ECE 325 – Electric Energy System Components
7- Synchronous Machines

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Content

(Materials are from Chapters 16-17)

- Synchronous Generators
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Synchronous Generators

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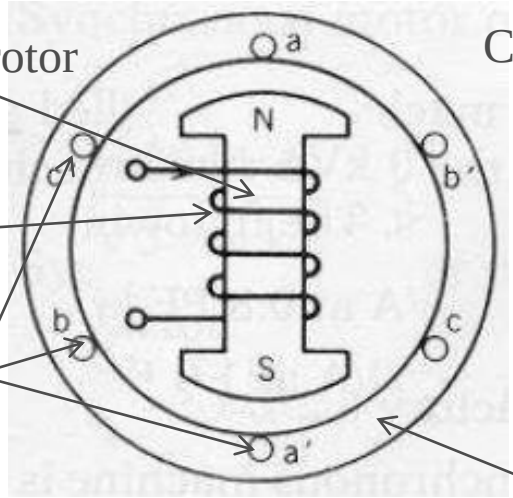
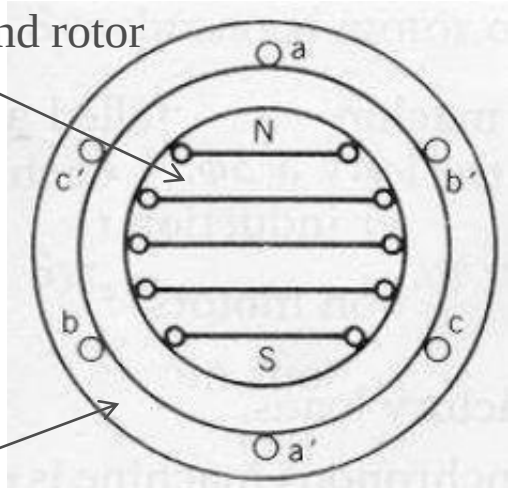
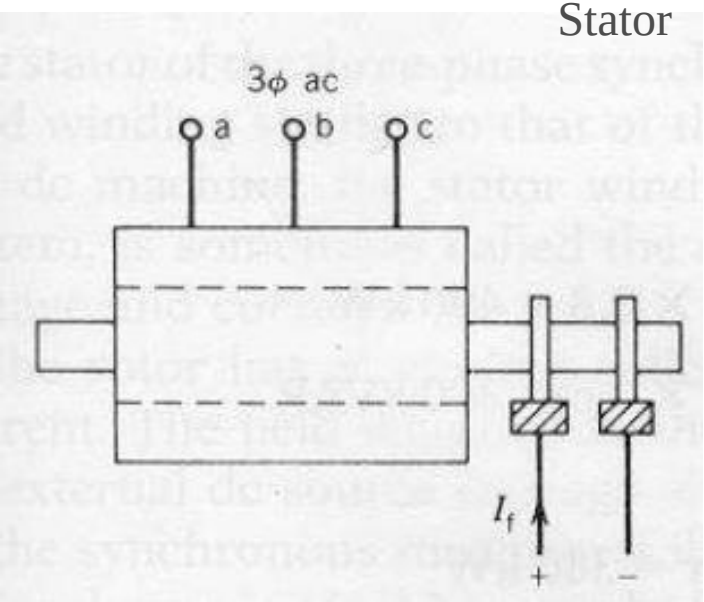
Armature winding

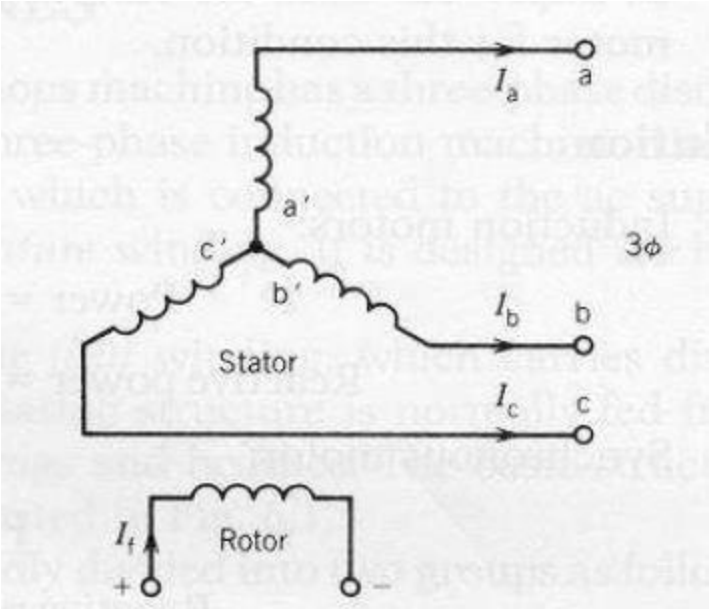




Stator

$f = pn/120$





Field current

Main features of the stator

- Identical to 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)

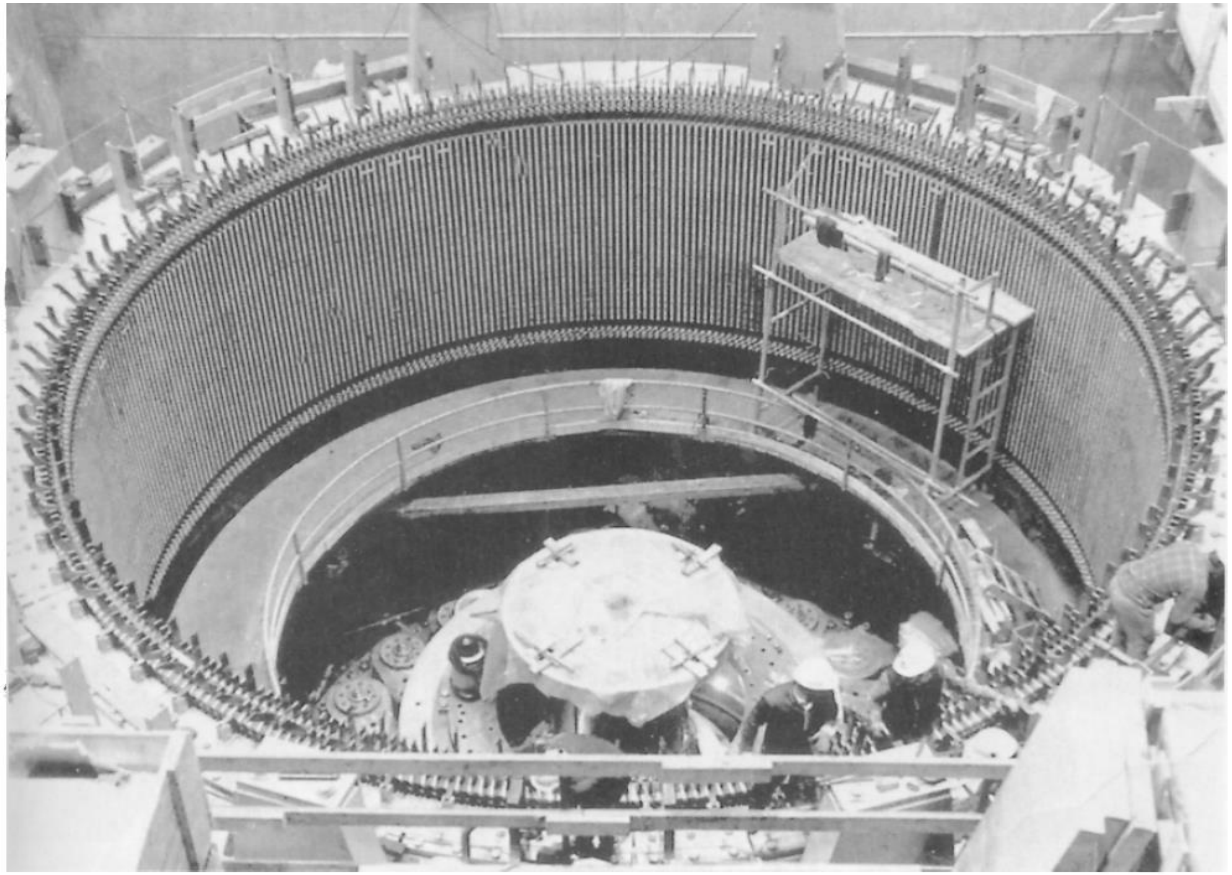


Figure 16.2a
Stator of a 3-phase, 500 MVA, 0.95 power factor, 15 kV, 60 Hz, 200 r/min generator. Internal diameter: 9250 mm; effective axial length of iron stacking: 2350 mm; 378 slots.
(*Courtesy of Marine Industrie*)

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
  - 70% of large synchronous generators (150~1500MVA)
  - 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

16 poles salient-pole rotor (12 MW)

Round rotor generator under construction

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

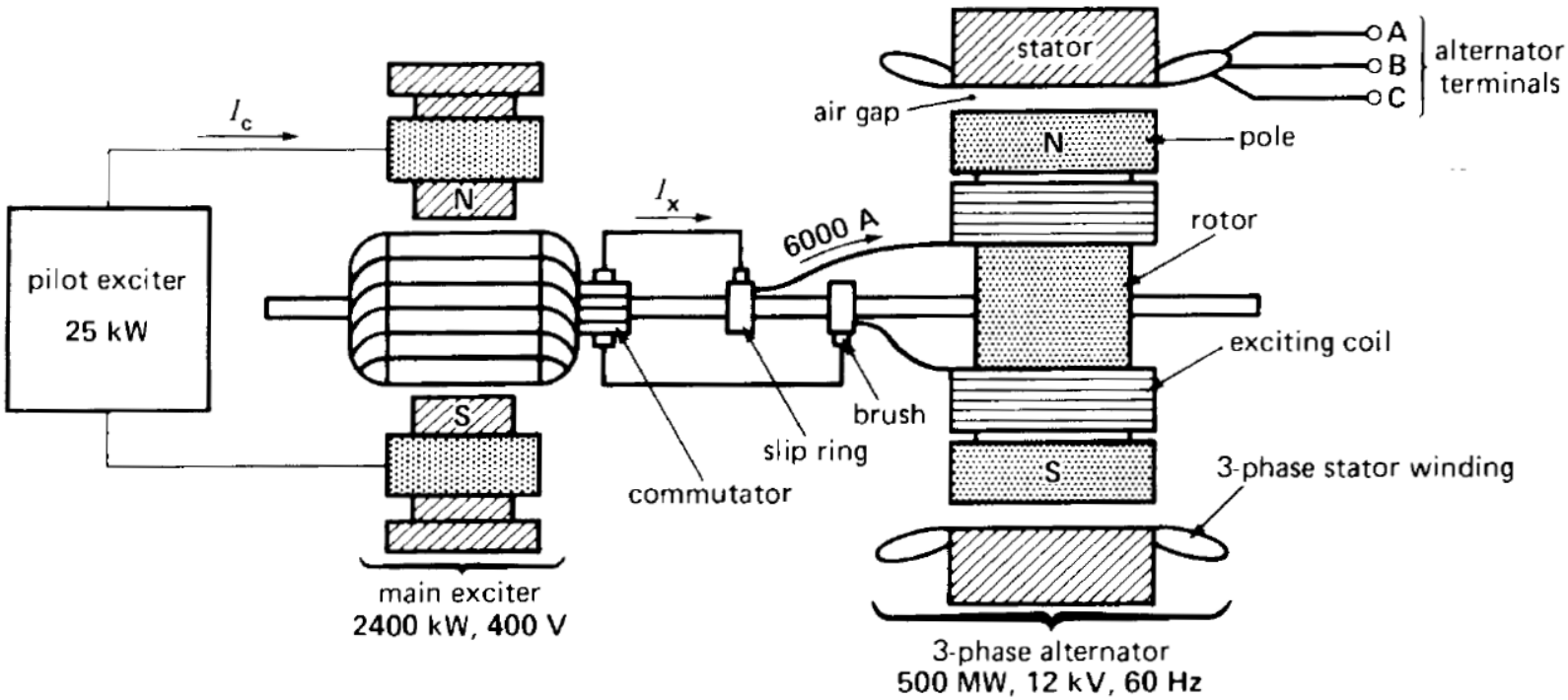


Figure 16.1
Schematic diagram and cross-section view of a typical 500 MW synchronous generator and its 2400 kW dc exciter. The dc exciting current I_x (6000 A) flows through the commutator and two slip-rings. The dc control current I_c from the pilot exciter permits variable field control of the main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

Brushless excitation

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

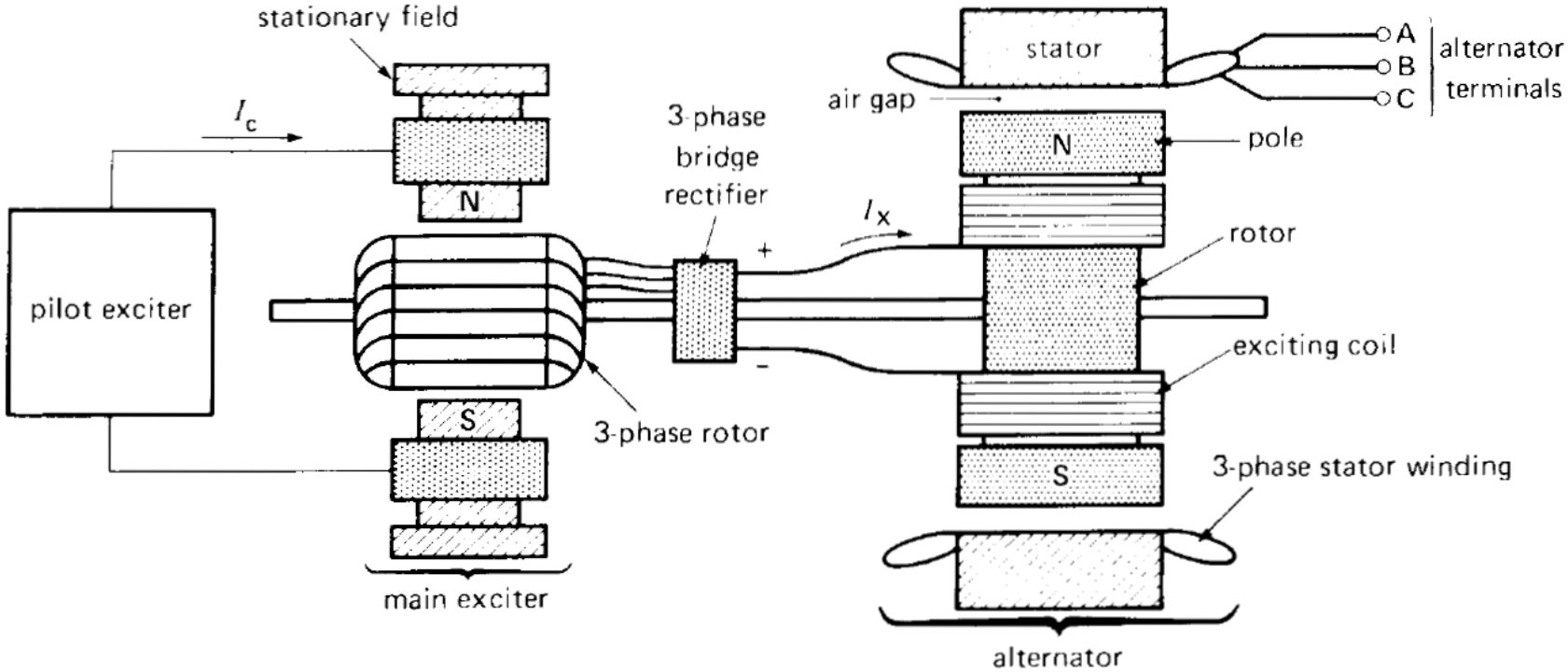
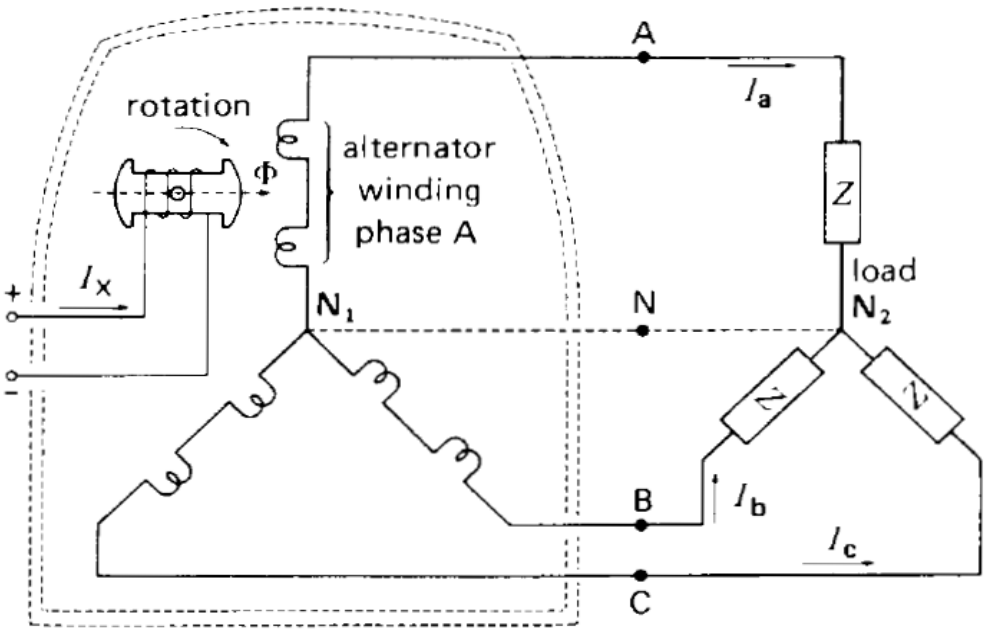


Figure 16.8
Typical brushless exciter system.

Factors affecting the size of synchronous generators

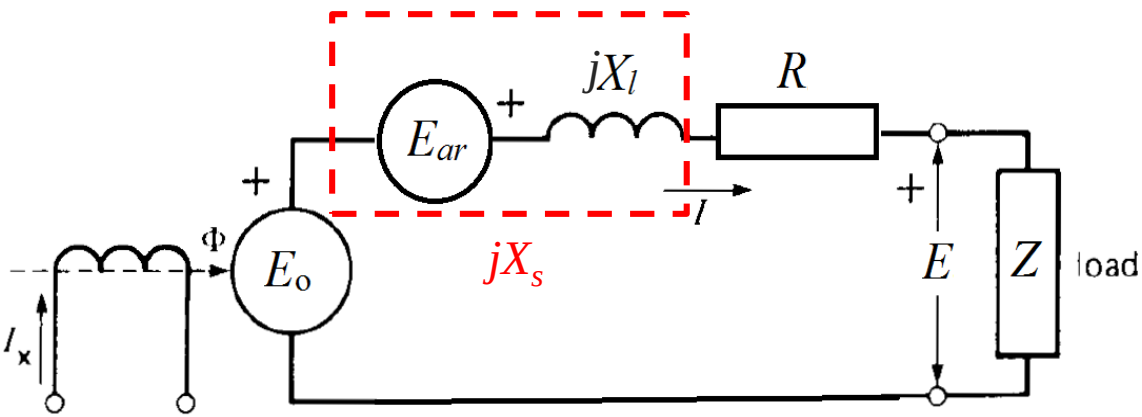
- Usually, a larger generator has
  - a larger capacity
  - a higher efficiency
  - a larger power output per kilogram (cheaper)
  - more serious cooling problems (higher power losses per unit surface area)

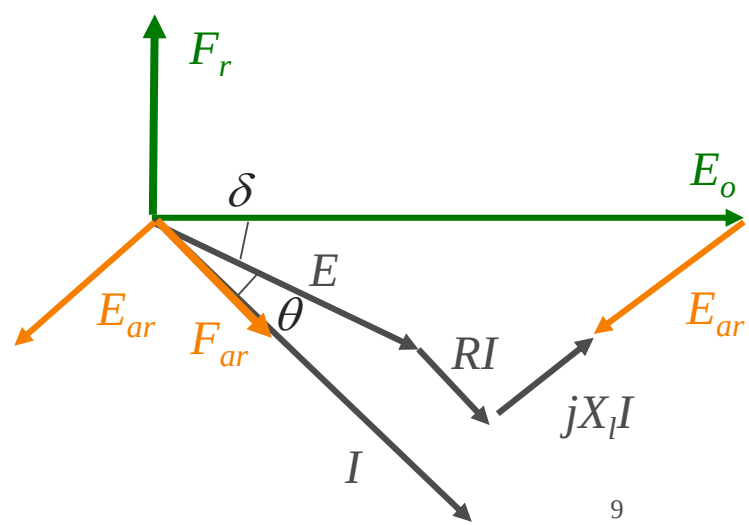
Equivalent circuit of a 3-phase AC generator



- 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
- $E_o+E_{ar}-jX_lI-R_aI-E=0$
- Let $E_{ar}=-jX_{ar}I$ and define synchronous reactance $X_s=X_{ar}+X_l$

$$E_o=jX_sI+R_aI+E$$

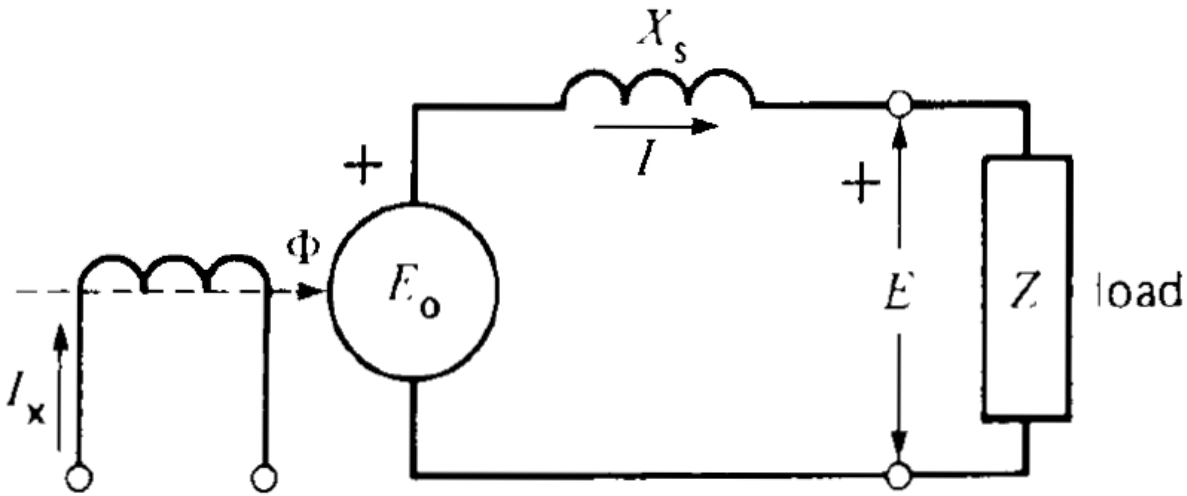




Determining the value of X_s

- **Open-circuit test**:
  - Open stator terminals 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

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



Per-unit X_S

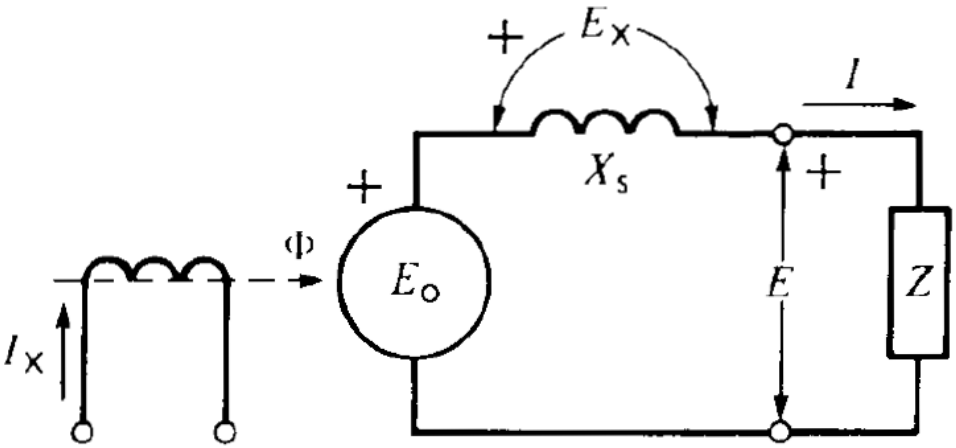
- Z_B = base impedance (line-to-neutral) of the generator [Ω]
- E_B = base voltage (line-to-neutral) [V]
- S_B = base power per phase [VA]

$$Z_B = E_B^2 / S_B$$

X_S (pu) = X_S / Z_B (usually in 0.8-2 pu)

R (pu) = R / Z_B

Synchronous generator connected to an isolated load



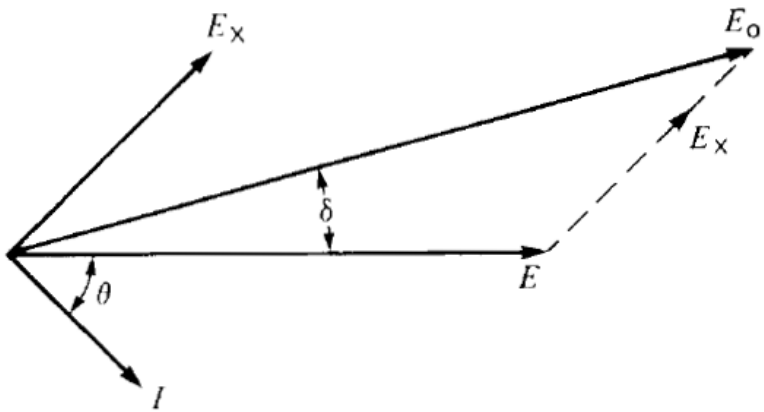


Figure 16.20
Phasor diagram for a lagging power factor load.

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

$$Z = |Z| \angle \theta$$

$$PF = \cos\theta$$

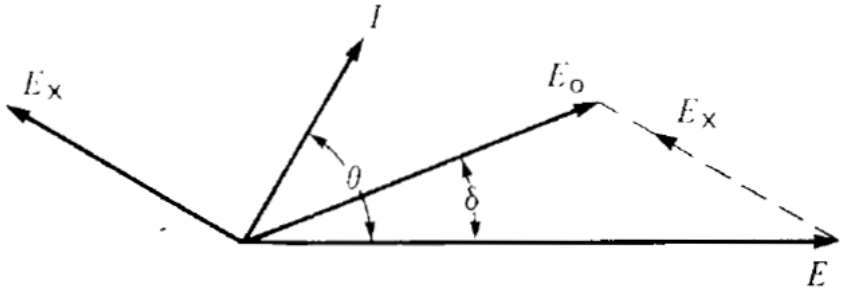


Figure 16.21
Phasor diagram for a leading power factor load.

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

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

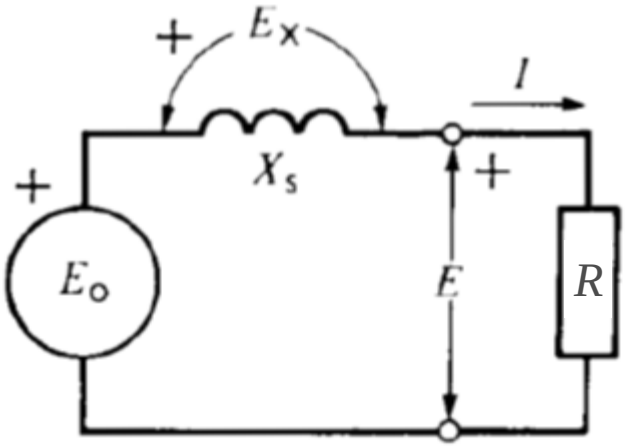
$$X_S=|E_o|/|I|=4000/800=5\ \Omega$$

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

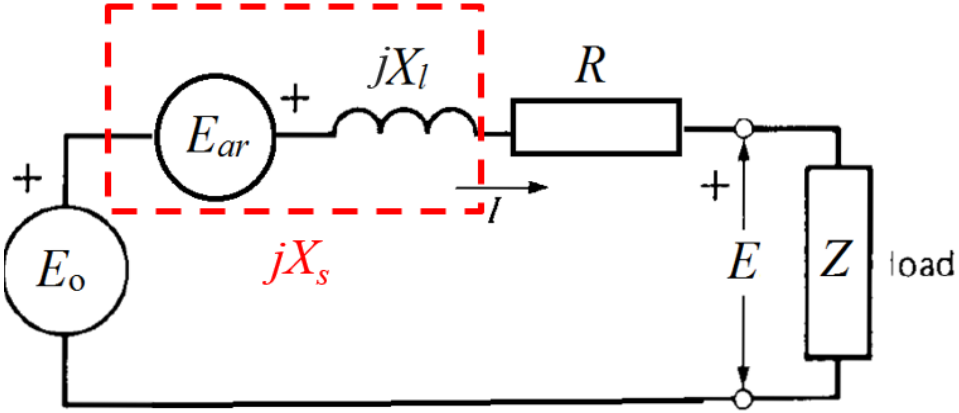
$$|Z|=\sqrt{R^2+X_S{}^2}=13\ \Omega$$

$$|E|=|I|R=|E_o|R/|Z|=4000\times12/13=3696\text{ V}$$

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



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

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

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

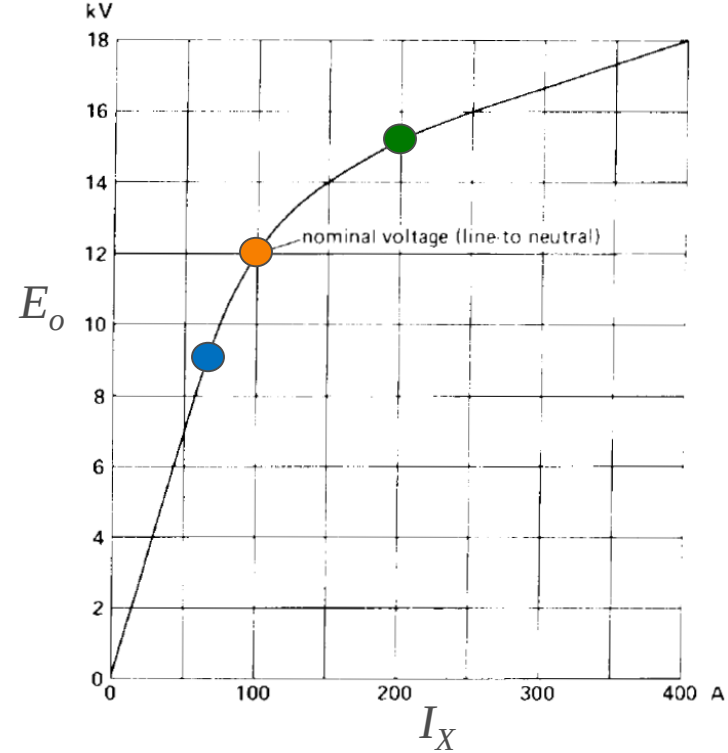
c. The total full-load copper losses

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

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

Example 16-4

A 36 MVA, 20.8 kV, 3-phase alternator has X_S=9Ω and a nominal current of 1 kA. The no-load saturation curve gives the relationship between E_o and exciting current I_X. If the excitation is adjusted so that terminal voltage E remains fixed at 20.8 kV, calculate the exciting current I_X required and draw the phasor diagram for



a. No-load

E_o=E=20.8/1.73=12 kV $\qquad$ I_X=100 A

b. Resistive load of 36 MW

P=36/3=12 MW

Z=$|E|^2/S^*$=E^2/P=12kV^2/12MW=12 Ω

I= E/Z=12000/12=1000A

E_o=E+j$X_s I$=12000+j9×1000 =15kV∠36.9^o

I_X=200 A

c. Capacitive load of 12 Mvar

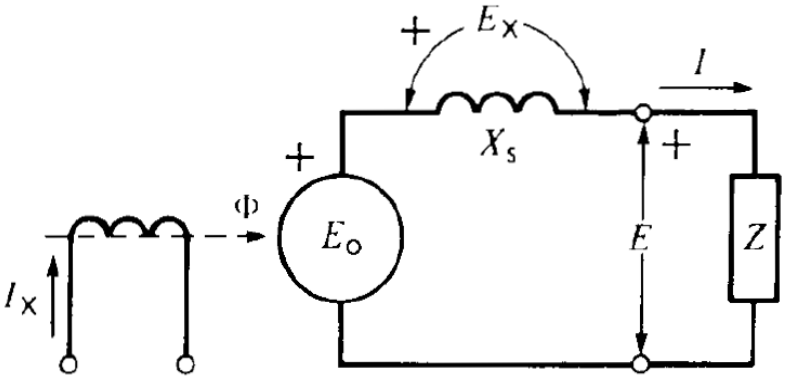
Q=-12/3= -4Mvar

Z=$|E|^2/S^*$=$E^2/(jQ)^*$= - j12kV^2/4Mvar= -j36 Ω

I= E/Z=12000/(-j36)=j333A

E_o=E+j$X_s I$=12000+j9×j333 =9kV∠0°

I_X=70 A



Regulation curves

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

E_{NL}: no-load voltage

E_B: rated voltage

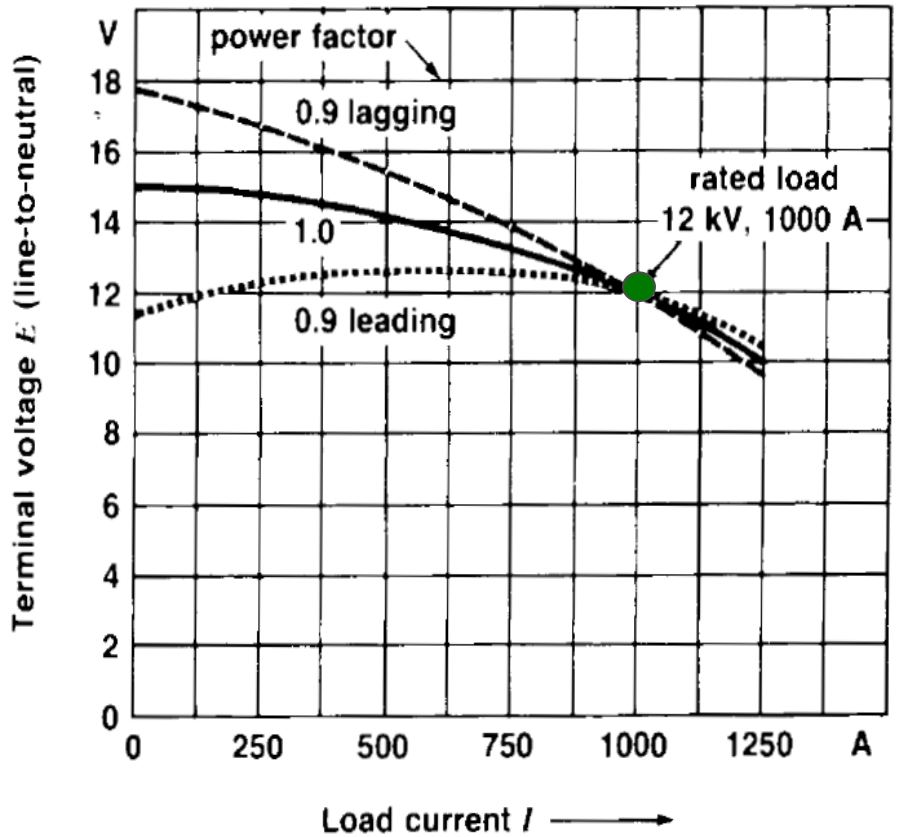
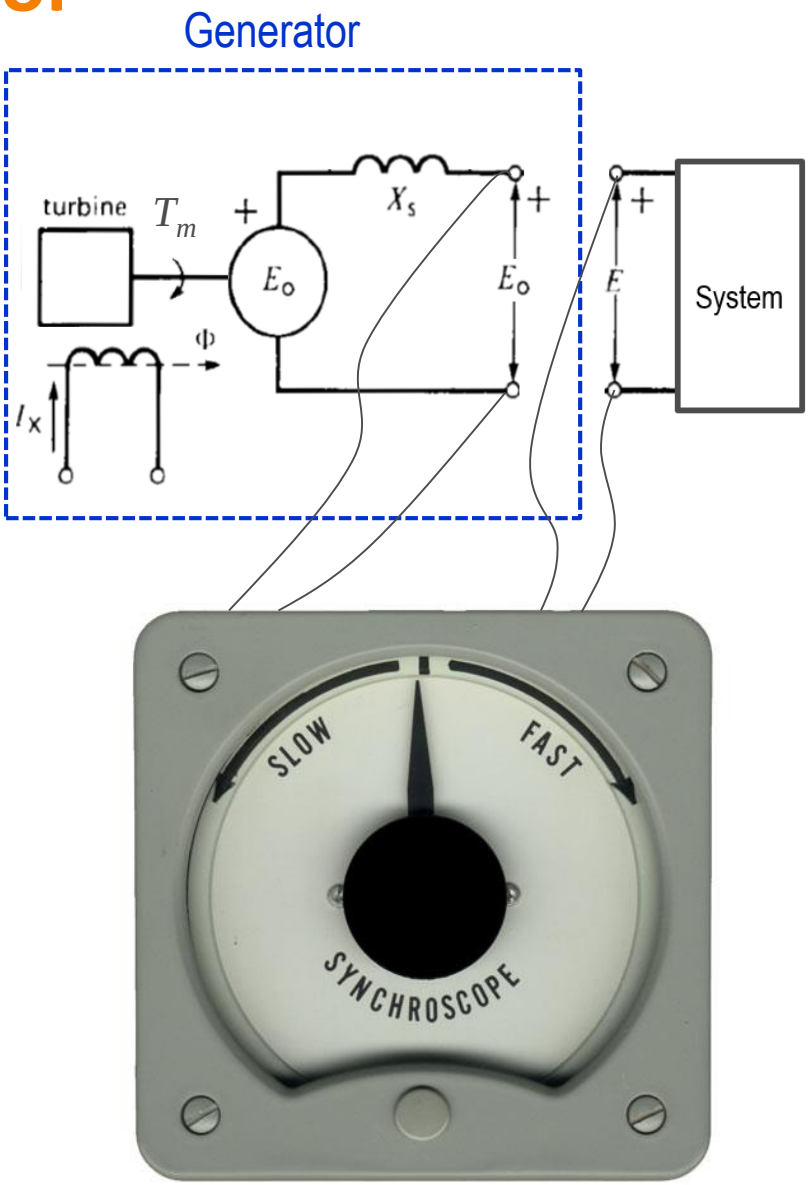


Figure 16.23
Regulation curves of a synchronous generator at three different load power factors.

Synchronization of a generator

- Synchronous generators of a power system under normal operations are all synchronized
  - They all have the same frequency
- To connect a generator to a system (or a bigger generator)
  1. Adjust the speed regulator of the generator turbine so that the generator frequency is close to the system frequency
  2. Adjust the excitation of the generator so that generator voltage E_o is equal to the system voltage E
  3. Observe the phase angle difference between E_o and E by means a synchroscope
  4. Connect the generator at the moment the point crosses the 0 marker

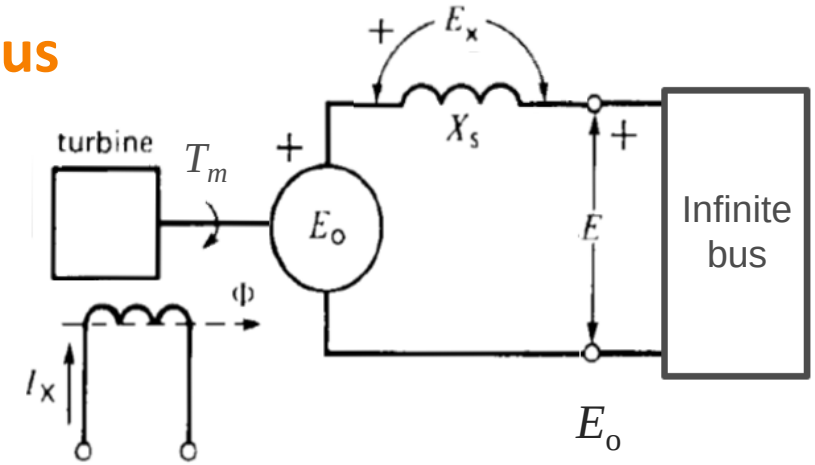


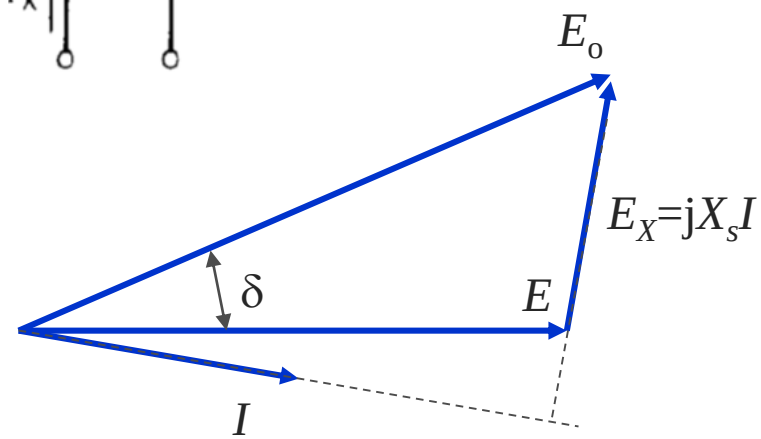
Synchronous generator on an infinite bus

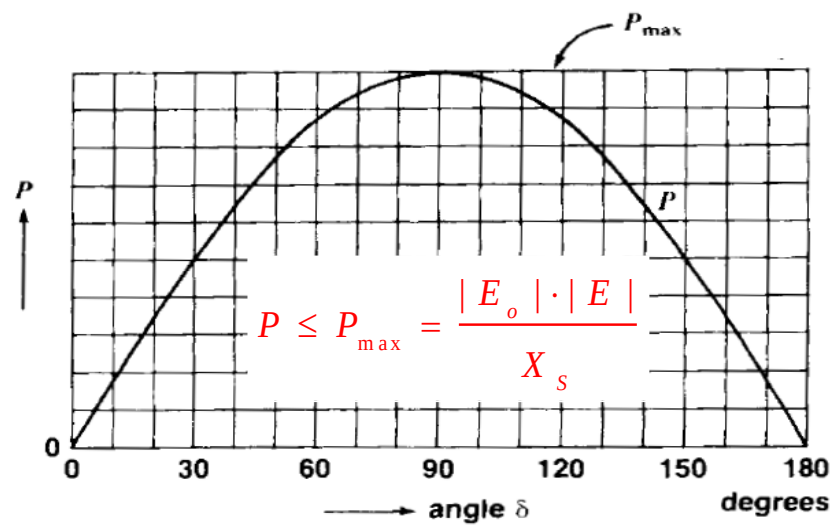
- An finite bus is a system so powerful that it has constant voltage and frequency no matter what apparatus is connected to it.
- For a generator on an infinite bus, only the exciting current I_X and the mechanical torque T_m exerted by the turbine vary
- If E_o=E (having identical magnitudes and phases), then I=0, the generator delivers no power and it is said to **float** on the line
- If $E_o \neq E$, $E_x = E_o - E$, $I = (E_o - E)/(jX_s)$
  - Complex power from E_o

    $$S_o = E_o I^* = E_o (E_o - E)^* / X_s^* = P_o + jQ_o$$
  - Complex power into the infinite bus

    $$S = EI^* = E(E_o - E)^* / X_s^* = P + jQ$$





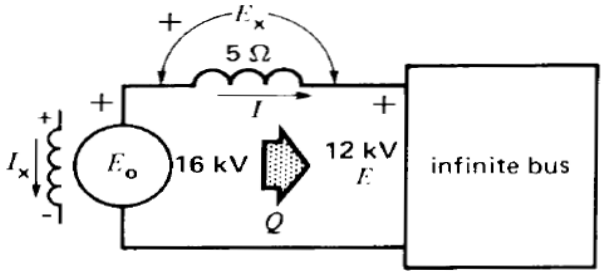


$$P_o = P = \frac{|E_o| \cdot |E|}{X_s} \sin\delta$$

$$Q_o = \frac{|E_o|^2}{X_s} - \frac{|E_o||E|}{X_s} \cos\delta$$

$$Q = \frac{|E_o||E|}{X_s} \cos\delta - \frac{|E|^2}{X_s}$$

Effect of varying the exciting current



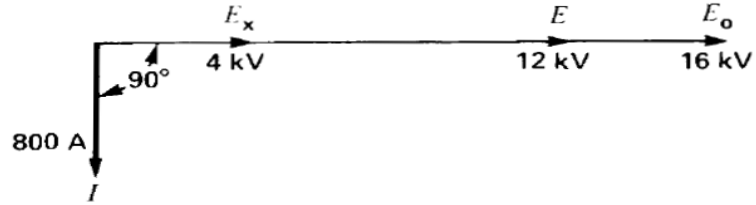
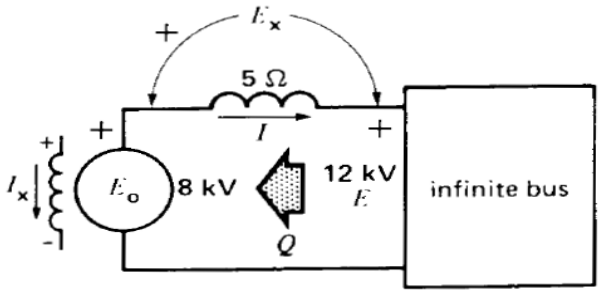


Figure 16.26b
Over-excited generator on an infinite bus.



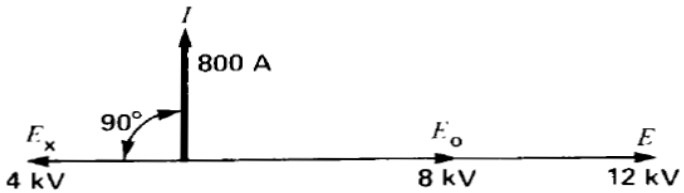
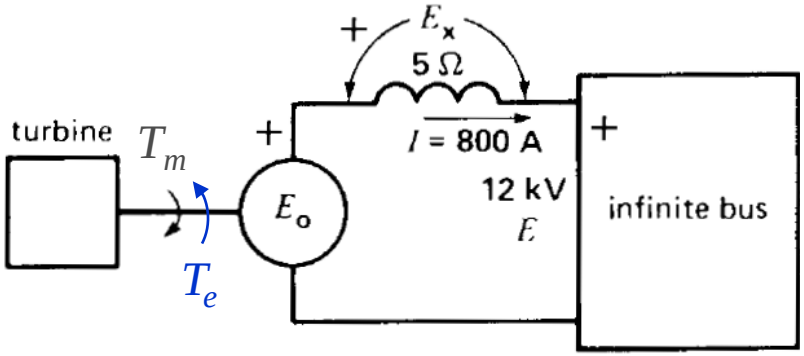


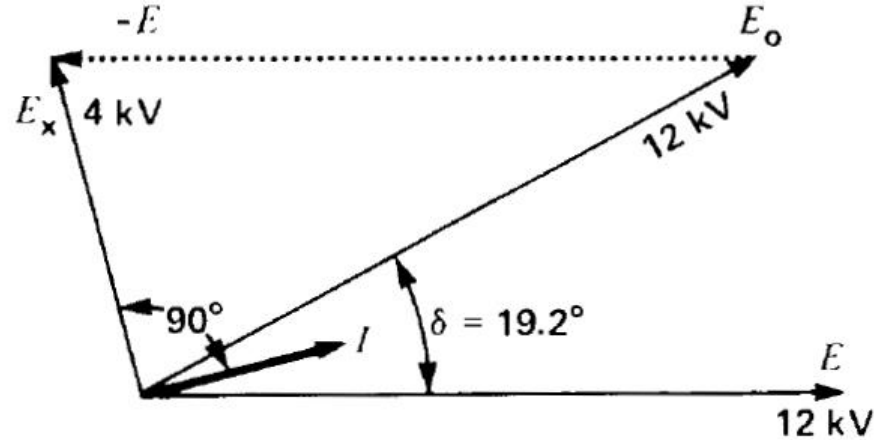
Figure 16.26c
Under-excited generator on an infinite bus.

When E_o and E are in phase

- There is always $P_o = P = 0$
- If $|E_o| > |E|$, the generator is over-excited and supplies reactive power to the infinite bus (it looks like an inductor)
- If $|E_o| < |E|$, the generator is under-excited and absorbs reactive power from the infinite bus (it looks like a capacitor)

Effect of varying the mechanical torque





- Starting from E_o=E (the generator floats on the line) and keeping $|E_o|=|E|$
  - Open the steam valve of the turbine to increase the mechanical torque T_m
  - The rotor will accelerate, and phasor E_o will lead phasor E by $\delta>0$
  - With the increase of δ, power output of the generator $P=|E|^2\sin\delta/X_s$ will increase, which exerts an increasing electric torque $T_e=9.55P/n$
  - Once $T_m=T_e$, the rotor will stop accelerating, δ will become constant and the generator will again run at synchronous speed
  - What is the direction of Q?

$$Q = -Q_o = \frac{|E|^2}{X_s}(\cos\delta - 1)$$

Control of active power

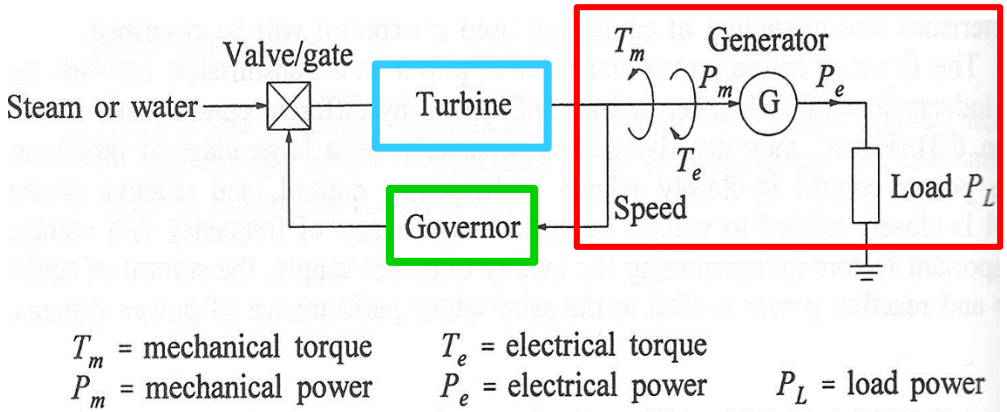
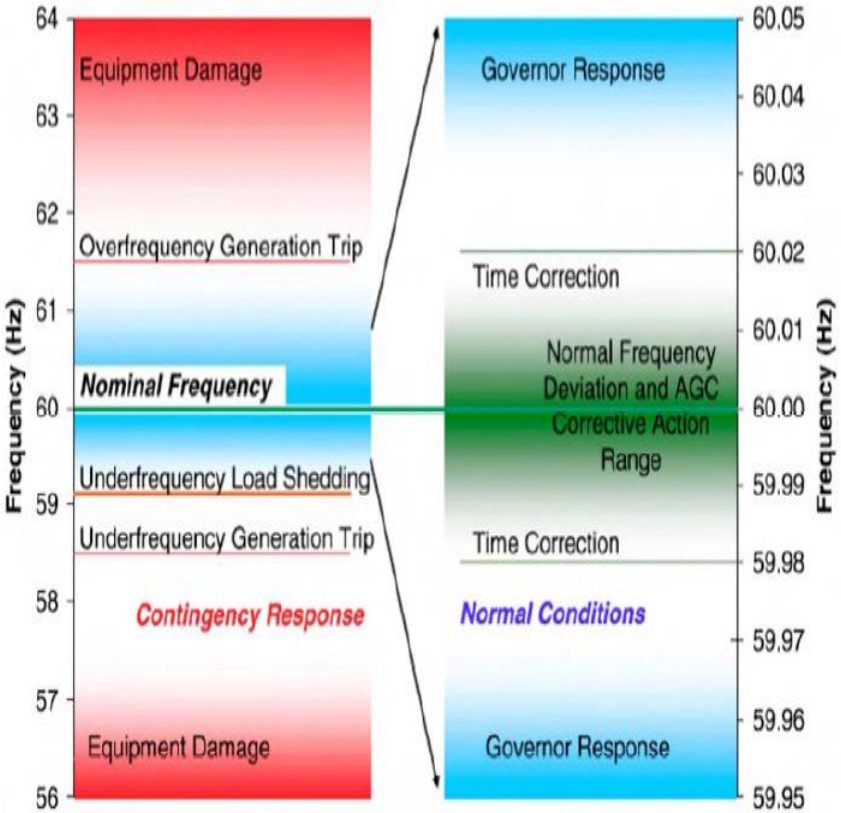


Figure 11.1 Generator supplying isolated load

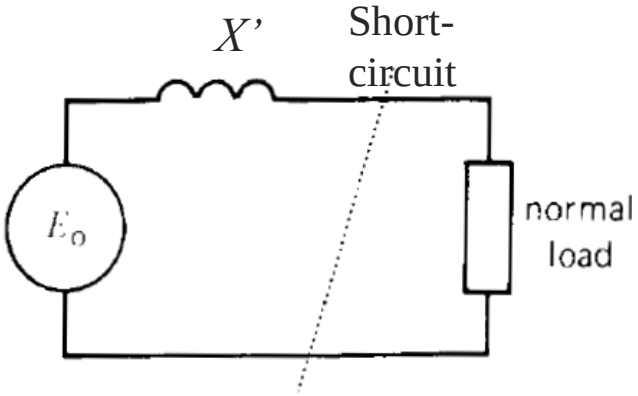


- A synchronous generator has a governor to control its speed
- A sensitive governor may detect a speed change of 0.01% to modify the valve/gate opening of the turbine so as to maintain an almost constant speed
- A large power system has a computer program called Automatic Generation Control (AGC) to control the active power and frequency of the entire system
- Each synchronous generator has over- and under-speed protections responding to abnormal frequency

Transient reactance

- For a sudden load current change such as a short-circuit, X_S is replaced by a dynamic reactance X' whose value varies with time
  - X' drops to a much lower value X'_d (called transient reactance, e.g. at $0.15X_S$)
  - The initial short-circuit current is much higher than the rated current

    $$I_{SC}=E_o/X'_d >> E_o/X_S$$
  - After a time interval T (typically, <10s), X' basically goes back to X_S
  - A short-circuit must be interrupted in 3-6 cycles by circuit breakers



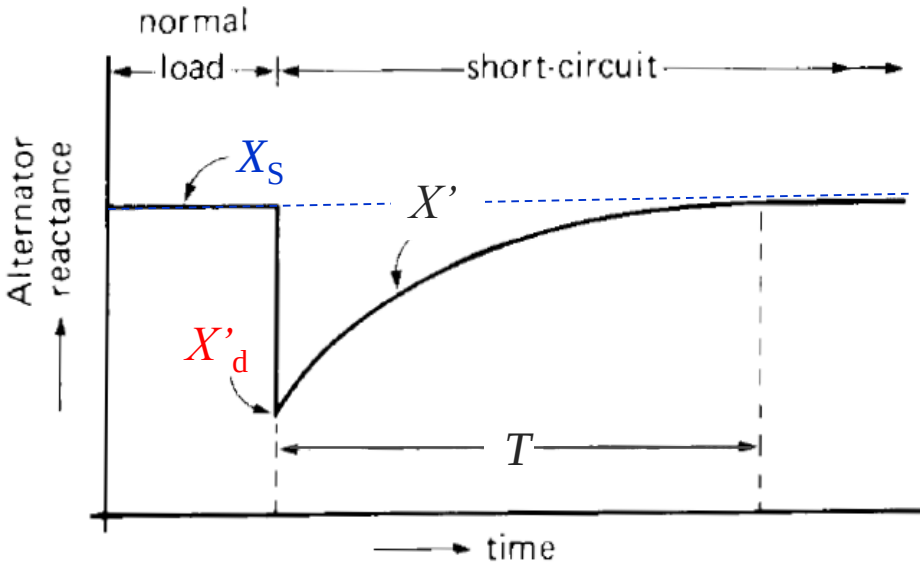


Figure 16.30
Variation of generator reactance following a short-circuit.

Examples 16-7, 16-8 and 16-9

Synchronous Motors

- Synchronous generators can operate either as generators or as motors
- Synchronous motors run in synchronism with the revolving field:
  - When the frequency is fixed, the motor speed stays constant irrespective of the load or voltage of the 3-phase line.

$$n_s = 120f/p$$

- Most synchronous motors used in industry are rated between 150 kW (200 hp) and 15 MW (20,000 hp), and run at speeds from 150 to 1800 r/min.

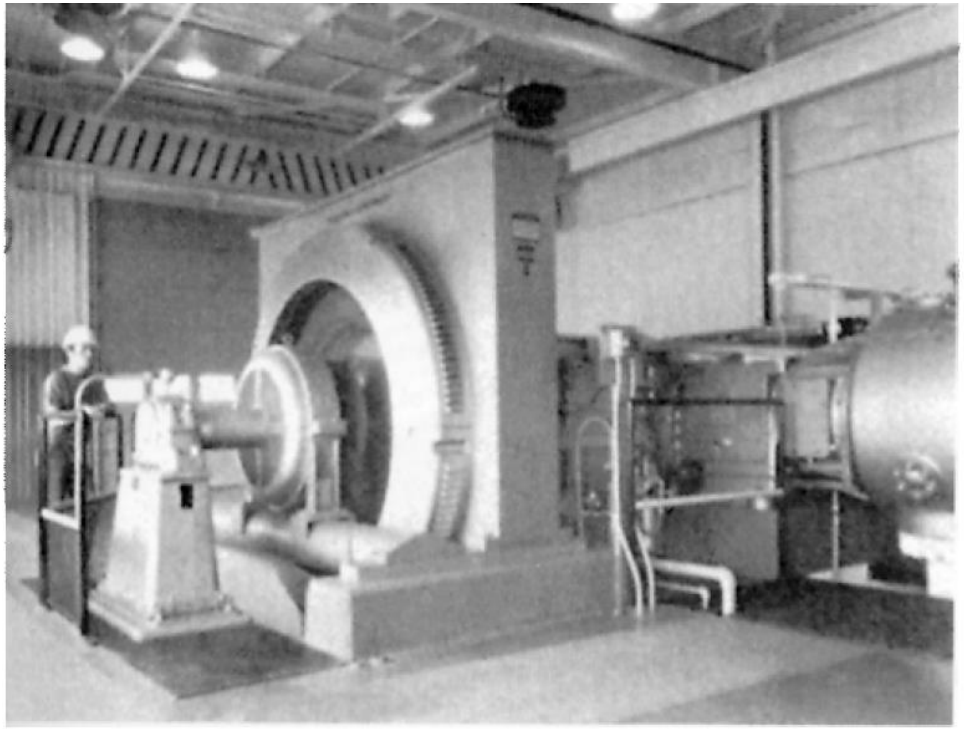


Figure 17.1
Three-phase, unity power factor synchronous motor rated 3000 hp (2200 kW), 327 r/min, 4000 V, 60 Hz driving a compressor used in a pumping station on the Trans-Canada pipeline. Brushless excitation is provided by a 21 kW, 250 V alternator/rectifier, which is mounted on the shaft between the bearing pedestal and the main rotor. (*Courtesy of General Electric*)

Motor under load

$$E_x = E - E_o = jIX_s \quad I = -j(E - E_o)/X_s$$

- At no-load,
  - The rotor and stator poles are lined up (E_o and E are in phase)
  - If E_o=E, the motor "floats" on the line (I=0)
- When a mechanical load is applied to the shaft,
  - The rotor poles fall behind the stator poles by mechanical angle α
  - E_o reaches its maximum later than E by electrical torque $\delta = p\alpha/2$
  - Complex power from the source $S=P+jQ$

$$P = \frac{|E_o|\cdot|E|}{X_s}\sin\delta \le \frac{|E_o|\cdot|E|}{X_s}$$

$$Q = \frac{|E|^2}{X_s} - \frac{|E_o||E|}{X_s}\cos\delta$$

  - Mechanical torque $T=9.55P/n_s$
  - $|E_o|$ is adjusted to be greater or less than $|E|$ depending on the desired power factor

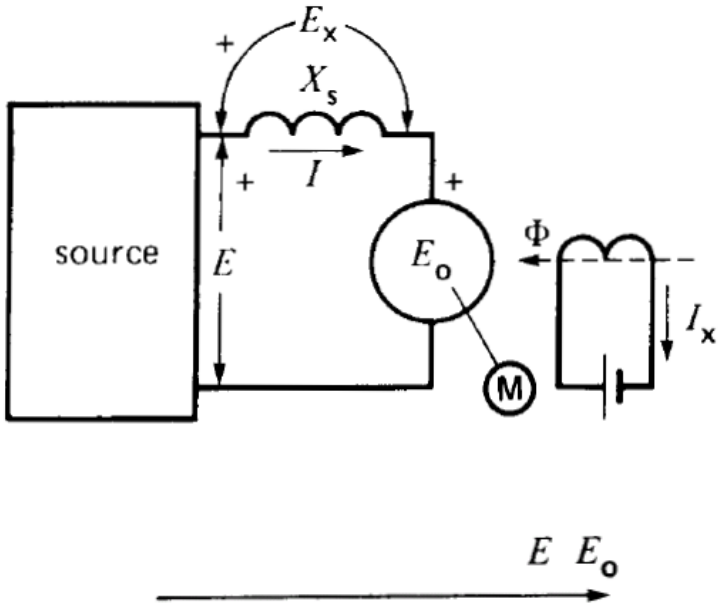


Figure 17.7b
Motor at no-load, with E_o adjusted to equal E.

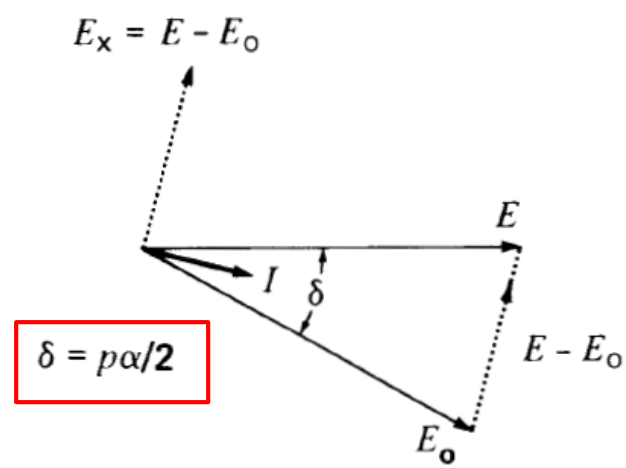


Figure 17.7c
Motor under load E_o has the same value as in Fig. 17.7b, but it lags behind E.

Examples 17-2a-b, 17-3, 17-4

Power factor rating

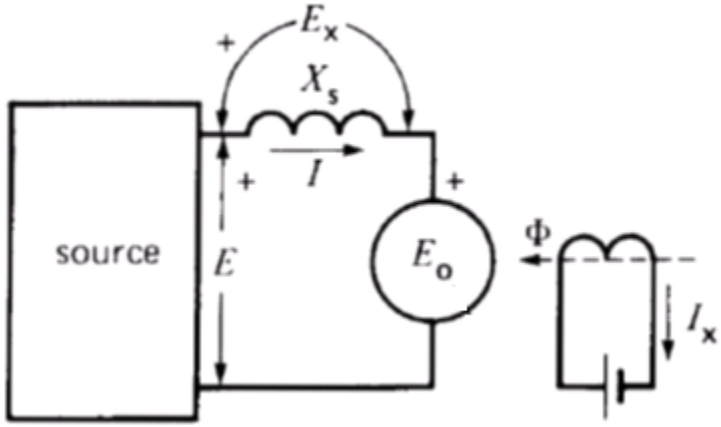
- Most synchronous motors are designed to operate at unity power factor
- However, if they also have to deliver reactive power, they are usually designed to operate at a full-load power factor of 0.8 (leading)
  - Can deliver 75% of its rated mechanical load

    If $|S|$=1 pu, P=0.8 pu and Q=0.6 pu = 75%×P
  - Bigger and most costly than motors operating at unity power factor

    $|I|=|S|/|E|=1.25|P|/|E|=125\%\times|I_{PF=1}|$
- **Synchronous condenser (synchronous capacitor):** Example 17-7
  - A synchronous motor running at no-load and its only purpose is to absorb or deliver reactive power on a 3-phase system by changing its DC excitation
  - Rated from 20 Mvar to 200 Mvar

$$Q = \frac{|E|^2}{X_s} - \frac{|E_o||E|}{X_s}\cos(0^\circ) = \frac{|E|^2}{X_s} - \frac{|E_o||E|}{X_s}$$

$$|E_o| = |E| - QX_s/|E|$$



Induction motors vs. Synchronous motors

- SMs are more complex to build but have less weight and cost than the IMs of the same rating

- SMs have a higher efficiency and a higher starting torque

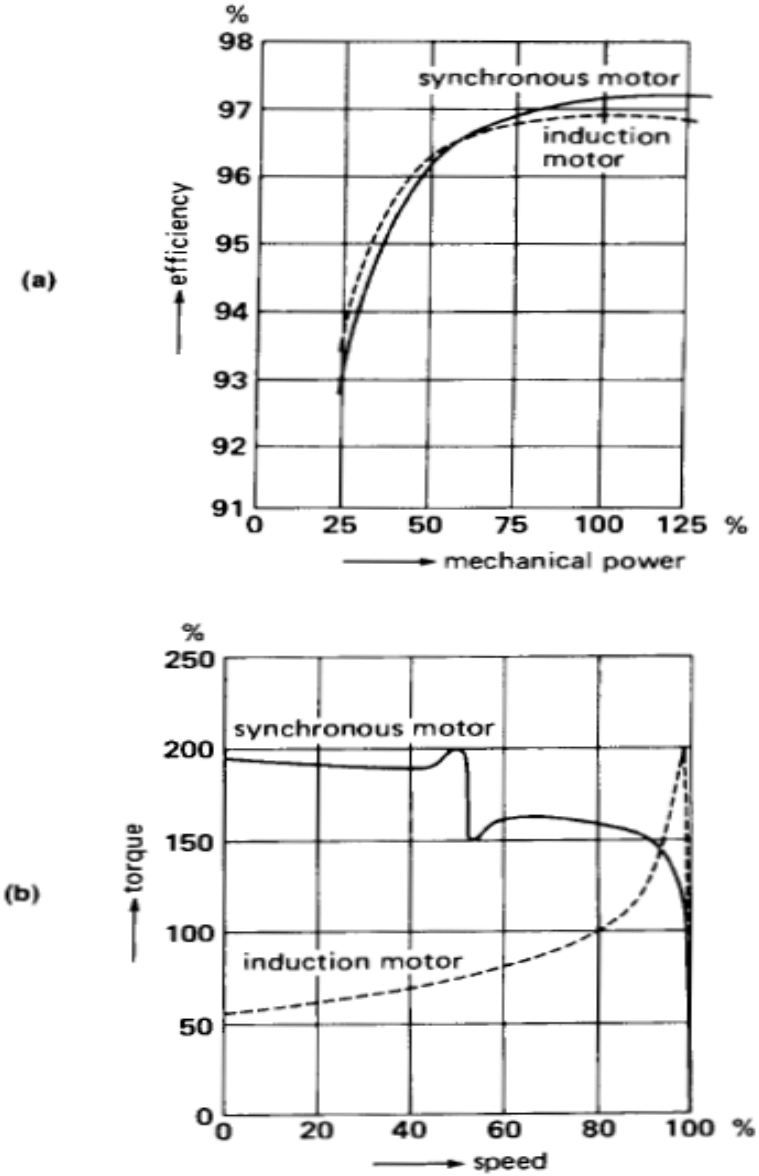


Figure 17.23
Comparison between the efficiency (a) and starting torque (b) of a squirrel-cage induction motor and a synchronous motor, both rated at 4000 hp, 1800 r/min, 6.9 kV, 60 Hz.

Homework Assignment #6

- Read Chapters 16
- Questions:
  - 16-8, 16-16, 16-17, 16-19, 16-22, 16-23, 16-24
- Due date:
  - hand in your solution to Denis at MK 205 or by email (dosipov@vols.utk.edu) before the end of 11/13 (Fri)