ECE 325 – Electric Energy System Components
7- Synchronous Machines

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Content

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- Synchronous Generators

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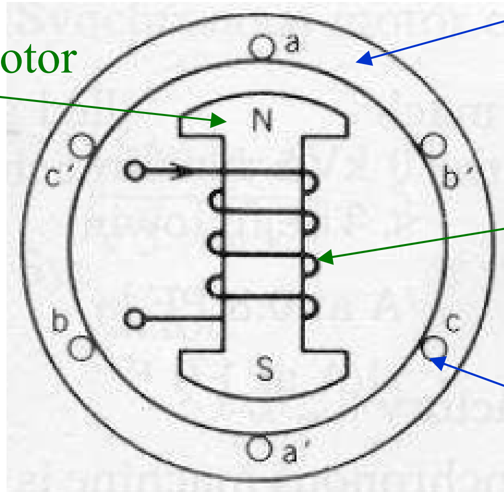
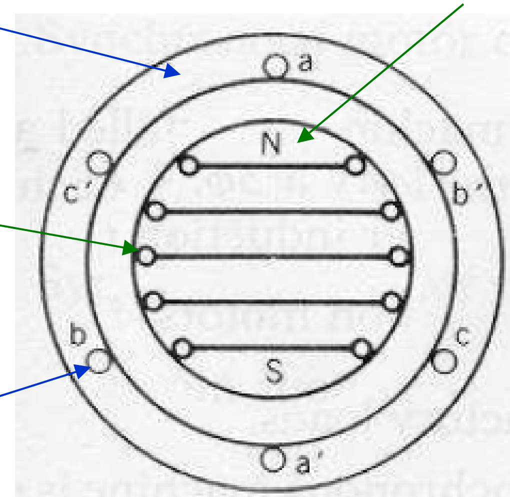
Synchronous Generators





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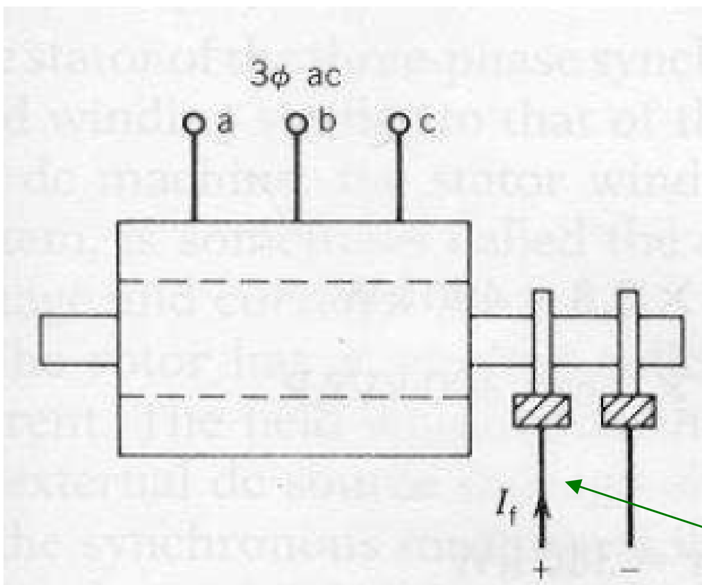
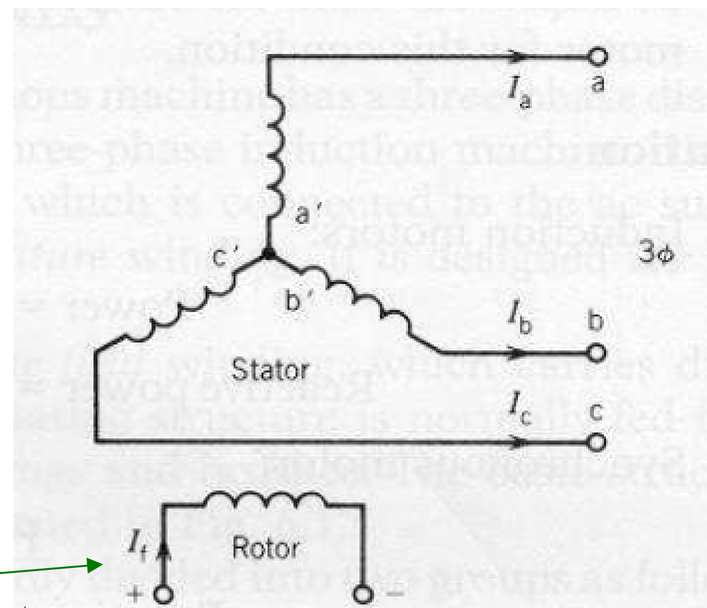
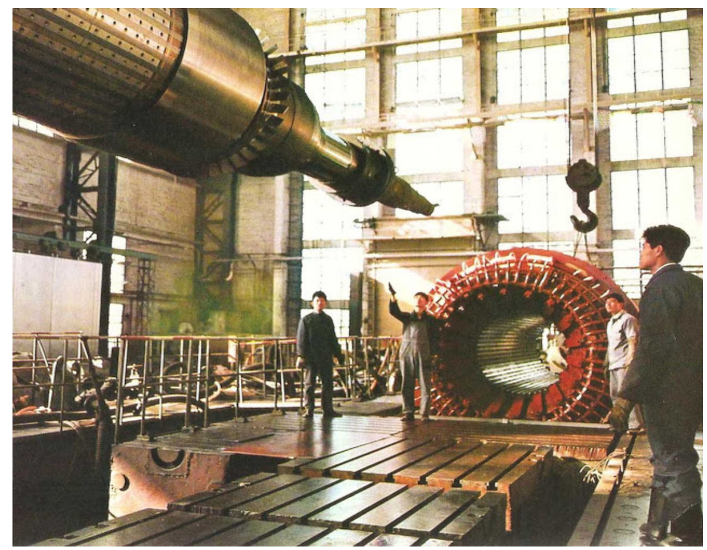




Types of Rotors

- Salient pole rotors
  - Have concentrated windings on poles and non-uniform air gap
  - Short axial length and large diameter to extract the maximum power from a waterfall
  - On hydraulic turbines operated at low speeds at 50-300 r/min (having a large number of poles)
  - Have a squirrel-cage windings (damper windings) embedded in the pole-faces to help damp out speed oscillations
- Cylindrical/round rotors
  - Distributed winding and uniform air gap
  - Large axial length and small diameter to limit the centrifugal forces
  - Steam and gas turbines, operated at high speeds, typically 1800-3600r/min (4 or 2-pole)
  - Eddy in the solid steal rotor gives damping effects
  - 70% of large synchronous generators (150~1500MVA)

16 poles salient-pole rotor (12 MW)



Round rotor generator under construction

(Source: http://emadrlc.blogspot.com)

Main features of the stator

- Same as the stator of a 3-phase inductor motor
- The winding is always in Y connection with the neutral grounded (the voltage per phase only 1/1.73 or 58% of that in Δ connection)
- Factors affecting the size of synchronous generators: usually, a larger generator has
  - a larger capacity
  - a higher efficiency
  - a larger power output per kilogram (cheaper)
  - more serious cooling problems (higher power losses per unit surface area)

Stator winding of a hydor-unit

An employee of Siemens Charlotte Turbine-Generator Center in the Stator winding area inspects the coils

Sources: Wikipedia & PatrickSchneiderPhoto.com

Field excitation and exciters

- Using a main exciter and a pilot exciter, the DC field excitation not only ensures a stable AC terminal voltage of the synchronous generator, but must also quickly respond to sudden load changes in order to maintain system stability.

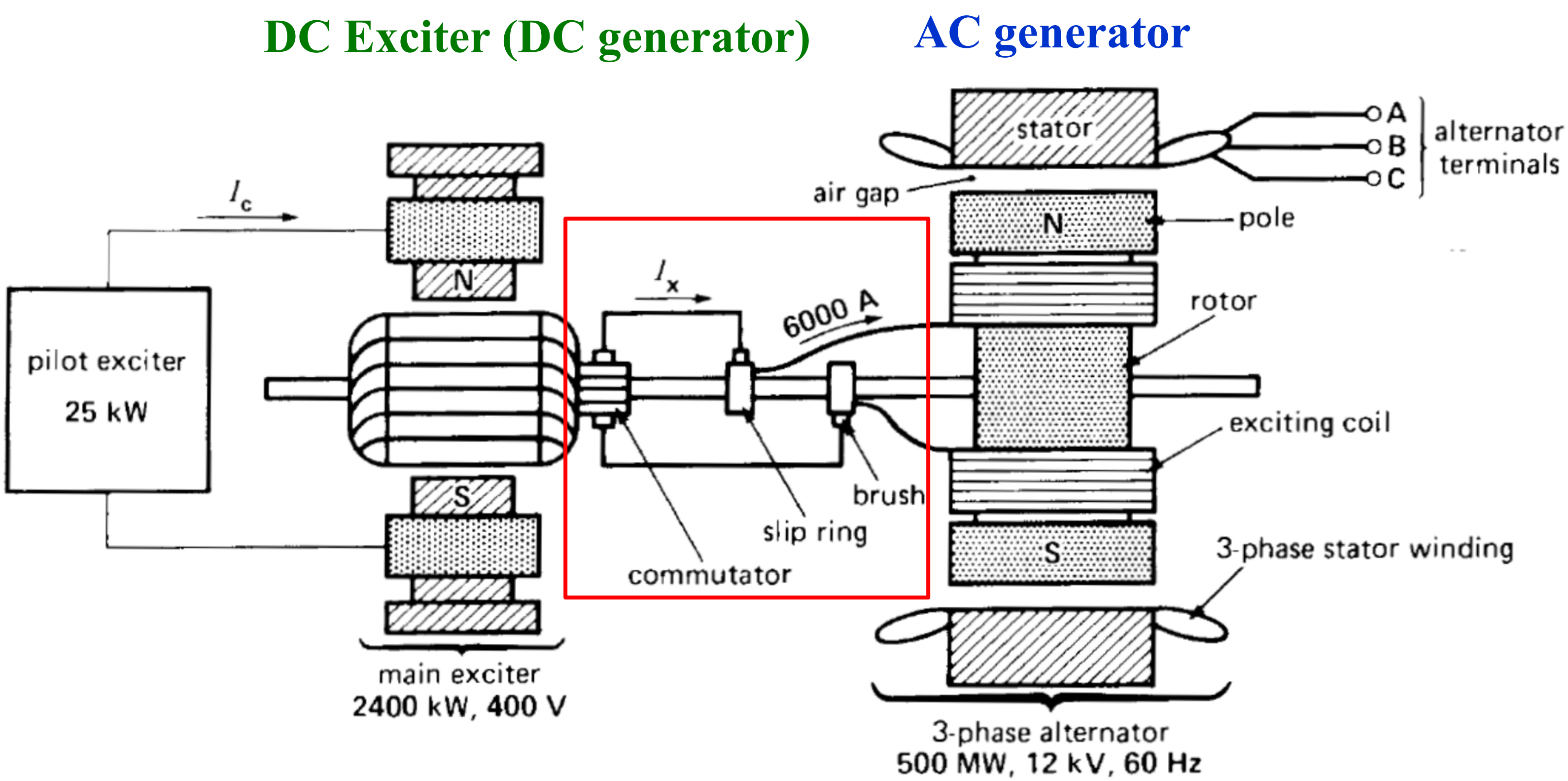


Figure 16.1
Schematic diagram and cross-section view of a typical 500 MW synchronous generator and its 2400 kW dc exciter. The dc exciting current I_x (6000 A) flows through the commutator and two slip-rings. The dc control current I_c from the pilot exciter permits variable field control of the main exciter, which, in turn, controls I_x.

Brushless excitation

- Electronic rectifiers replace the commutator, slip-rings and brushes

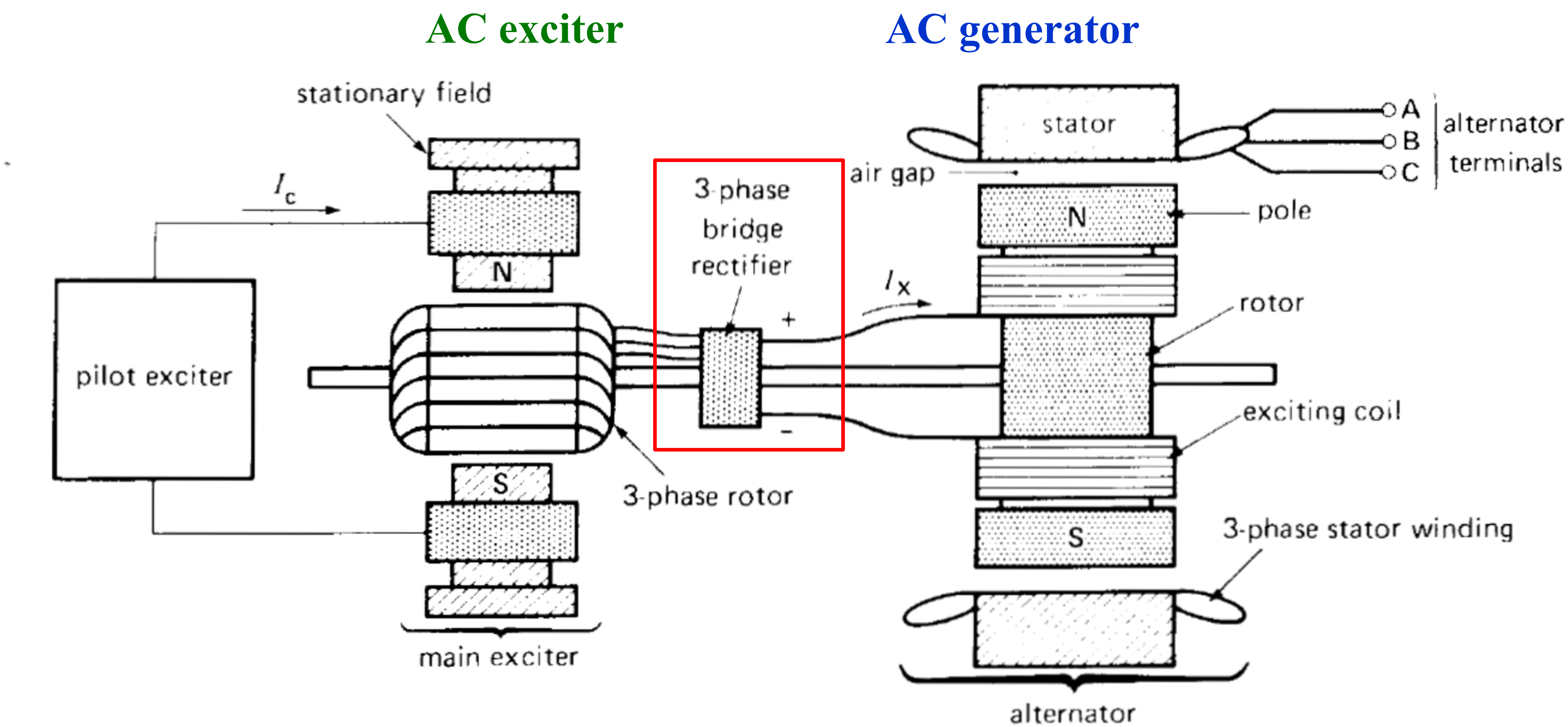
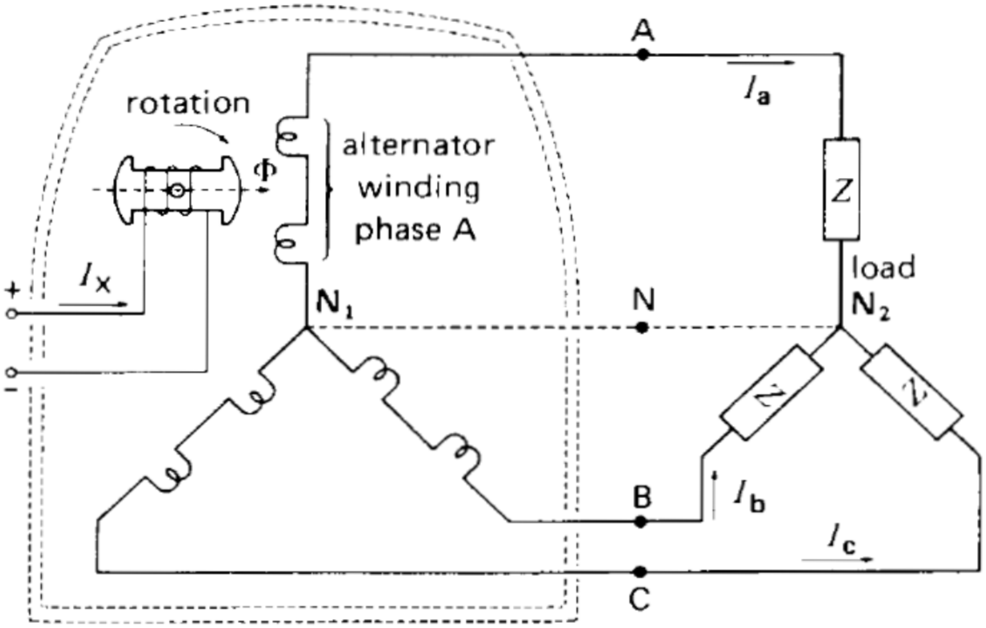


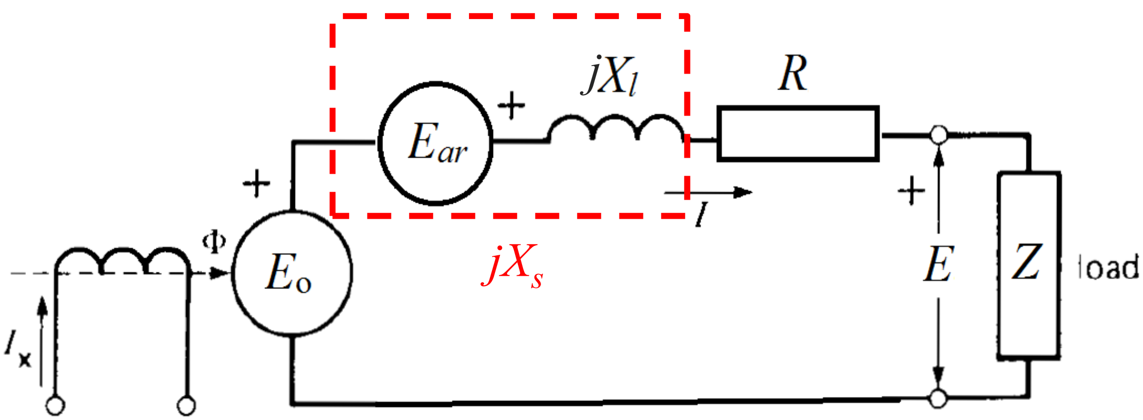
Figure 16.8
Typical brushless exciter system.

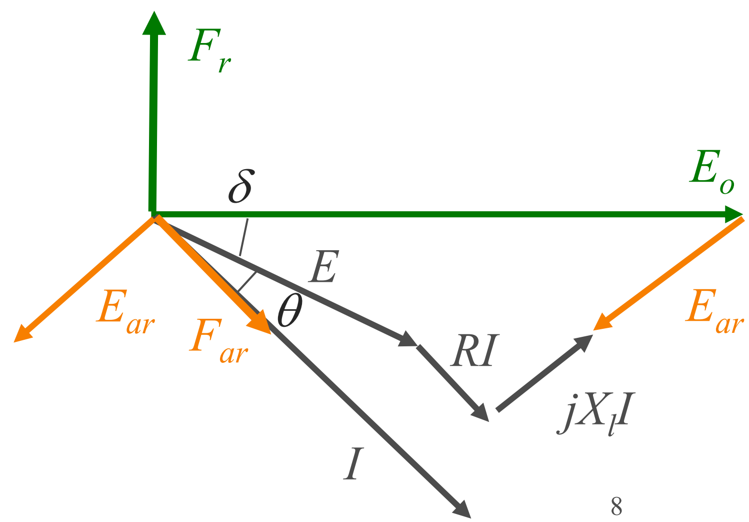
Equivalent circuit of a 3-phase AC generator



- E_o is induced by rotor flux ϕ (field current I_X)
- E_{ar} is induced by armature flux ϕ_{ar} (armature current I)
- X_l is leakage reactance
- R is armature resistance
- KVL: $E_o+E_{ar}=jX_lI+R_aI+E$
- Let $E_{ar}=-jX_{ar}I$: $E_o=j(X_l+X_{ar})I+R_aI+E$
- Define $X_s=X_{ar}+X_l$ (called synchronous reactance)

$$E_o=jX_sI+R_aI+E$$



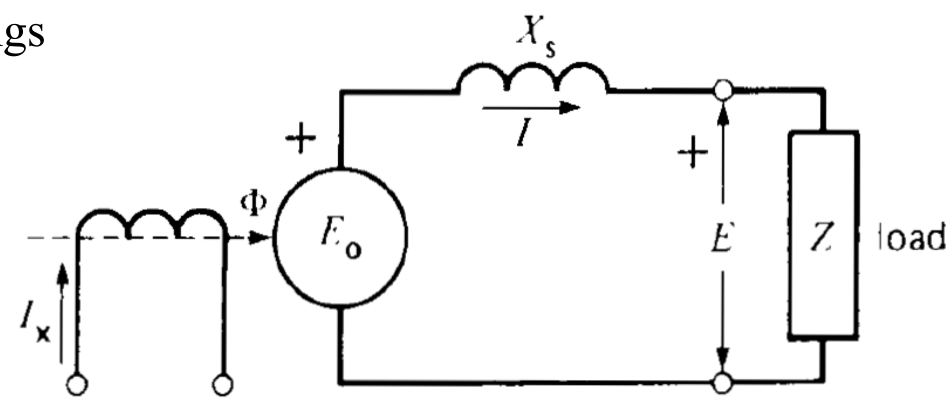


Determining the value of X_s

- **Open-circuit test**:
  - Open stator terminals (I=0) and drive the generator at the rated speed
  - Raise exciting current I_X until the rated line-to-line voltage is attained.
  - Measure the corresponding I_X=I_{Xn} and line-to-neutral voltage E_n
- **Short-circuit test:**
  - Reduce the excitation to 0 and short-circuit three stator terminals.
  - With the generator running at rated speed, gradually raise I_X to I_{Xn}.
  - Record current I_{SC} in the stator windings

If armature resistance R is ignorable:

$$X_S = E_n / I_{SC}$$



- **Per-unit X_S :** X_S (pu) = X_S/Z_B (usually in 0.8-2 pu)

$Z_B = E_B^2/S_B$ base impedance (line-to-neutral) of the generator [Ω]

E_B = base voltage (line-to-neutral) [V]

S_B = base power per phase [VA]

Synchronous generator connected to an isolated load

$$E_o = E_X + E = jX_s I + ZI$$

$$Z = |Z|\angle\theta \qquad PF = \cos\theta$$

$$\text{Voltage Regulation} = \frac{|E_{NL}| - |E_B|}{|E_B|} \times 100$$

E_{NL}: no-load voltage (E_o)

E_B: rated voltage (E_n)

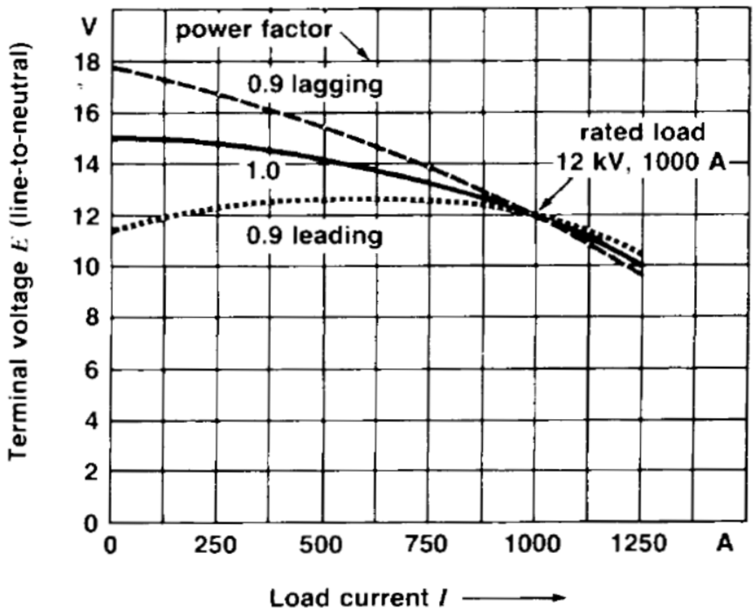
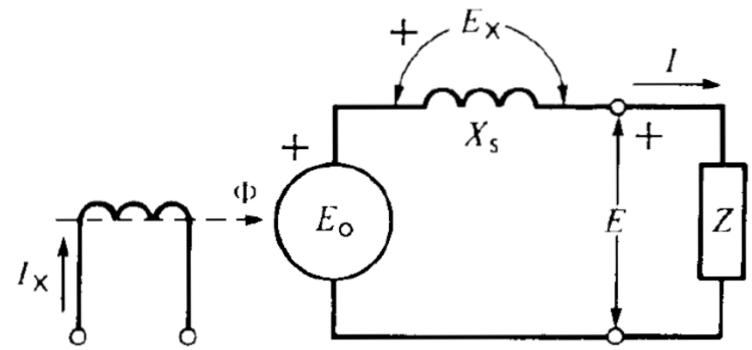


Figure 16.23
Regulation curves of a synchronous generator at three different load power factors.



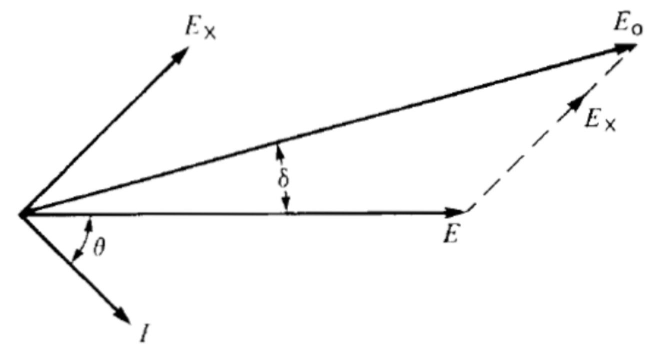


Figure 16.20
Phasor diagram for a lagging power factor load.

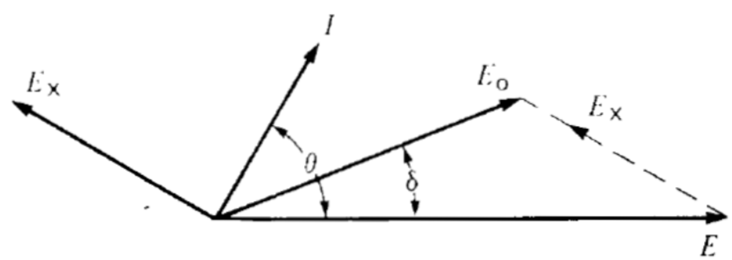


Figure 16.21
Phasor diagram for a leading power factor load.

Example 16-2

A 3-phase synchronous generator produces an open-circuit line voltage of 6928V when the DC exciting current is 50A. The AC terminals are then short-circuited, and the three line currents are found to be 800A

a. Calculate the synchronous reactance per phase

$$|E_o| = E_{oL}/1.73 = 6928/1.73 = 4000\text{V}$$

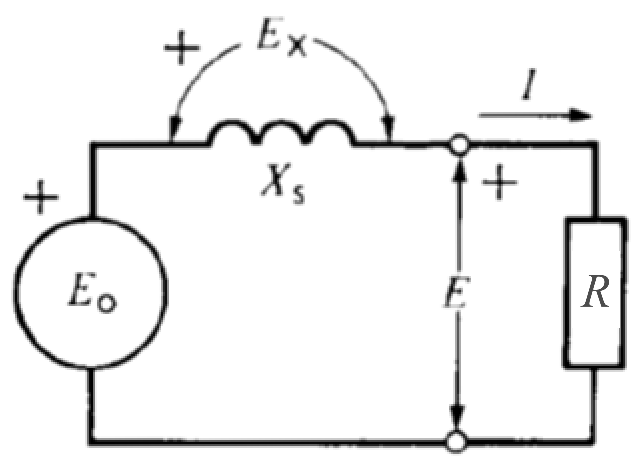
$$X_S = |E_o|/|I| = 4000/800 = 5\ \Omega$$

b. Calculate the terminal voltage if three 12 Ω resistors are connected in Y across the terminals

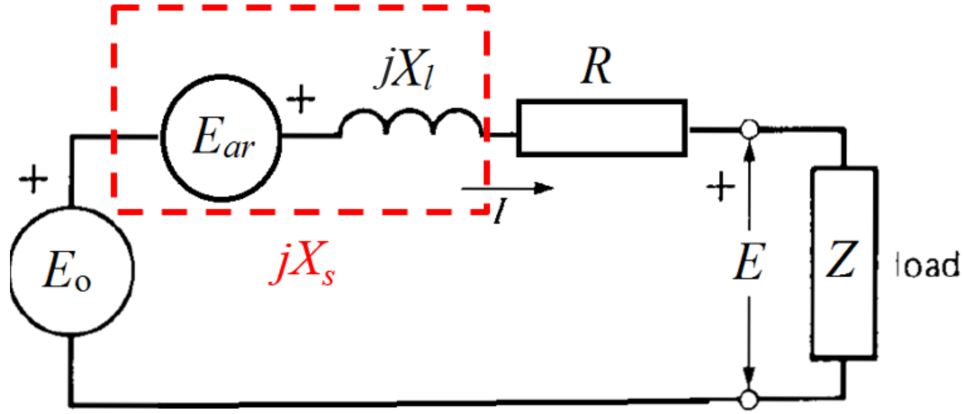
$$|Z| = \sqrt{R^2 + {X_S}^2} = 13\ \Omega$$

$$|E| = |I|R = |E_o|R/|Z| = 4000 \times 12/13 = 3696\ \text{V}$$

$$E_L = 1.73|E| = 6402\ \text{V}$$



Example 16-3



A 30MVA, 15kV, 60Hz AC generator has a synchronous reactance X_S=1.2 pu and a winding resistance R= 0.02 pu. Calculate

a. Its base voltage, base power and base impedance

$E_B=E_L/1.73=15000/1.73=8660$ V

$S_B=30/3=10$ MVA

$Z_B=E_B{}^2/S_B=8600^2/10^7=7.5\ \Omega$

b. The actual values of X_S and R per phase

$X_S=X_S(\text{pu})\times Z_B= 1.2 \times 7.5 = 9\ \Omega$

$R=R(\text{pu})\times Z_B= 0.02 \times 7.5 = 0.15\ \Omega$

c. The total full-load copper losses

$I(\text{pu})=E(\text{pu})/Z(\text{pu})=1/1=1$ pu

$P_{loss} = 3I^2R \times S_B= 3 \times 1 \times 0.02 \times 10 = 0.6$ MW