Chapter 4
Synchronous Machines

Edit by Shaheen

Synchronous Machine

- Synchronous machines are AC machine that have a field circuit supplied by an external DC source.
  - DC **field winding** on the rotor,
  - AC **armature winding** on the stator
- Origin of name: syn = equal, chronos = time
- Synchronous machines are called '***synchronous***' because their mechanical shaft speed is directly related to the power system's line frequency.

Synchronous Machine

Construction

- Energy is stored in the inductance
- As the rotor moves, there is a change in the energy stored
- Either energy is extracted from the magnetic field (and becomes mechanical energy – motor)
- Or energy is stored in the magnetic field and eventually flows into the electrical circuit that powers the stator – generator

Synchronous Machine

- DC field windings are mounted on the (rotating) rotor - which is thus a rotating electromagnet
- AC windings are mounted on the (stationary) stator resulting in three-phase AC stator voltages and currents

- The main part in the synchronous machines are
  1. **Rotor**
  2. **Stator**

Synchronous Machine

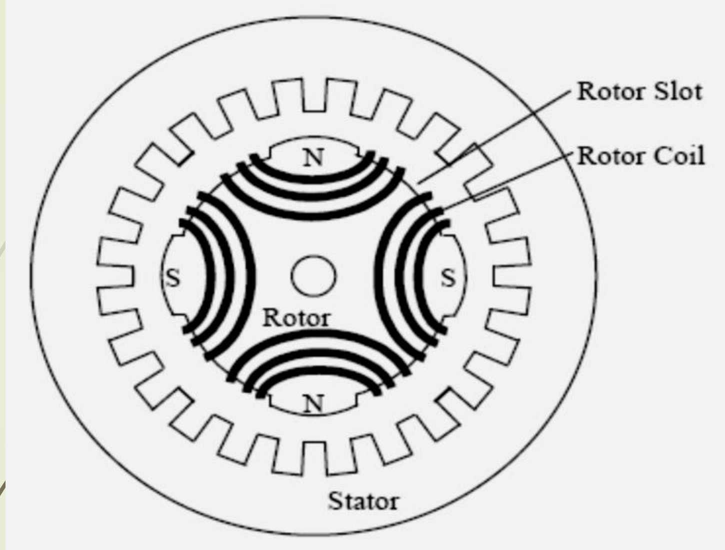
Rotor

There are two types of rotors used in synchronous machines:

1. **Cylindrical (or round) rotors**
2. **Salient pole rotors**

- Machines with cylindrical rotors are typically found in higher speed higher power applications such as turbo-generators. Using 2 or 4 poles, these machines rotate at 3600 or 1800 rpm (with 60hz systems).
- Salient pole machines are typically found in large (many MW), low mechanical speed applications, including hydro-generators, or smaller higher speed machines (up to 1-2 MW).
- Salient pole rotors are less expensive than round rotors.

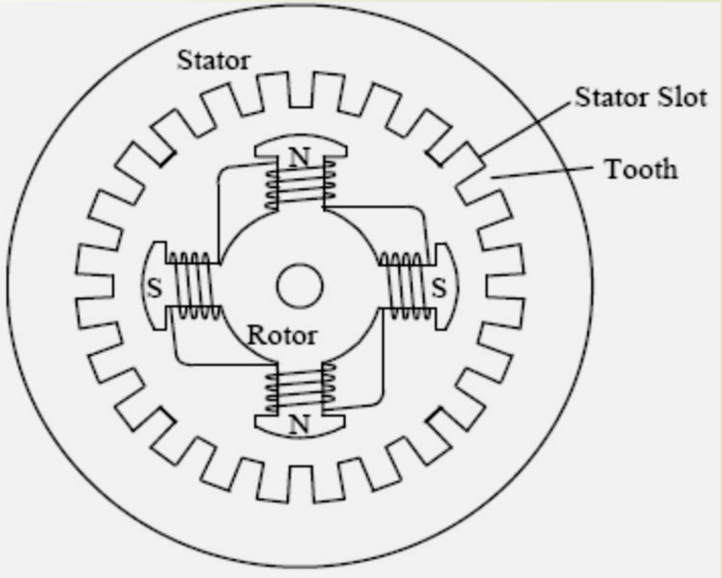
Synchronous Machine



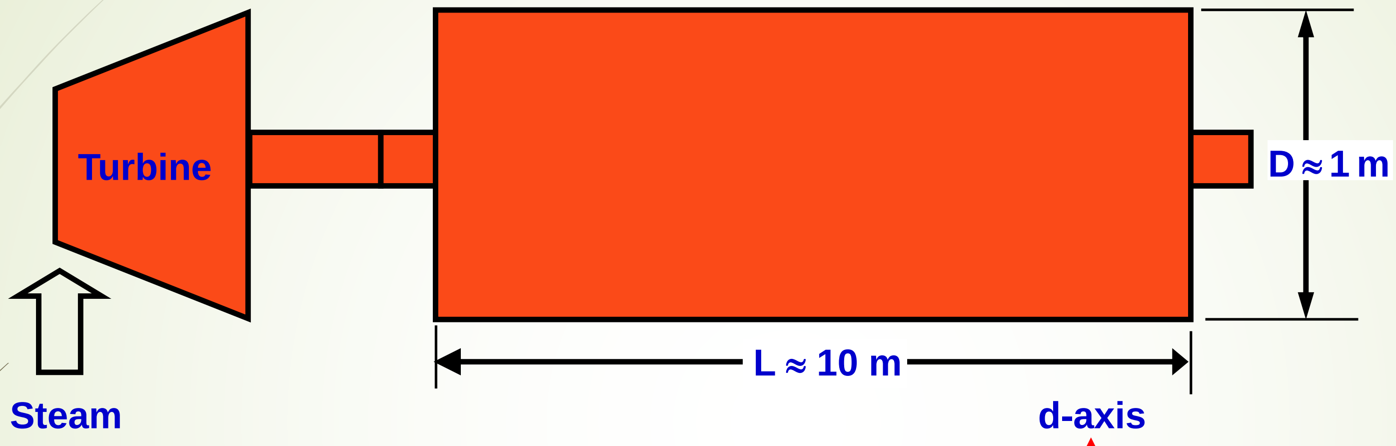
Construction-Rotor

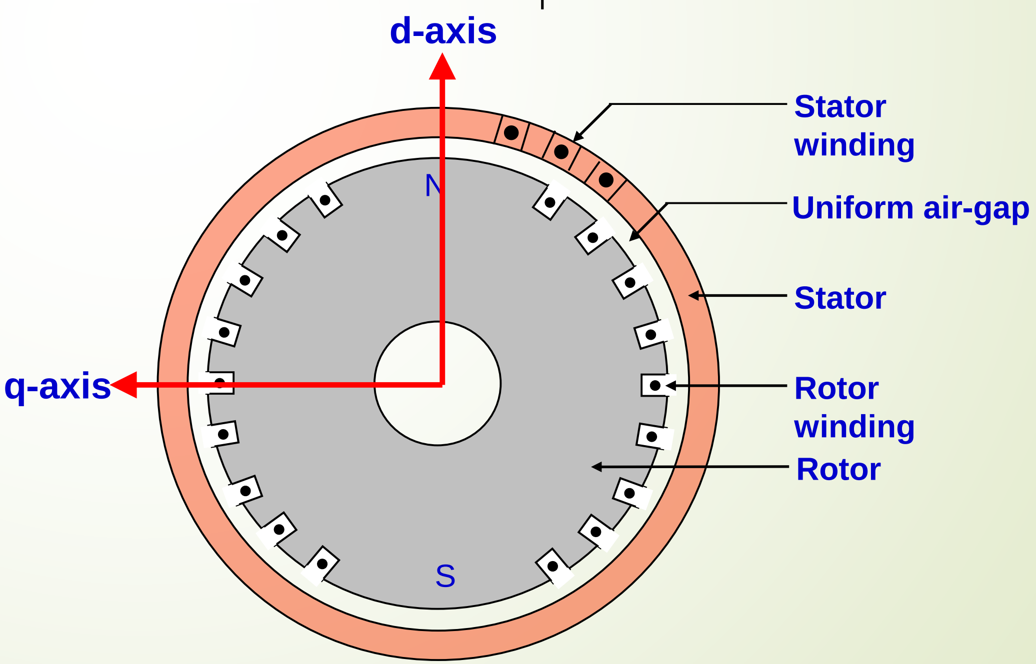
1. Cylindrical (or round) rotor

2. Salient-pole rotor



Synchronous Machine – Cylindrical rotor





High speed

3600 r/min Þ 2-pole

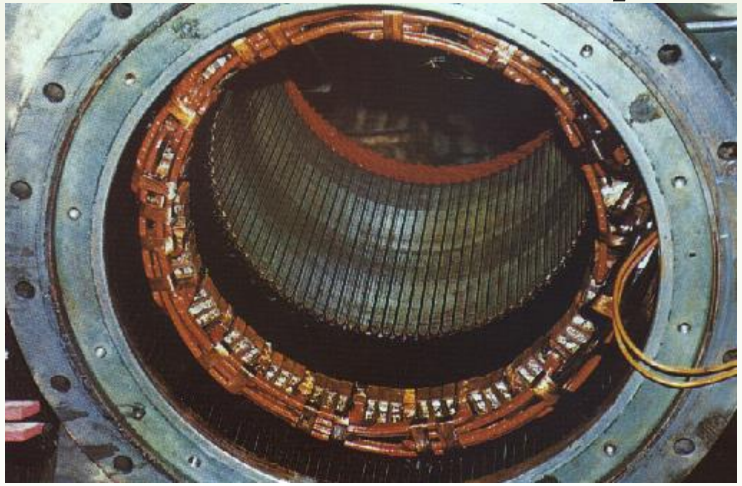
1800 r/min Þ 4-pole

î Direct-conductor cooling (using hydrogen or water as coolant)

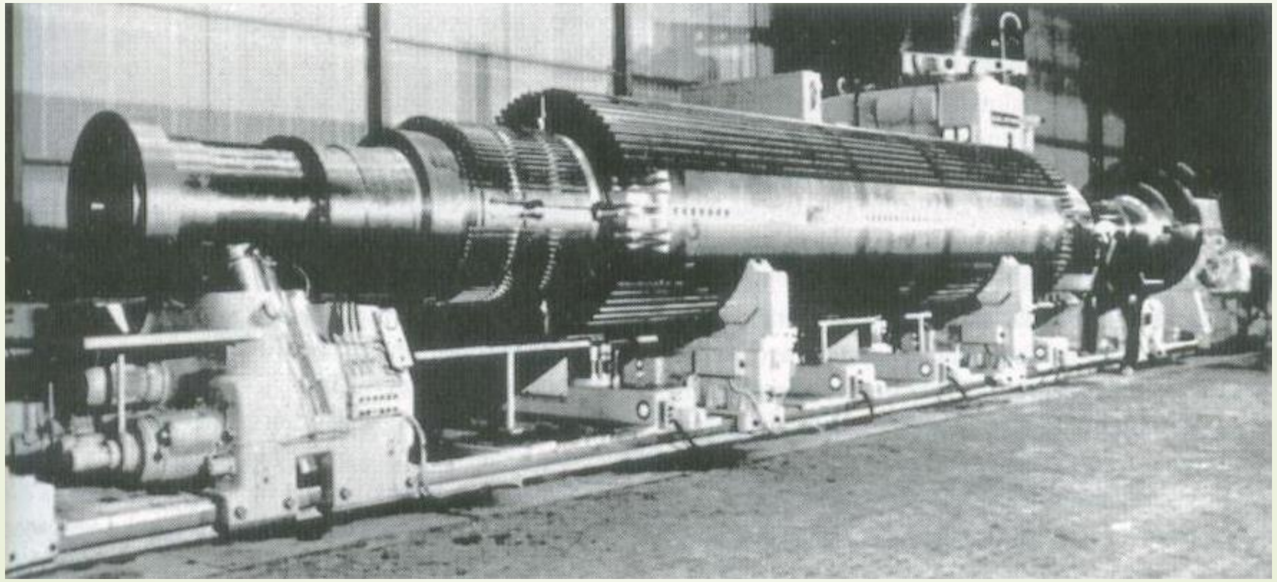
î Rating up to 2000 MVA

Turbo-generator

Synchronous Machine – Cylindrical rotor



Stator

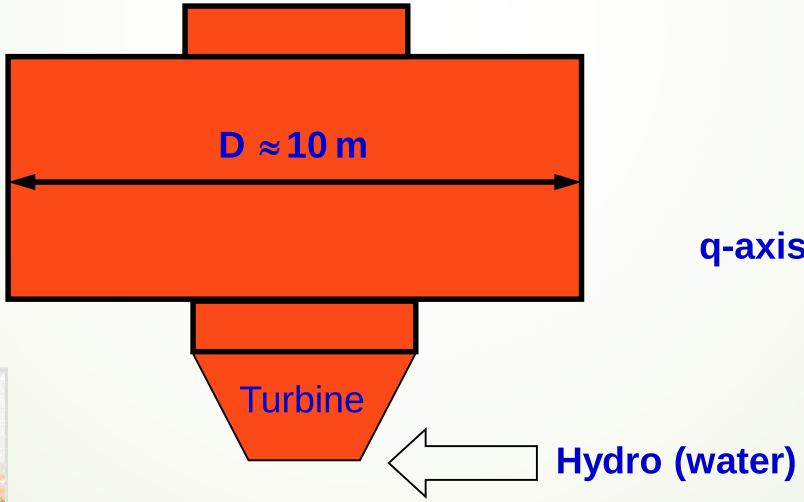


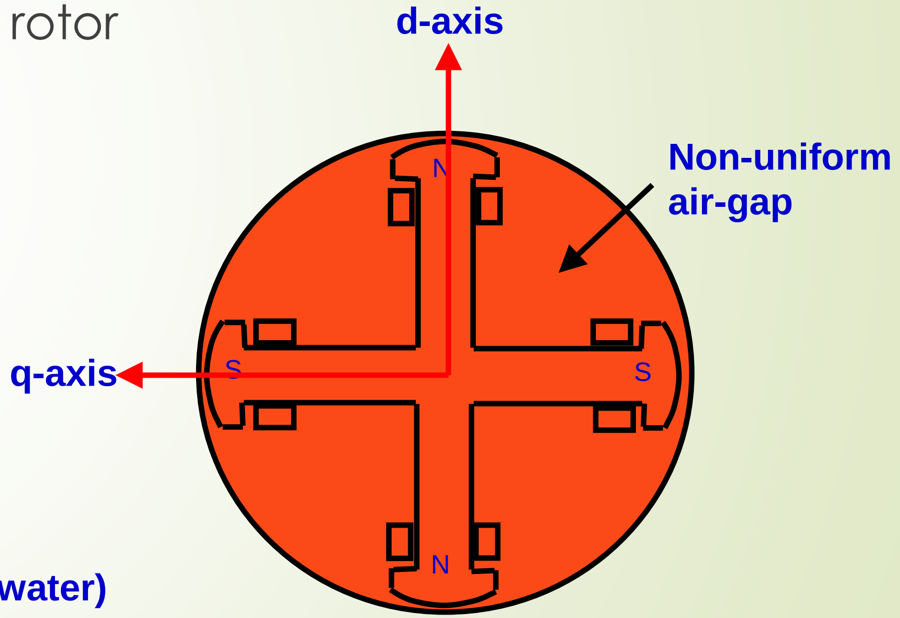
Cylindrical rotor

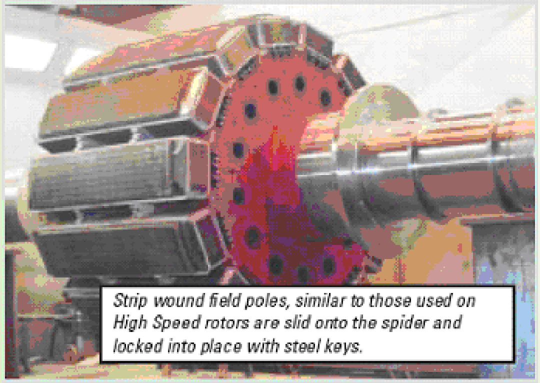
Synchronous Machine – Salient Pole

- Most hydraulic turbines have to turn at low speeds (between 50 and 300 r/min)

- A large number of poles are required on the rotor

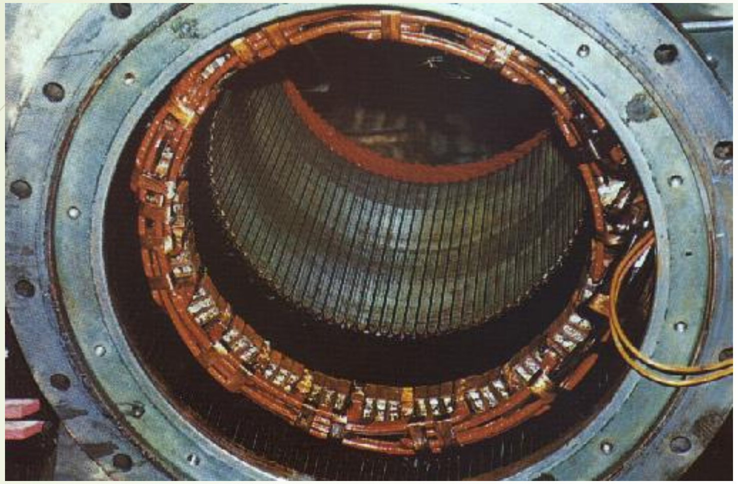




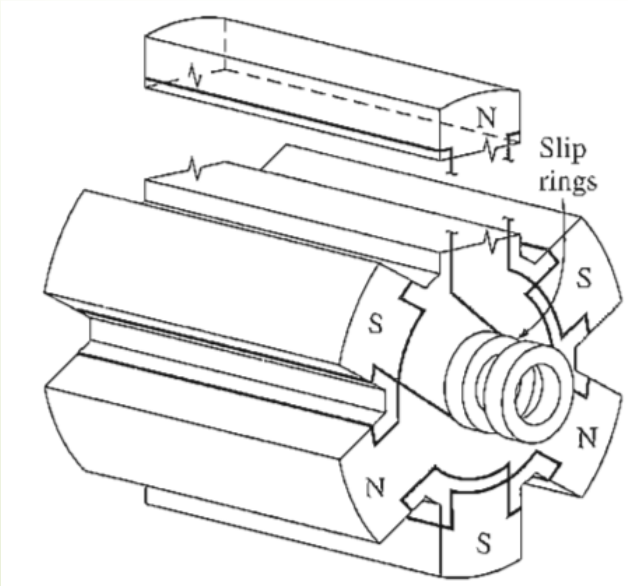


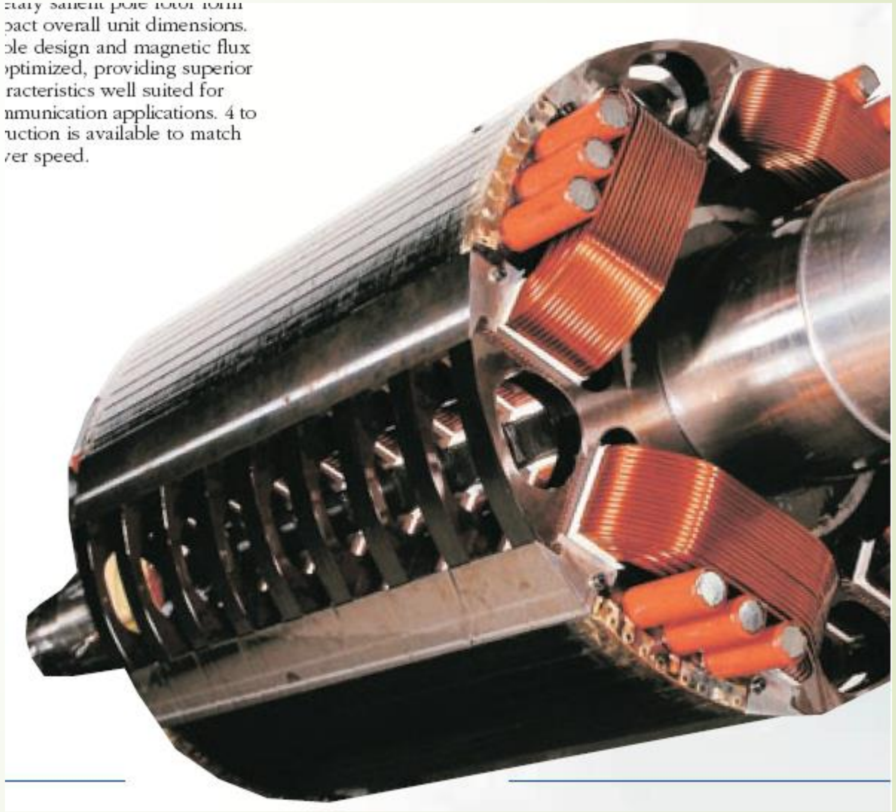
Hydro-generator

Synchronous Machine – Salient Pole



Stator





Salient-pole rotor

Synchronous Machine – Salient Pole

- Synchronous machine rotors are simply rotating electromagnets built to have as many poles as are produced by the stator windings.
- DC currents flowing in the field coils surrounding each pole magnetize the rotor poles.
- The magnetic field produced by the rotor poles locks in with a rotating stator field, so that the shaft and the stator field rotate in synchronism.
- Salient poles are too weak mechanically and develop too much wind resistance and noise to be used in large, high-speed generators driven by steam or gas turbines. For these big machines, the rotor must be a solid, cylindrical steel forging to provide the necessary strength.

Synchronous Machine – Salient Pole

- Axial slots are cut in the surface of the cylinder to accommodate the field windings.
- Since the rotor poles have constant polarity they must be supplied with direct current.
- This current may be provided by an external dc generator or by a rectifier.
  - In this case the leads from the field winding are connected to insulated rings mounted concentrically on the shaft.
  - Stationary contacts called brushes ride on these slip rings to carry current to the rotating field windings from the dc supply.
  - The brushes are made of a carbon compound to provide a good contact with low mechanical friction.
  - An external dc generator used to provide current is called a " brushless exciter ".

Exciter Circuits

Field circuit dc current supply:

- External dc supply by means of slip rings and brushes
- Special dc power source mounted on the shaft –brushless [in large generators].

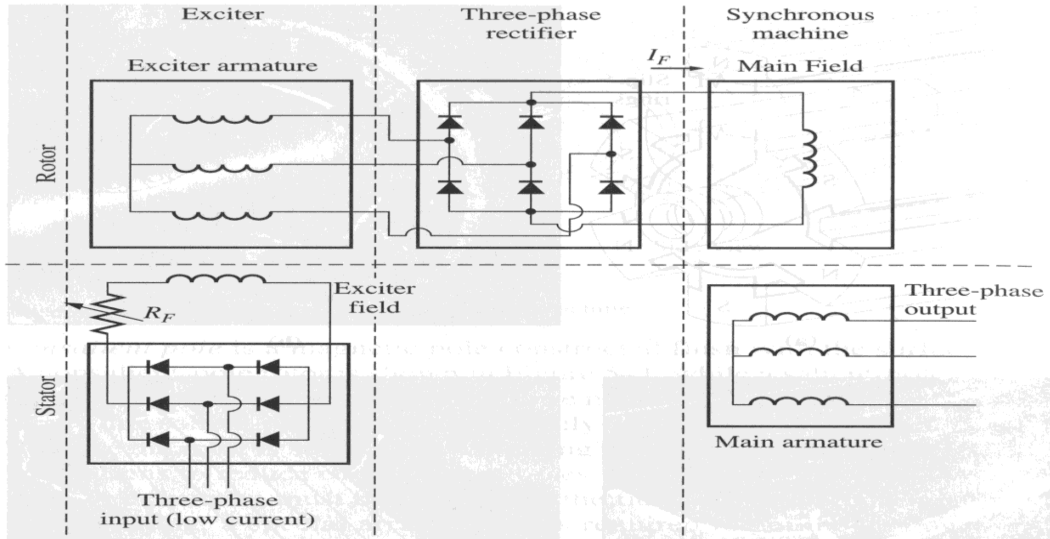


FIGURE 5–3
A brushless exciter circuit. A small three-phase current is rectified and used to supply the field circuit of the exciter, which is located on the stator. The output of the armature circuit of the exciter (on the rotor) is then rectified and used to supply the field current of the main machine.

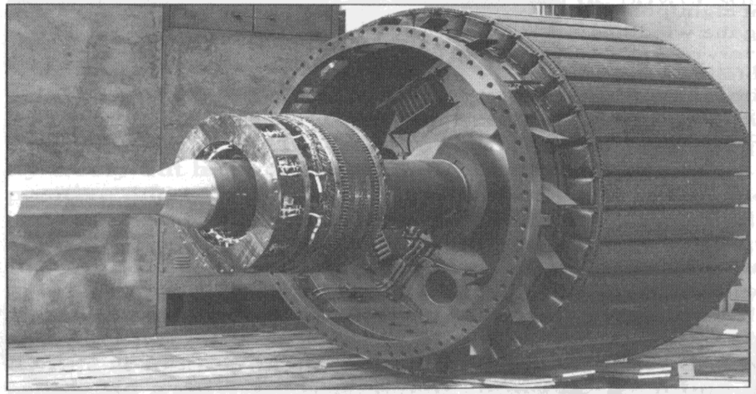
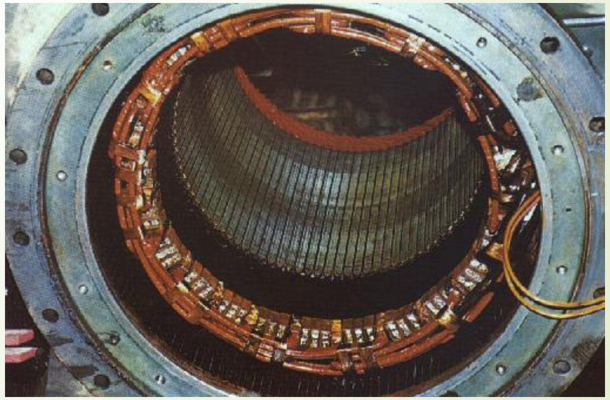


FIGURE 5–4
Photograph of a synchronous machine rotor with a brushless exciter mounted on the same shaft. Notice the rectifying electronics visible next to the armature of the exciter. (Courtesy of Westinghouse Electric Company.)

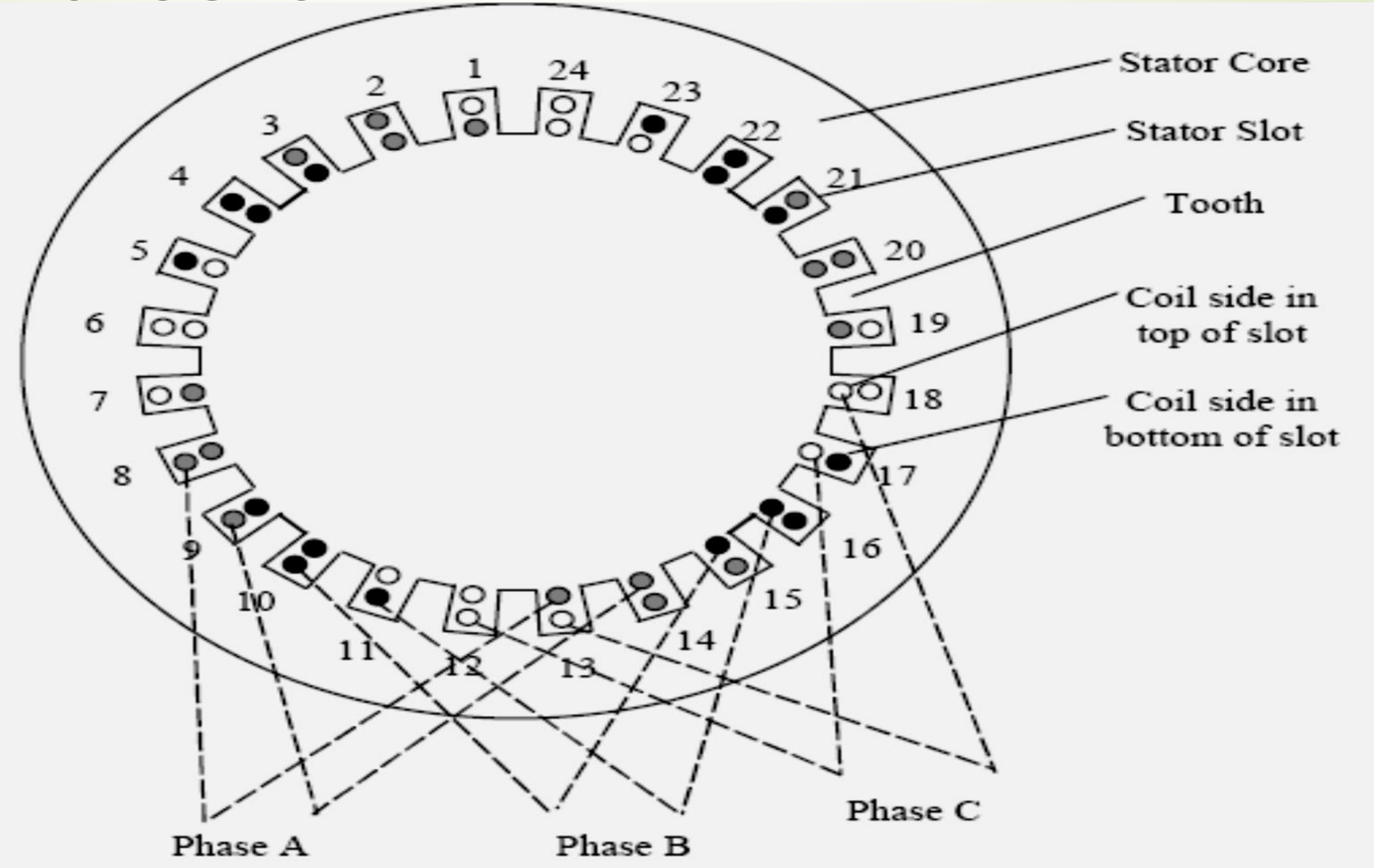
Synchronous Machine

Stator

- The stator of a synchronous machine carries the armature or load winding which is a three-phase winding.
- The armature winding is formed by interconnecting various conductors in slots spread over the periphery of the machine's stator. Often, more than one independent three phase winding is on the stator. An arrangement of a three-phase stator winding is shown in Figure below. Notice that the windings of the three-phases are displaced from each other in space.

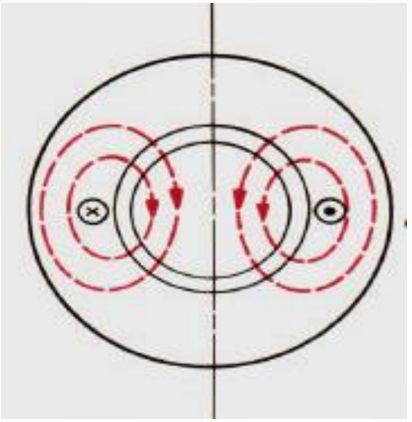


Synchronous Machine – Stator construction

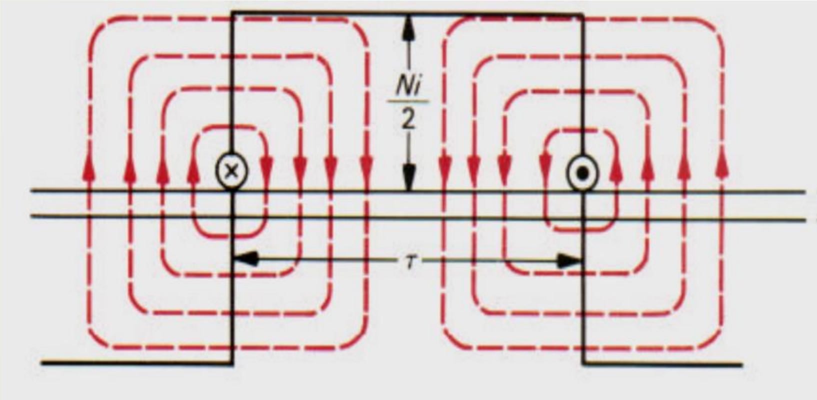


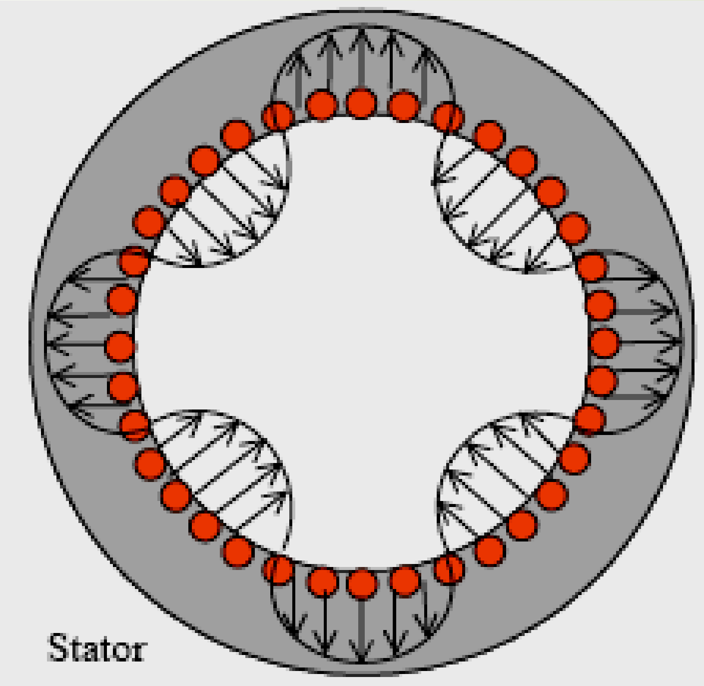
Synchronous Machine

- Magnetomotive Forces (MMF's) and Fluxes Due to Armature and Field Windings



- Flux produced by a stator winding





- Cycles of MMF around the Stator

Synchronous Machine

- The frequency of the induced voltage is related to the rotor speed by:

$$n_S = \frac{120 \cdot f_e}{P} \qquad (rpm)$$

- where P is the number of magnetic poles
- f_e is the power line frequency in Hz.
- N_s = mechanical speed of magnetic field, in r.p.m (equal speed of rotor for synchronous machines)
- Typical machines have two-poles, four-poles, and six-poles

The speed of rotation

- Synchronous means that the electrical frequency produced is locked with the mechanical rate of rotation of the generator.

$$f_e = \frac{n_m P}{120} \Rightarrow n_m = \frac{120 f}{P}$$

- $n_m = n_{sync}$

Internal voltage of Syn. Generator

- The internal voltage in SG is given by following formula:

$$E_A = \sqrt{2}\pi N_c \phi f = 4.444 N_c B A f$$

$$E_A = \frac{2\pi f}{\sqrt{2}} N_c \phi = \frac{N_c}{\sqrt{2}} \omega \phi$$

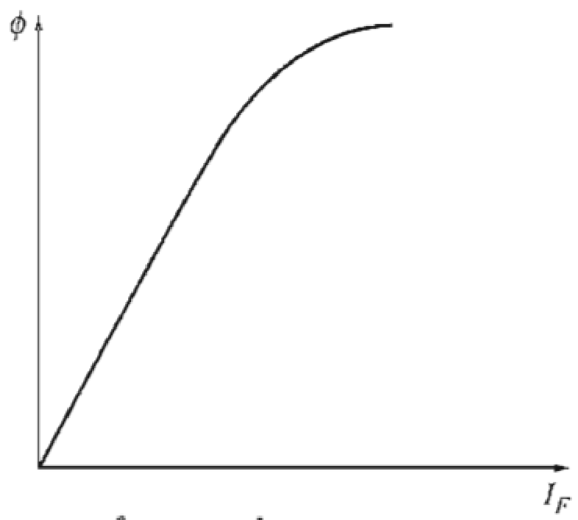
$$E_A = K \phi \omega$$

N = number of turns,
B= flux density,
A = cross sectional area of the magnetic circuit,
f = frequency,
ϕ= flux per pole

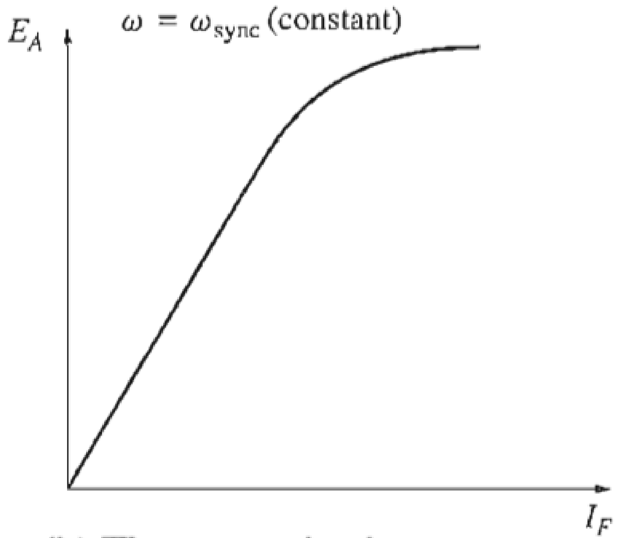
K : constant represents construction of machine

ω : radian /s

EA: is proportional to flux and speed , flux depend on the current flowing the rotor-field circuits field



(a) Plot of flux versus field current for a synchronous generator.



(b) The magnetization curve

Example

Example 1

- A hydraulic turbine turning at 200 r/min is connected to a synchronous generator. If the induced voltage has a frequency of 60 Hz, how many poles does the rotor have?

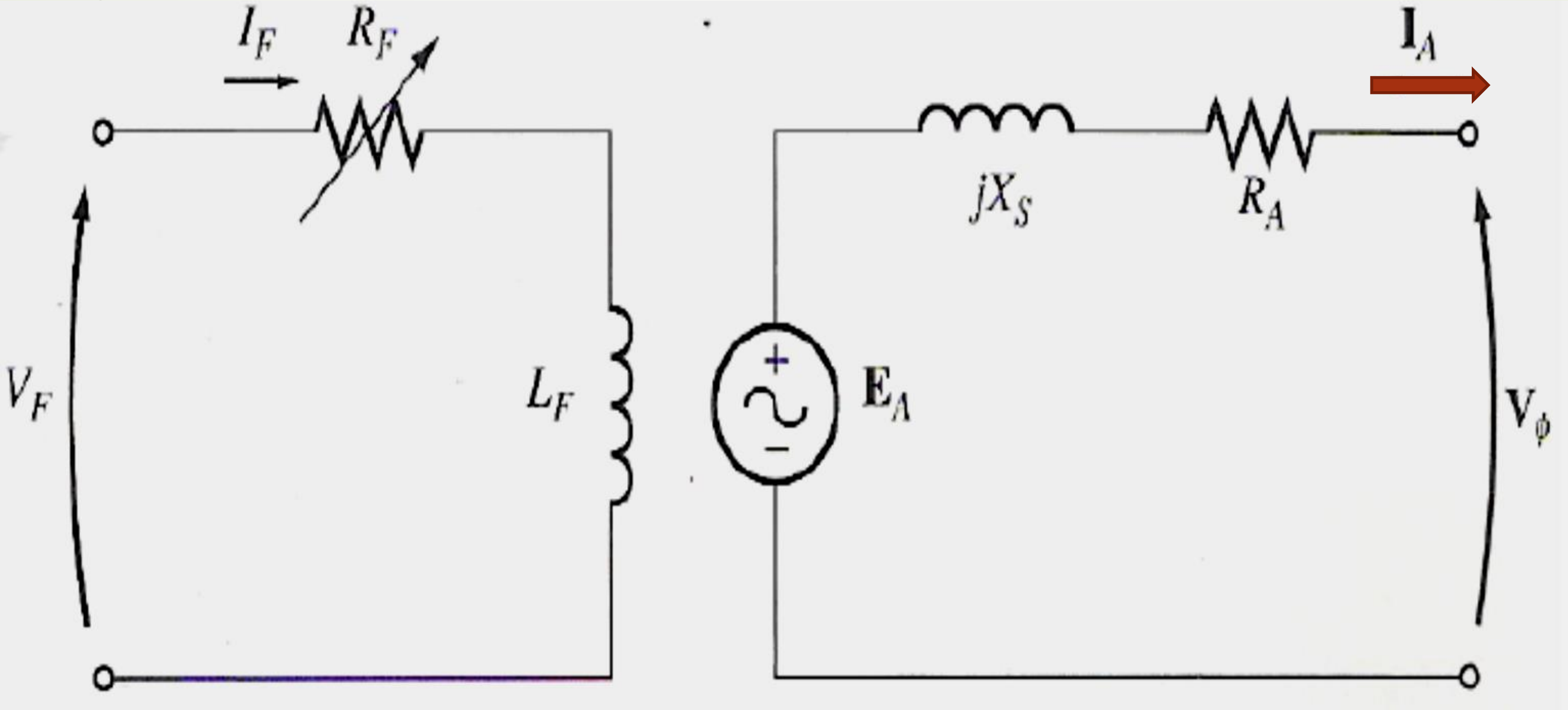
$$P = 120 * f / N_{sync} = 120 * 60/200 = 36$$

Example 1

- Determine the rotation speed (r/min)for SG consists of :
  - 2 poles, 50 HZ, 2 poles 60 Hz,
  - 4 poles 50 HZ, 4 poles 60 Hz

Determine number of poles for 50 Hz ,operate at 1000 r/min SG?

Synchronous Generator



The equivalent Circuit of the Synchronous Generator

- The voltage ***EA*** is the induced voltage produced in one phase of a synchronous generator. ***EA*** is not usually the voltage that appears at the terminals of the generator. The only time ***EA*** is the same as the output voltage ***Vφ*** of the phase when there is no armature current flowing in the machine (during no load).

- There are many factors that cause the difference between E_A and $V\phi$ including:
  - The distortion of the air-gap magnetic field by the current flowing in the stator, called **armature reaction**.
  - The resistance of the armature coils,
  - The self inductance of the armature coils
  - The effect of salient pole rotor shape

If the generator operates at a terminal voltage VT while supplying a load corresponding to an armature current Ia, then;

$$E = V_T + I_a(R_a + jX_d)$$

In an actual synchronous machine, the reactance is much greater than the armature resistance, in which case;

$$Z_S \approx jX_d$$

Among the steady-state characteristics of a synchronous generator, its voltage regulation and power-angle characteristics are the most important ones. As for transformers, the voltage regulation of a synchronous generator is defined at a given load as;

$$percent\quad voltage\quad regulation = \frac{|E| - |V_T|}{|V_T|} \times 100\%$$

Per Phase Equivalent Circuit of the Synchronous Generator

$$V_\phi = E_A + E_{stator}$$

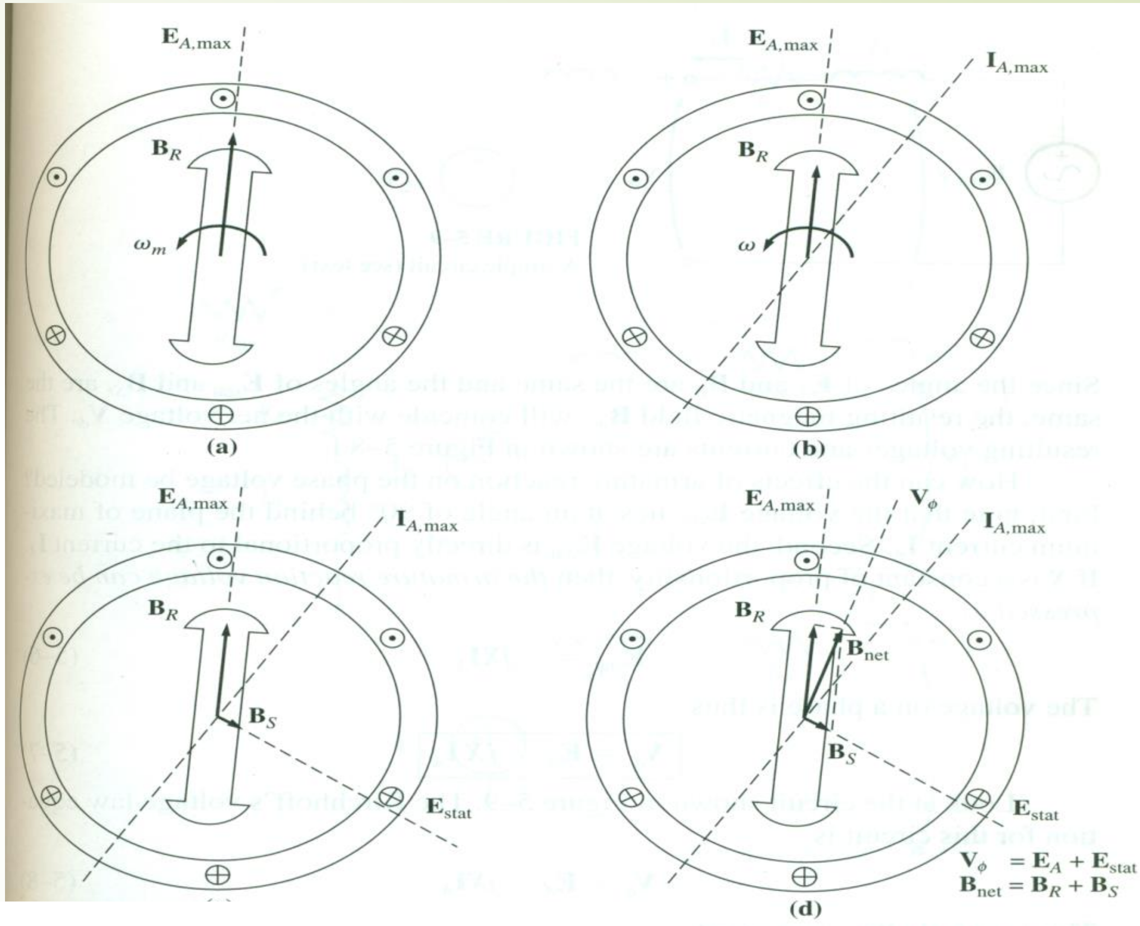
$$E_{stator} = -jXI_A$$

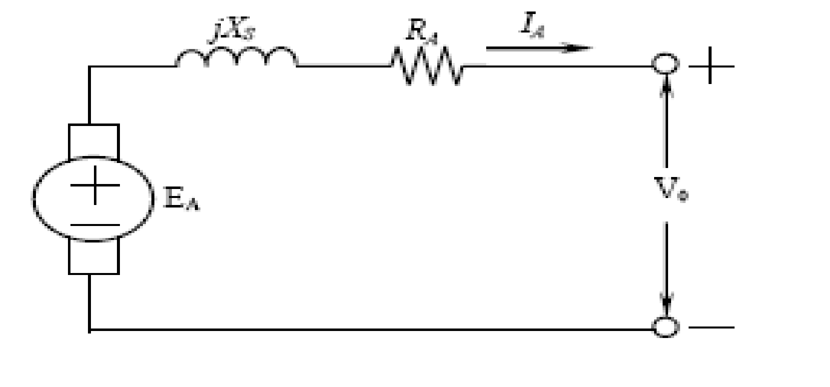
$$V_\phi = E_A - jXI_A$$

- X: represents the effect of armature reaction reactance only.
- *In addition to the armature reaction .The stator coils have self inductance and resistance, therefore we define:*

$$X_S = X + X_A$$

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





Three Phase Equivalent Circuit of the Synchronous Generator

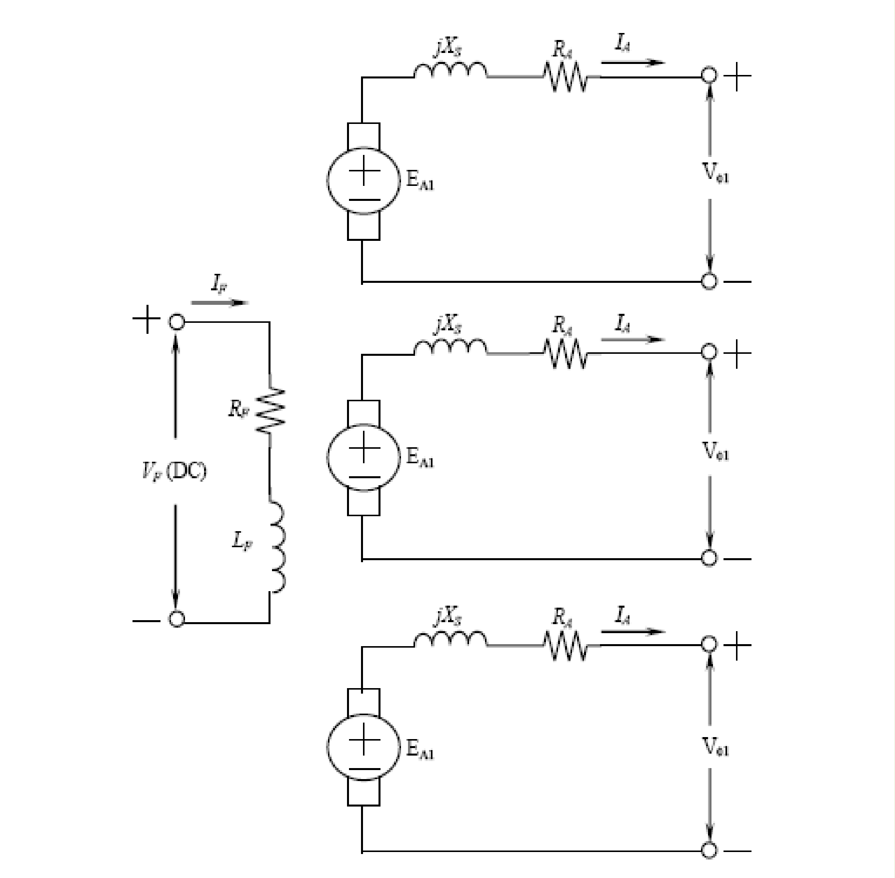
- You observe the DC power source supplying the rotor field circuit. The figure also shows that each phase has an induced voltage with a series *XS* and a series *RA*. The voltages and currents of the three phases are identical but 120 apart in angle.

- *The three phases can be either **Y** or Δ . If they are **Y** connected, then the terminal voltage **VT** is related to the phase voltage by*

$$V_T = \sqrt{3} V_\phi$$

If Δ connected :

$$V_T = V_\phi$$



The full equivalent circuit of a three-phase synchronous generator

Synchronous Generator Example 2

- A three-phase, wye-connected 2500 kVA and 6.6 kV generator operates at full-load. The per-phase armature resistance R_a and the synchronous reactance, X_d, are (0.07+j10.4)Ω. Calculate the percent voltage regulation at

(a) 0.8 power-factor lagging, and

(b) 0.8 power-factor leading.

Solution.

(a) Since $R_a << X_d$ then R_a can be neglected.

$$V_T = \frac{6600V}{\sqrt{3}} = 3811V$$

$$I_a = \frac{2500kVA}{\sqrt{3}\cdot 6.6kV} = 218.7A$$

$$lagging:$$

$$\phi = \arccos(0.8pf) = 36.9°$$

$$E = V_t + I_a X_d = (3811V\angle 0°) + (218.7A\angle -36.9°)(j10.4\Omega) = 5485V\angle 19.3°$$

$$V.R. = \frac{|E| - |V_T|}{|V_T|} = \frac{5485V - 3811V}{3811V} = 44\%$$

(b)

$$leading:$$

$$\phi = \arccos(0.8pf) = -36.9°$$

$$E = (3811V\angle 0°) + (218.7A\angle +36.9°)(j10.4) = 3048V\angle 36.6°$$

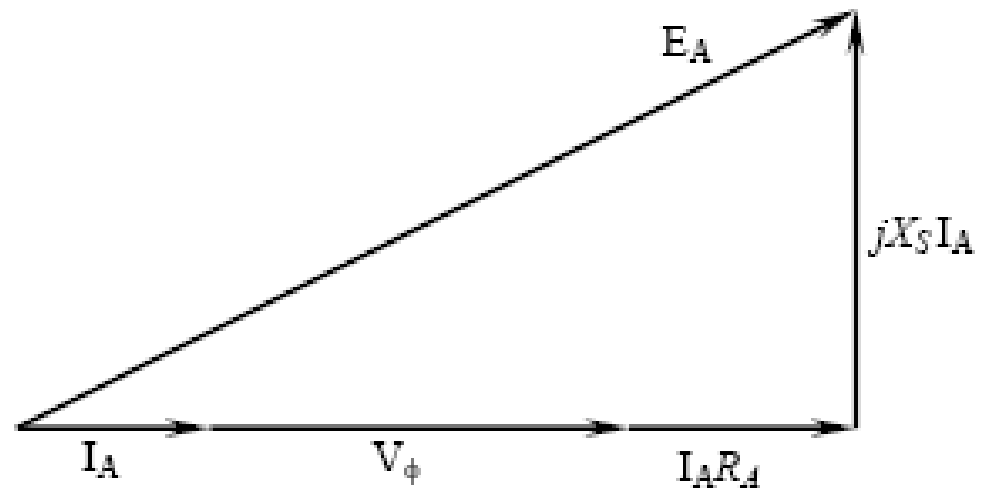
$$V.R. = \frac{3048V - 3811V}{3811V} = -20\%$$

The voltage regulation is dependent on the power factor.

Phasor Diagram

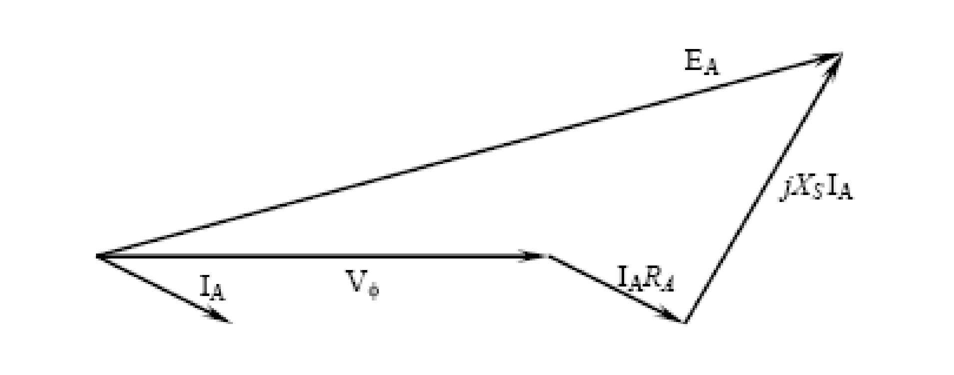
- Voltages in a synchronous generator are expressed as **phasors** because they are AC voltages. Since we have **magnitude** and **angle**, the relationship between voltage and current must be expressed by a two-dimensional plot.

- It is noticed that, for a given **phase voltage** and armature current, a larger induced voltage ***EA*** is required for lagging loads than leading loads.



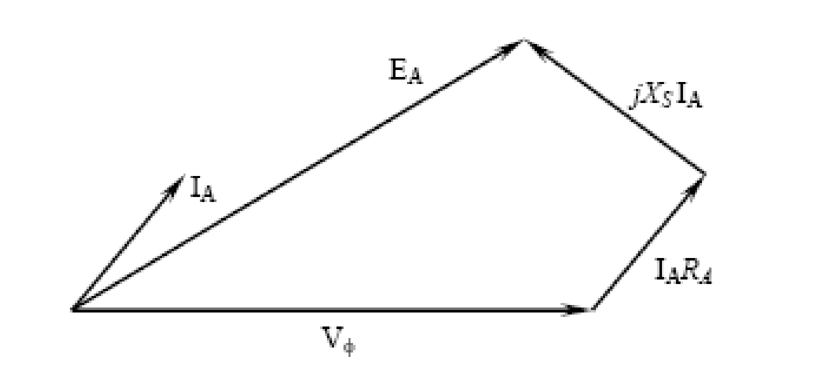
Phasor diagram of a synchronous generator at unity power factor (purely resistive Load).

Phasor Diagram



Phasor diagram of a synchronous generator at lagging factor (Inductive Load).

Phasor diagram of a synchronous generator at leading factor (Capacitive Load).



Notice that larger internal voltage is needed for lagging loads, therefore, larger field currents is needed with lagging loads to get same terminal voltage $E_A = K\phi\omega$

Synchronous Generator

<u>Losses</u>

Rotor

- resistance; iron parts moving in a magnetic field causing currents to be generated in the rotor body
- resistance of connections to the rotor (slip rings)

Stator

- resistance; magnetic losses (e.g., hysteresis)

Mechanical

- friction at bearings, friction at slip rings

Stray load losses

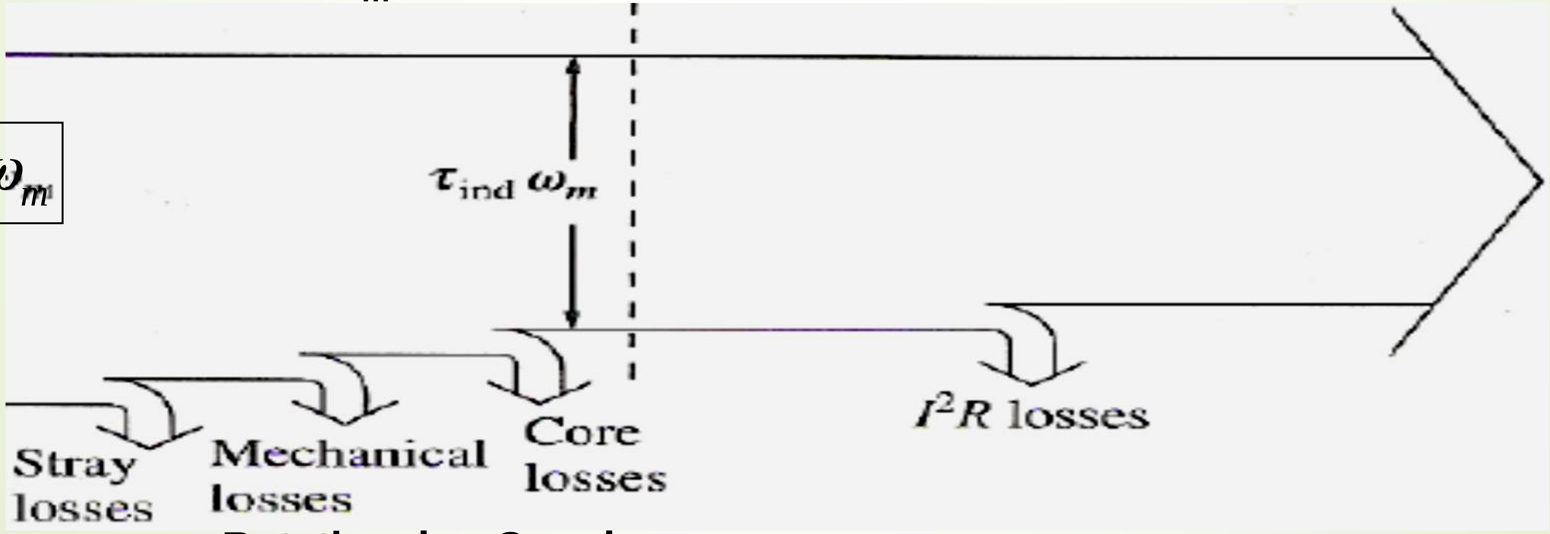
- due to non-uniform current distribution

Power Relationships

- Not all the mechanical power going into a synchronous generator becomes electrical power out of the machine. The difference between input power and output power represents the losses of the machine. The input mechanical power is the shaft power in the generator.

$P_{converted}$ (P_m) $P_{conv} = \tau_{ind}\,\omega_m$

P_{in} (Motor) $P_{in} = \tau_s\,\omega_m$



P_{out} $\sqrt{3}V_T I_L \cos\theta$

Stray losses (P_{st})

Rotational losses (P_r)

Core losses (P_c) $P_c = P_r + P_{st}$

Copper losses (P_{cu}) $3I_A^2 R_A$

Synchronous Generator

The input mechanical power is the shaft power in the generator given by equation:

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

The power converted from mechanical to electrical form internally is given by

$$P_{conv} = \tau_{ind}\omega_m$$

$$P_{conv} = 3E_A I_A \cos\gamma$$

$$where\ \gamma\ is\ the\ angle\ between\ E_A\ and\ I_A$$

The real electric output power of the synchronous generator can be expressed in line and phase quantities as

$$P_{out} = \sqrt{3}V_T I_L \cos\theta$$

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

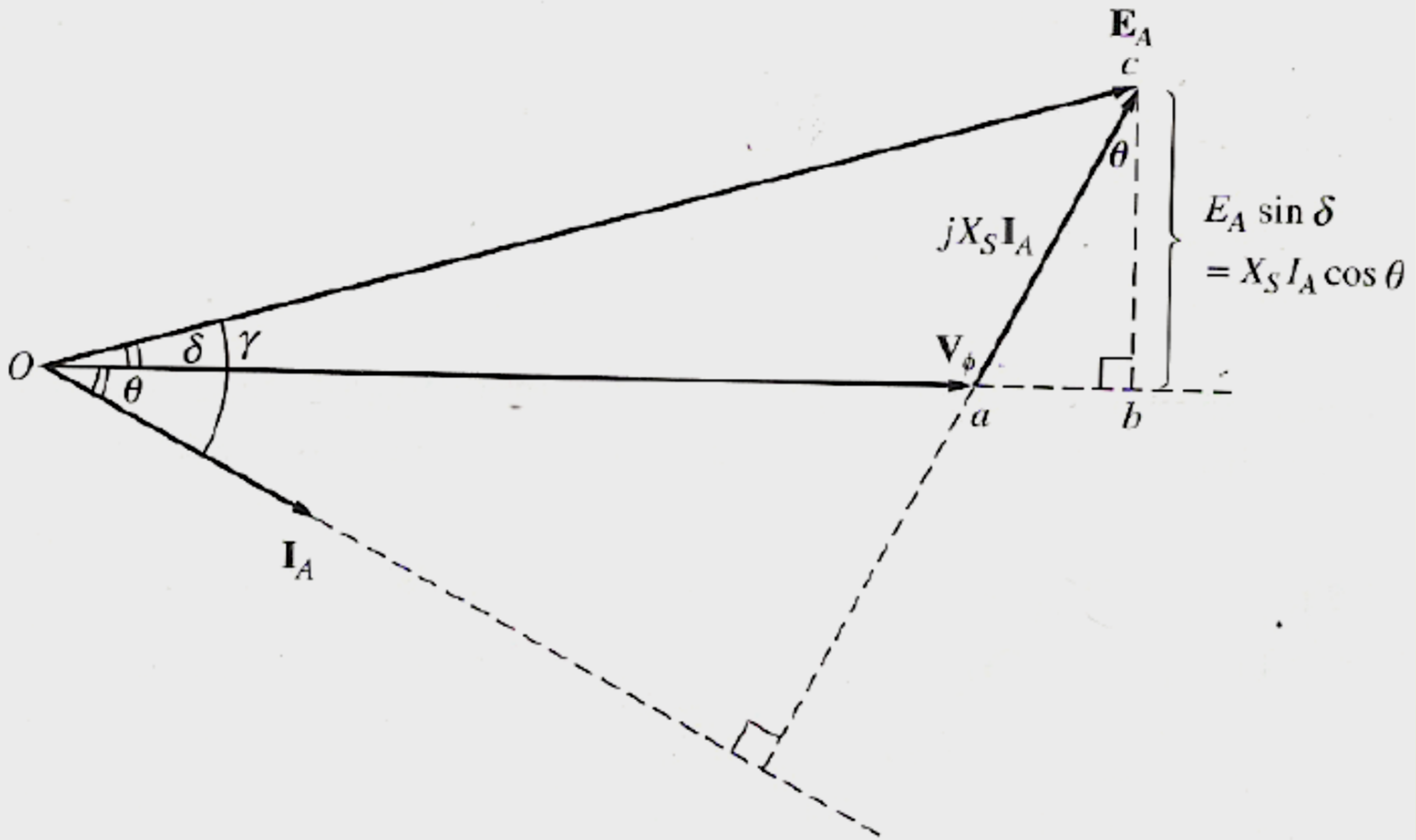
and reactive output power

$$Q_{out} = \sqrt{3}V_T I_L \sin\theta$$

$$Q_{out} = 3V_\phi I_A \sin\theta$$

Synchronous Generator

In real synchronous machines of any size, the armature resistance R_A is more than 10 times smaller than the synchronous reactance X_S ($X_s >> R_A$). Therefore, R_A can be ignored



Power Relationships

The power converted from mechanical to electrical is given by;

$$P_{conv} = \tau_{ind}\,\omega_m \qquad = 3E_A I_A \cos\gamma$$

Where γ is the angle between E_A and I_A:

If the armature resistance R_A is ignored ($X_S >> R_A$), Therefore:

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

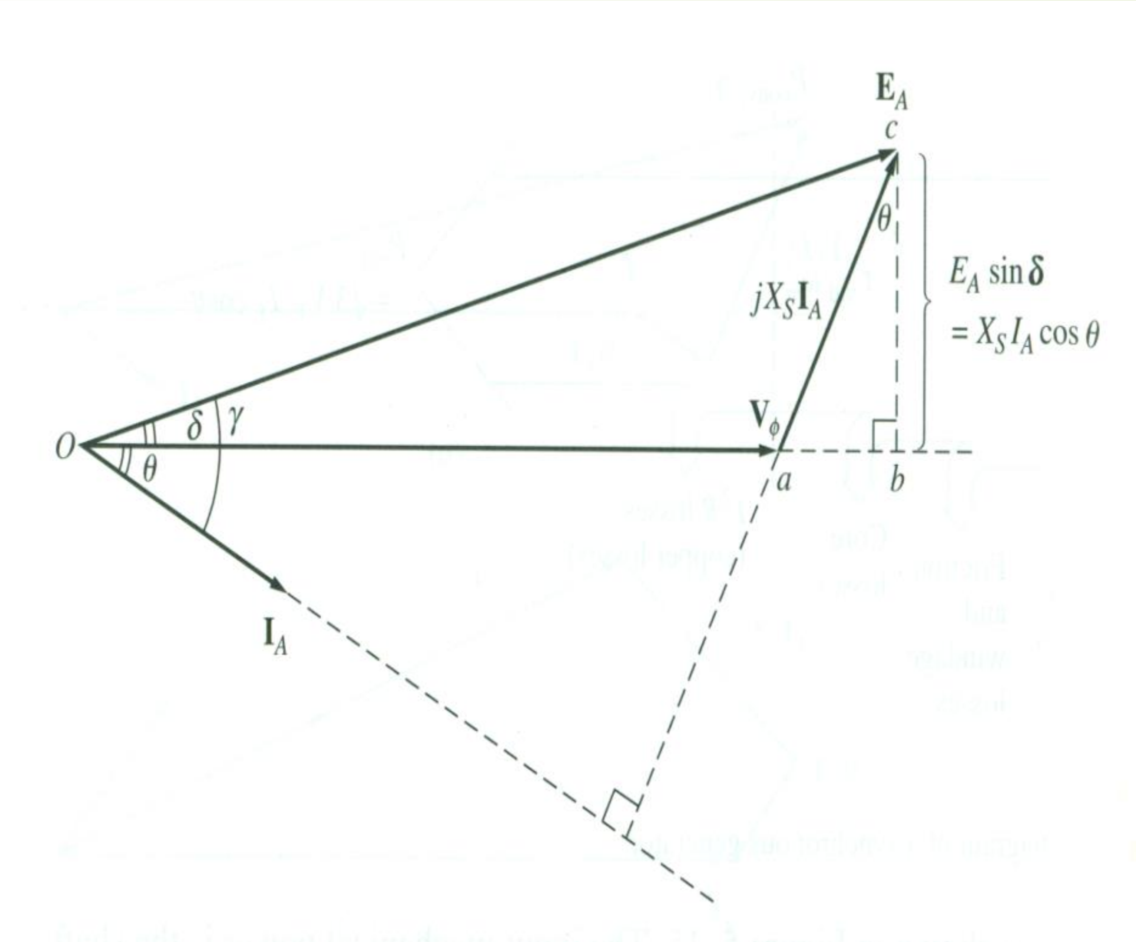
Substituting this equation into P_{out}, gives;.

$$\therefore \quad P = \frac{3V_\phi E_A \sin\delta}{X_S}$$

Where δ is the angle between E_A and V_T.

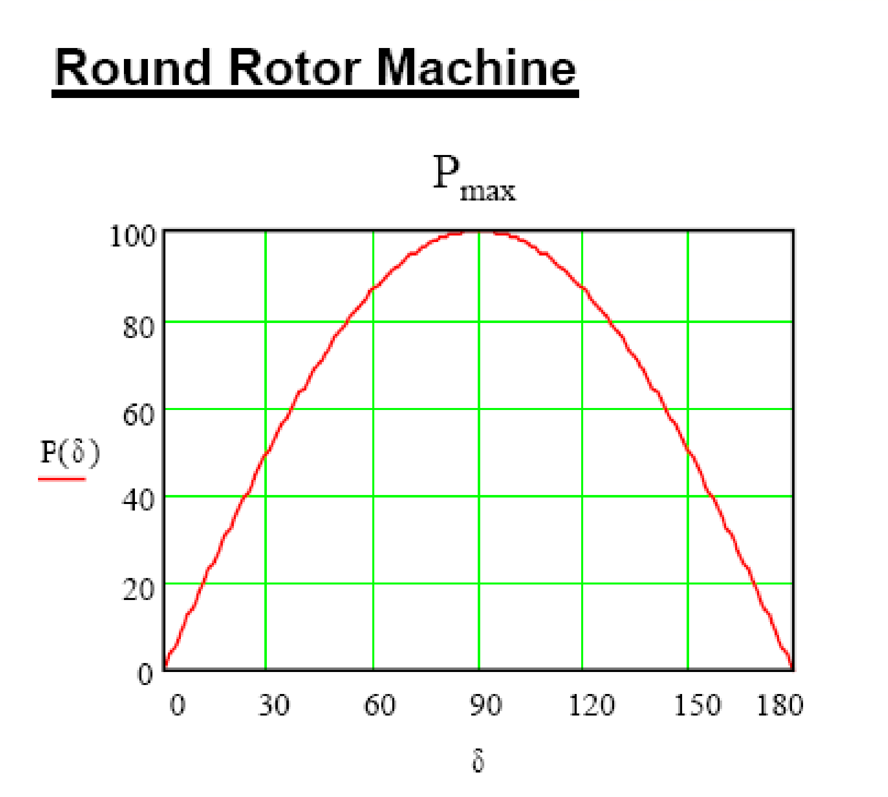
The induced torque can be express as;.

$$\therefore \tau_{ind} = \frac{3V_\phi E_A \sin\delta}{\omega_m X_S}$$



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 reverse.



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

Efficiency

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

$$P_{in} = P_{out} + P_{losses}$$

Example:

- *A 480-V, 200-KVA, 0.8 PF lagging, 60-HZ, 2-poles, Y-connected synchronous generator has a synchronous reactance of 0.25 Ω and an armature resistance of 0.04 Ω. At 60 Hz, its friction and windage losses are 6 KW and its core losses are 4 KW. Assume that the field current of the generator has been adjusted to a value of 4.5 A so that the open-circuit terminal voltage of the generator is 477 V.*

Determine:

a) The terminal voltage of the generator, if it is connected to Δ-connected load with an impedance of $5\angle 30^{\circ}$ Ω.

b)The efficiency.

c)Sketch the phasor diagram of this generator

d)If another identical Δ-connected load is connected in parallel, determine the new terminal voltage.

e)Sketch the new phasor diagram after adding the new load.

$$I_A = \frac{E_A}{|R_A + jX_S + Z|} = \frac{275\ \text{V}}{|0.03 + j0.25 + 1.667\angle 30°|} = \frac{275\ \text{V}}{1.829\ \Omega} = 150\ \text{A}$$

$$V_\phi = I_A Z = (150\ \text{A})(1.667\ \Omega) = 250\ \text{V}$$

$$V_T = \sqrt{3}\, V_\phi = \sqrt{3}\,(250\ \text{V}) = 433\ \text{V}$$

The efficiency of the generator under these conditions 3can be found as follows:

$$P_{\text{OUT}} = 3 V_\phi I_A \cos\theta = 3(250\ \text{V})(150\ \text{A})(0.8) = 90\ \text{kW}$$

$$P_{\text{CU}} = 3 I_A^{\,2} R_A = 3(150\ \text{A})^2 (0.03\ \Omega) = 2\ \text{kW}$$

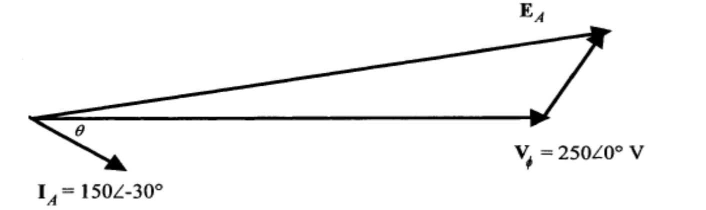
$$P_{\text{F\&W}} = 6\ \text{kW}$$

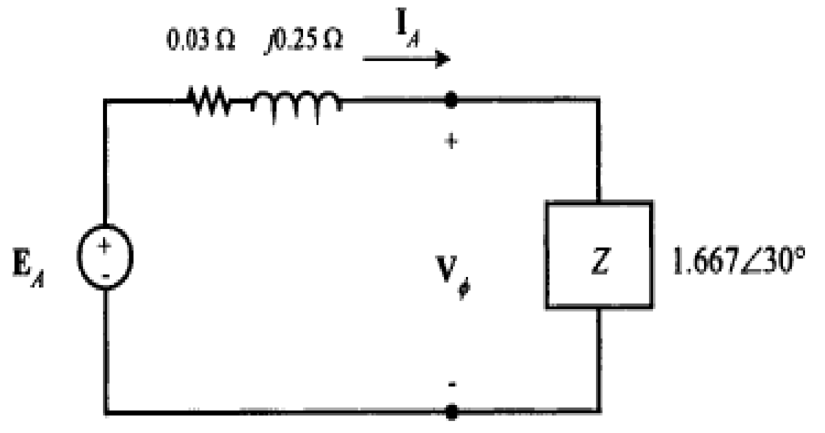
$$P_{\text{core}} = 4\ \text{kW}$$

$$P_{\text{stray}} = (\text{assumed } 0)$$

$$P_{\text{IN}} = P_{\text{OUT}} + P_{\text{CU}} + P_{\text{F\&W}} + P_{\text{core}} + P_{\text{stray}} = 102\ \text{kW}$$

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \times 100\% = \frac{90\ \text{kW}}{102\ \text{kW}} \times 100\% = 88.2\%$$



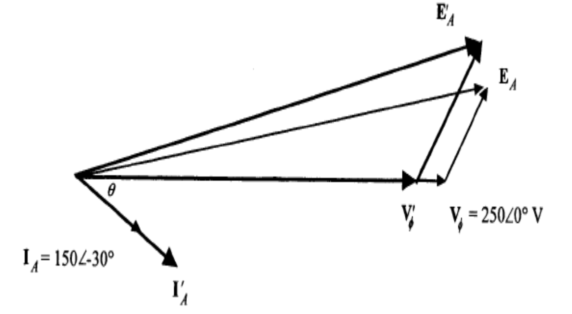


$$I_A = \frac{E_A}{|R_A + jX_S + Z|} = \frac{275\ \text{V}}{|0.03 + j0.25 + 0.8333\angle 30°|} = \frac{275\ \text{V}}{1.005\ \Omega} = 274\ \text{A}$$

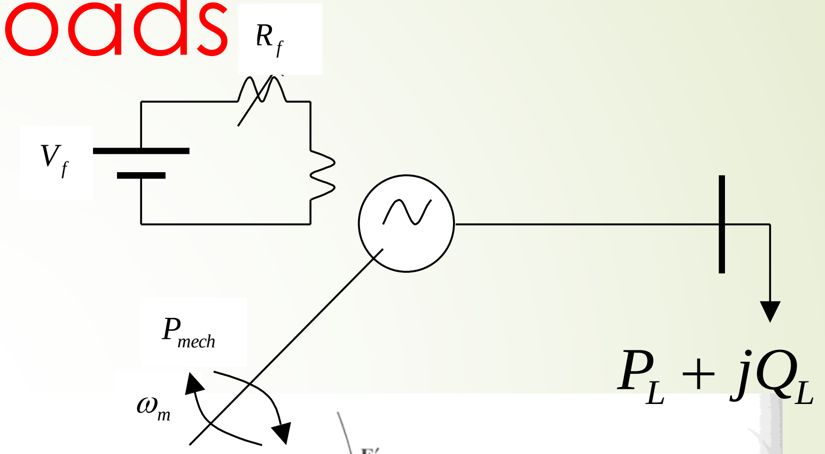
Therefore, the magnitude of the phase voltage is

$$V_\phi = I_A Z = (274\ \text{A})(0.8333\ \Omega) = 228\ \text{V}$$

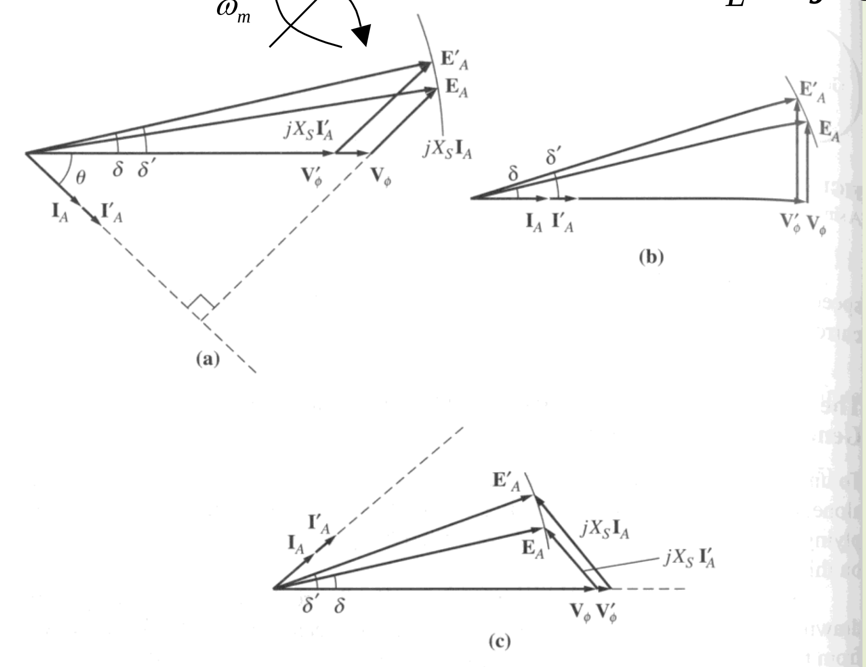
$$V_T = \sqrt{3}\, V_\phi = \sqrt{3}\,(228\ \text{V}) = 395\ \text{V}$$



The Synchronous Generator Operating Alone- Variable Loads



- The behavior of Synch. Generator depend on the power factor of the load and whether the generator operating alone or parallel . By assuming SG operating alone , what happens when we increase the load on this generator?
  - At lagging power factor the increase of load current will decrease the terminal voltage significantly.
  - At unity power factor, the increase of load current will decrease the terminal voltage only slightly.
  - At leading power factor the increase of load current will increase the terminal voltage.



Voltage Regulation

- As the load on the generator increases, the terminal voltage drops (lagging and unity PF loads cases). 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, EA has to be adjusted to keep the terminal voltage VT constant.

∴ Voltage Regulation, VR;

$$\frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\,\%$$

-If SG operate at lagging power factor the VR is very high.(Positive voltage regulation).
-If SG operate at unity power factor just small positive VR
- At leading power factor VR is negative.

How the terminal voltage is corrected?

- Recall: $V_{\phi} = E_A - jX_S I_A$

  and $E_A = K\phi\omega$

- Since the frequency (ω) should not be changed, then Φ must be changed.

The procedure:

- Decreasing the field resistance will increase its field current.

- The increase of field current will increase the flux and increase the EA, and the Vφ will increase.

Parallel Operation of Synch Generators

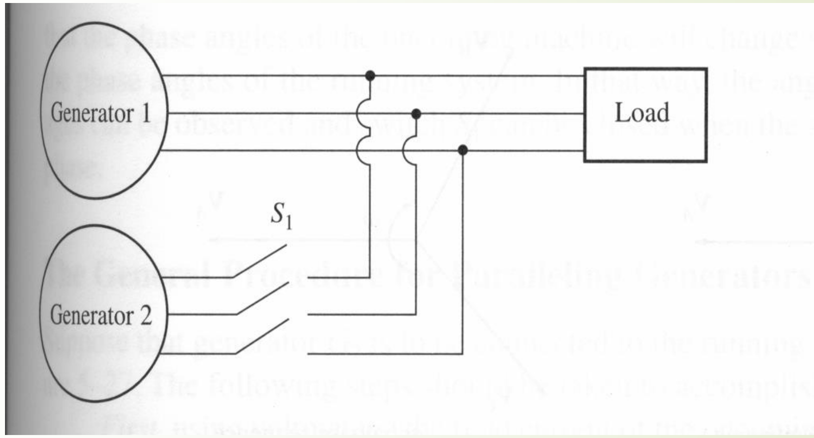
Benefits:

- Increases the real and reactive power supply in the system.
- Increase the reliability of the power system.
- Allows shut down and preventive maintenance for some generators.
- Allows the operation near full load then maximum efficiency can be obtained.

The conditions required for Paralleling Syn. Generators

The following requirements have to be satisfied prior to connecting an alternator to other generator.

1. The rms line voltage of the two generators must be equal.
2. The two generators must have the same phase sequence (aa' bb' cc').
3. The frequency of the oncoming alternator must be slightly higher than the frequency of the running system.

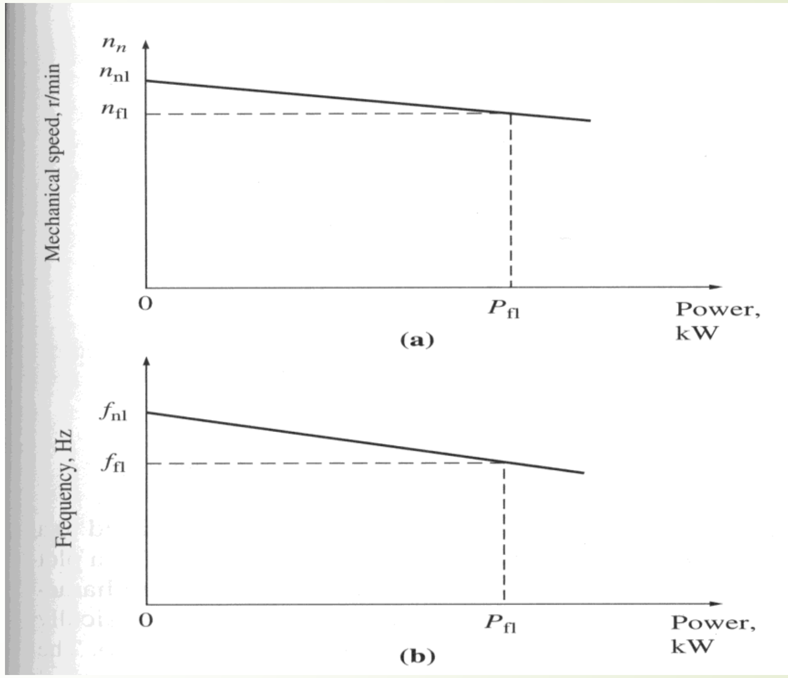


Frequency Power and Voltage

The speed droop of prime mover:

$$SD = \frac{n_{nl} - n_{fl}}{n_{fl}} \times 100\,\%$$

where: n_{nl} : No load speed
n_{fl} : No load speed



The relation between power and frequency:

$$P = s_p(f_{nl} - f_{sys})$$

where: P: output power
Sp: slope of the curve in kwh/Hz
f_{nl}: No load frequency
f_{fl}: Full load frequency

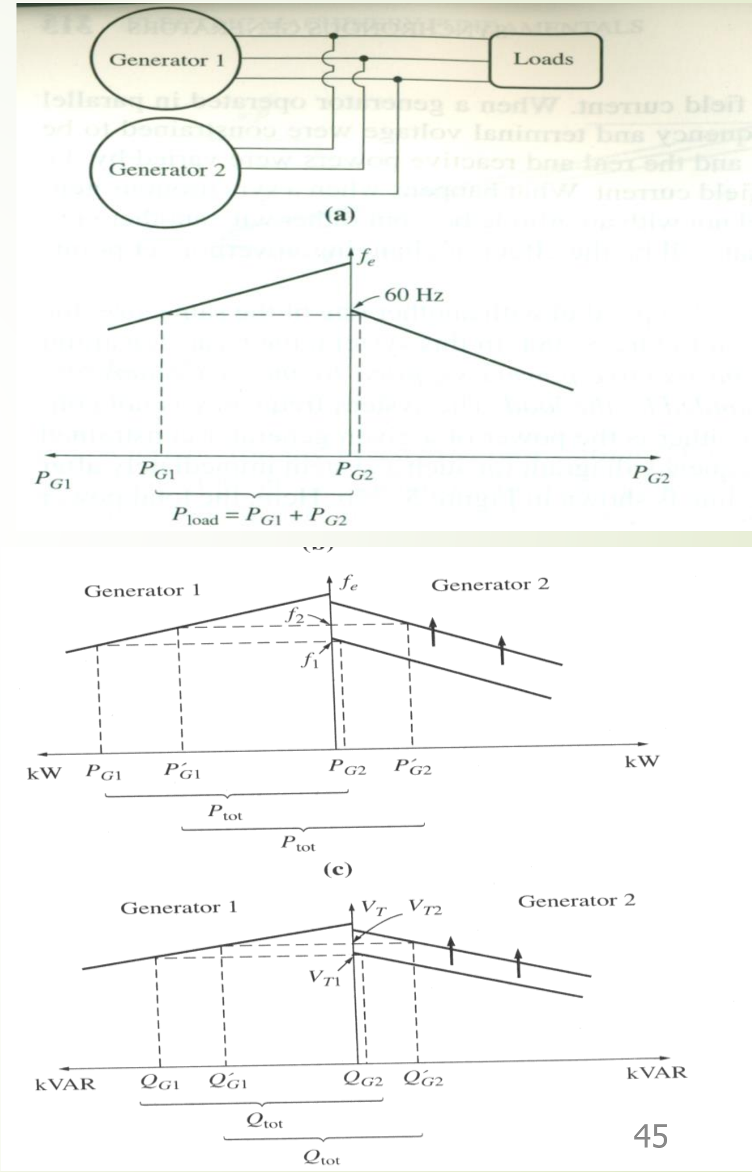
The relation between reactive power and voltage:

$$Q = s_p(V_{nl} - V_{sys})$$

Q: output reactive power
Sp: slope of the curve in kvar/Hz
V_{nl}: No load voltage
V_{fl}: Full load voltage

Parallel operation of two Syn. generators of the same size

- **The sum of the real and reactive powers supplied by the two generators must equal to the P and Q demanded by the load. This will not change unless demand change**
- The system frequency is not constrained to constant, and neither is the power of a given generator is constrained to constant.
- **The increase of the governor set point will increase the system frequency, increase the real power supplied by G1 and reduce the power of second G2.**
- **The increase of field current will increase the system terminal voltage, increase reactive power of G1 and reduce reactive power of G2.**



Connection with infinite bus

The following requirements have to be satisfied prior to connecting an alternator to the **infinite bus (connection line)**.

1. The line voltage of the (incoming) alternator must be equal to the constant voltage of the of the infinite bus.
2. The frequency of the incoming alternator must be exactly equal to that of the infinite bus.
3. The phase sequence of the incoming alternator must be identical to the phase sequence of the infinite bus.