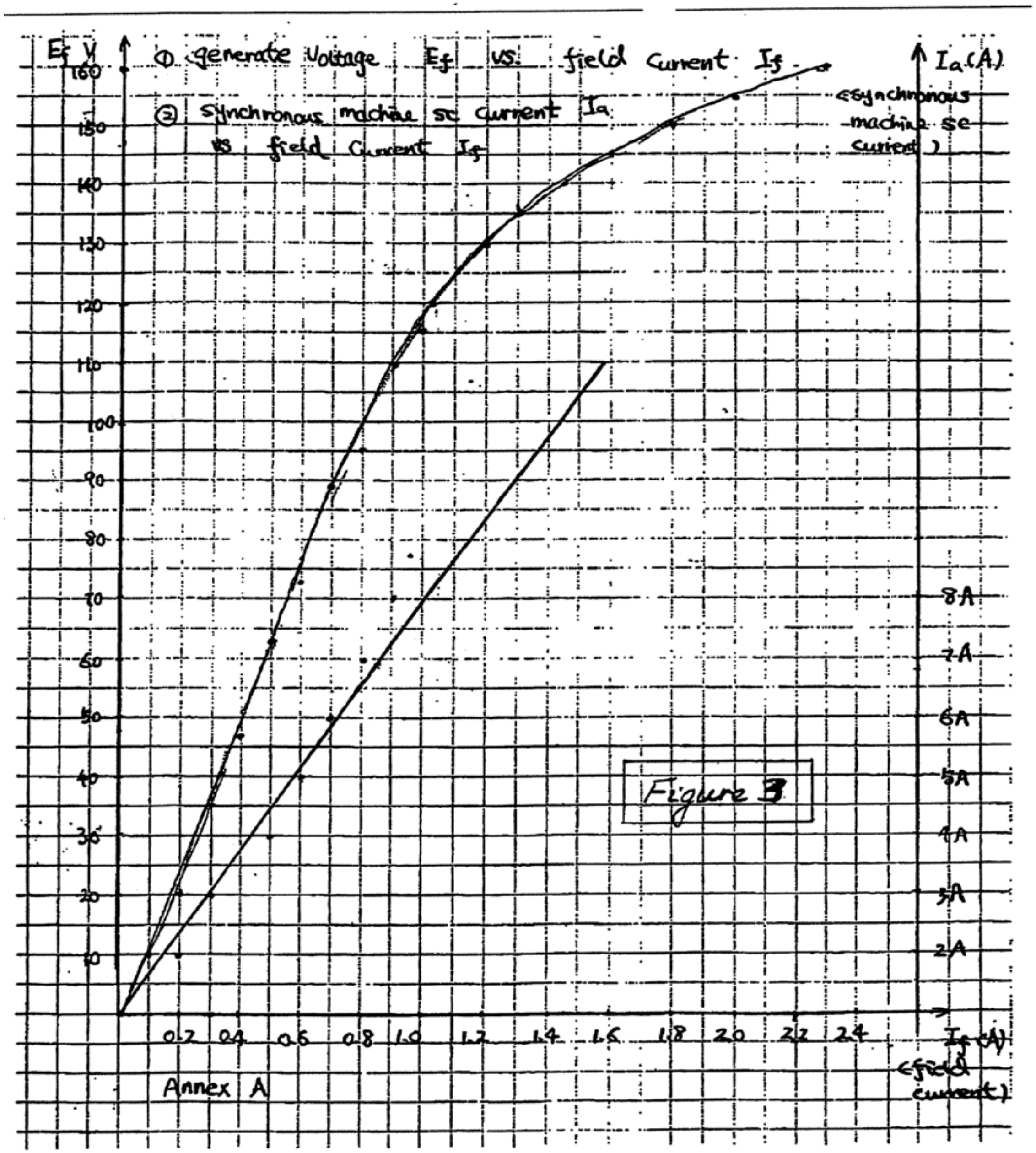
$$E_f = 25 I_f$$

(a) Determine the field current required to establish rated armature current at 0.8 pf lagging.

(b) Draw a neatly-labeled phasor diagram for the above conditions.

(c) What is the maximum power that the generator can supply without losing synchronization if the excitation is not changed?

# Q1



Ef V
① generate Voltage Ef vs. field Current If
② synchronous machine sc current Ia vs field Current If
Ia (A)
(synchronous machine sc current)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
8A
7A
6A
5A
4A
3A
2A
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
If (A)
(field current)
Annex A
Figure 3

## Q2

Two three-phase, 6.6 kV, Y-connected synchronous generators are operating in parallel to supply a load of 3000 kW at 0.8 power factor lagging. The synchronous reactance per phase of machine *A* is $j10\ \Omega$, while that of machine *B* is $j12\ \Omega$ (winding resistance and losses are negligible). The excitation of machine *A* is adjusted so that it delivers 150 A at a lagging power factor, and the governors that control the input torque of the generator prime movers are set such that the load is shared equally between the two machines.

a. Determine the following for each machine:

   i. the armature current;

   ii. the power factor;

   iii. the excitation voltage, Ef; and,

   iv. the power angle.

b. Neatly sketch a phasor diagram for machine *A*, taking the terminal voltage as the reference. Ensure all phasors are labelled, and all angles indicated.

# Q3

A 2500 hp, 6600 V, 60 Hz, 3600 rpm, three-phase, Y-connected, round rotor synchronous motor, operating at rated load and 0.84 power factor leading, has an efficiency of 96.5 percent, neglecting field losses and armature resistance losses. The synchronous reactance per phase is 15.8 Ω. Sketch a phasor diagram for this motor for the given operating condition, and determine:

a. rotational losses;
b. the armature current;
c. the excitation voltage; and,
d. maximum output torque available from this motor.