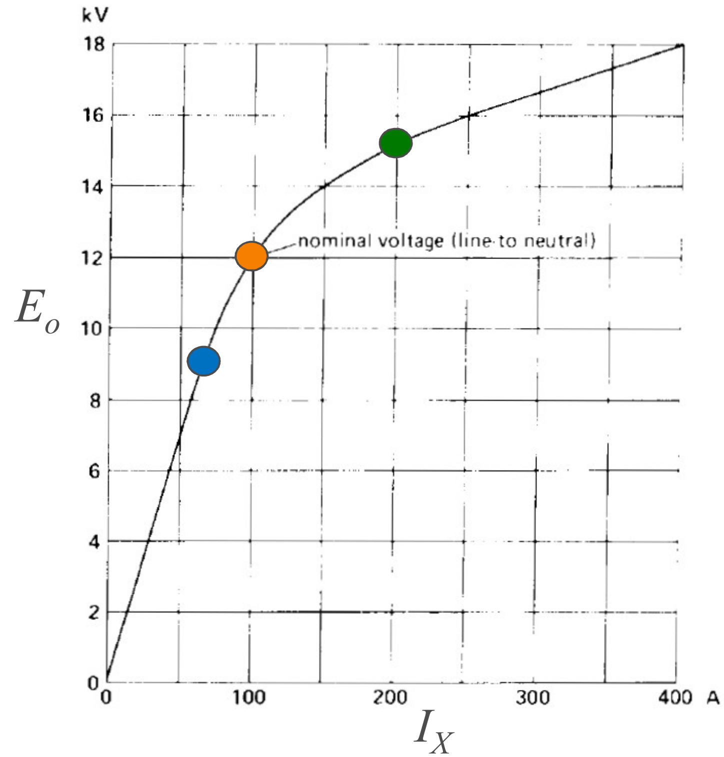
Example 16-4

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 conditions a-c:



a. No-load

E_o=E=20.8/1.73=12 kV 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

$E_o=E+jX_sI$=12000+j9×1000 =15kV∠36.9°

I_X=200 A

c. Capacitive load of 12 Mvar

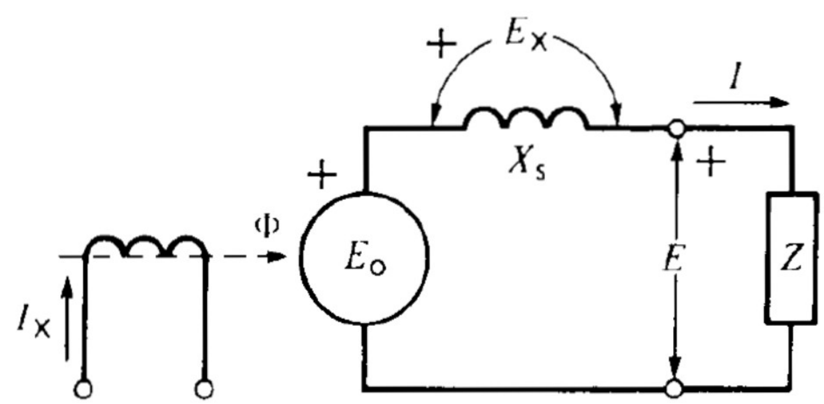
Q=-12/3= -4Mvar

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

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

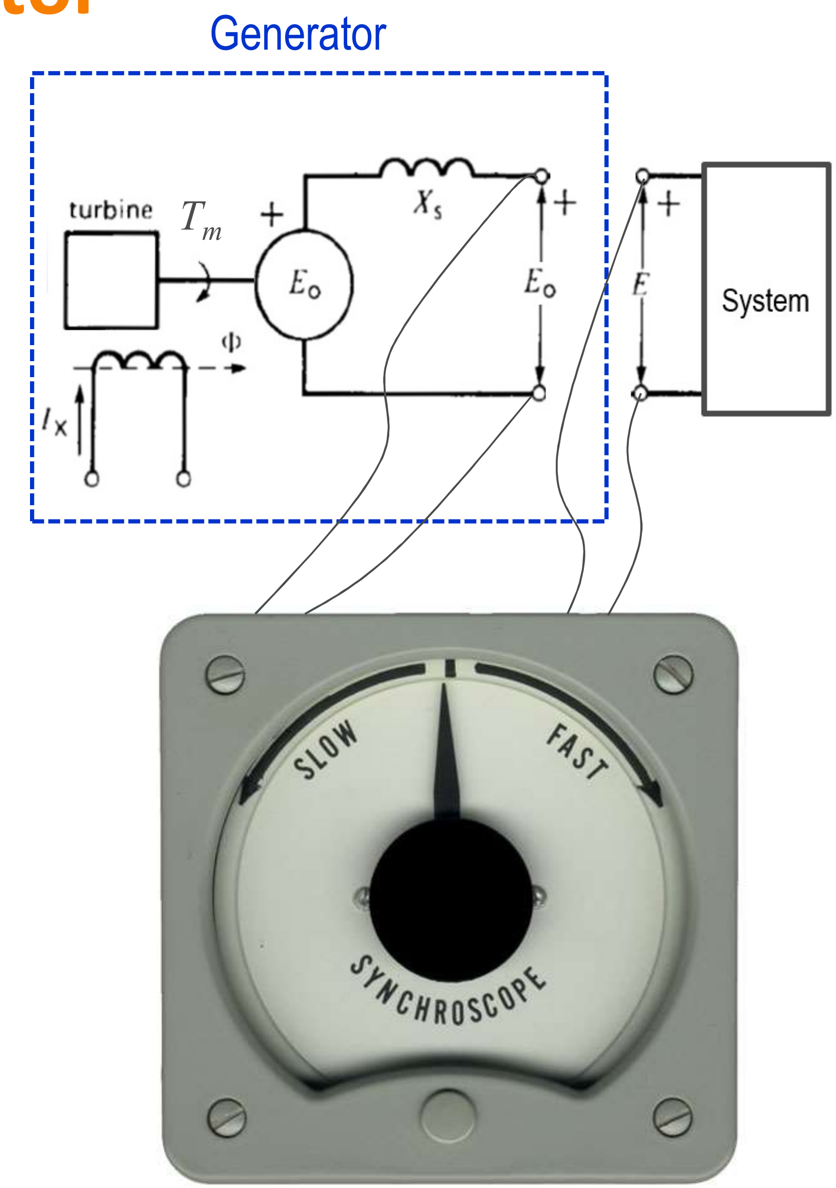
$E_o=E+jX_sI$=12000+j9×j333 =9kV∠0°

I_X=70 A



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

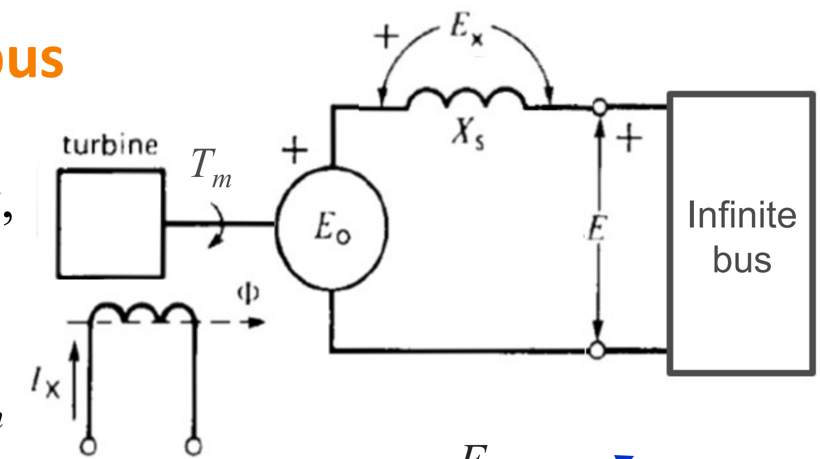


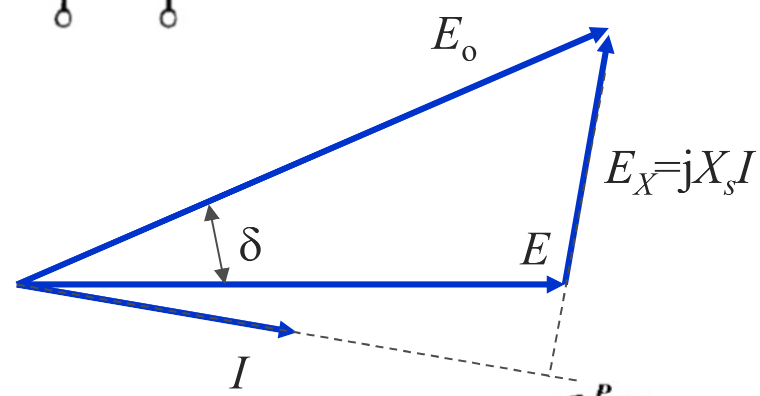
Synchronous generator on an infinite bus

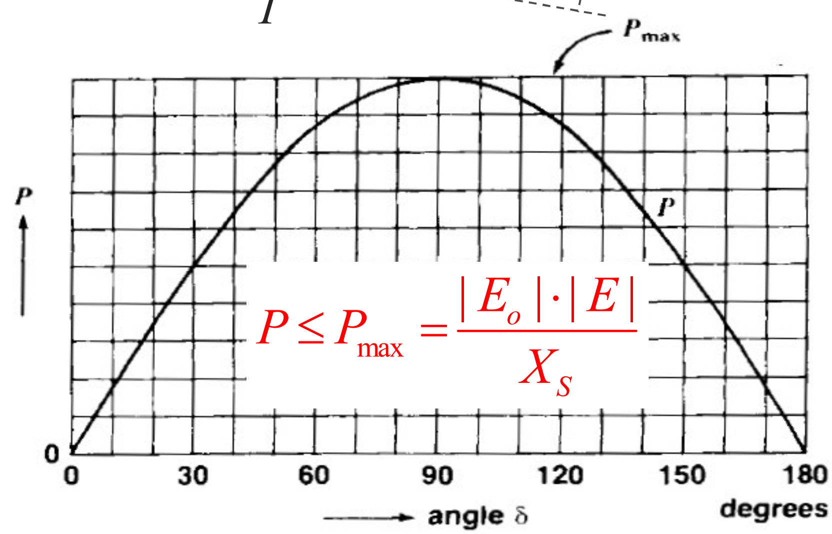
- An infinite bus is a system so powerful that it has constant voltage E and frequency, e.g. 60Hz, no matter what apparatus is connected to it.
- For a generator on an infinite bus, only the exciting current I_X and the mechanical torque T_m exerted by the turbine vary
- If E_o=E (having identical magnitudes 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

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







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

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

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

Learn Example 16-7

Effect of varying the exciting current

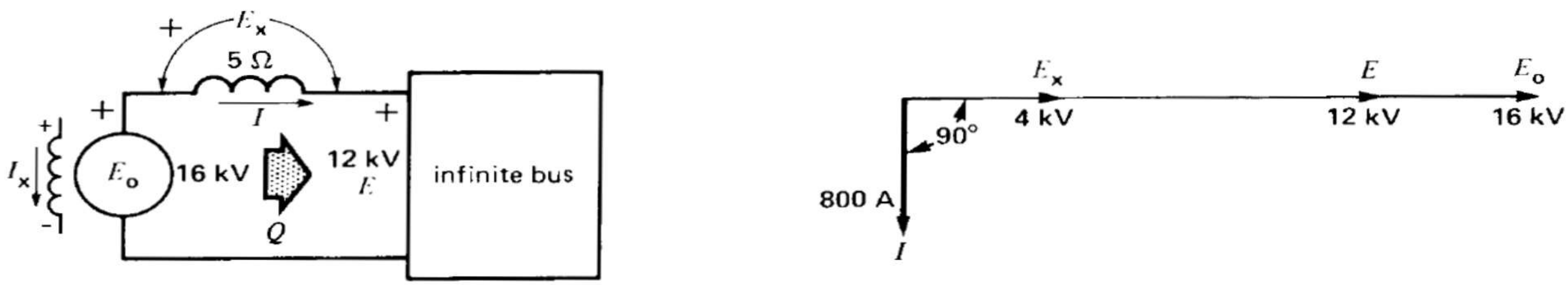


Figure 16.26b
Over-excited generator on an infinite bus.

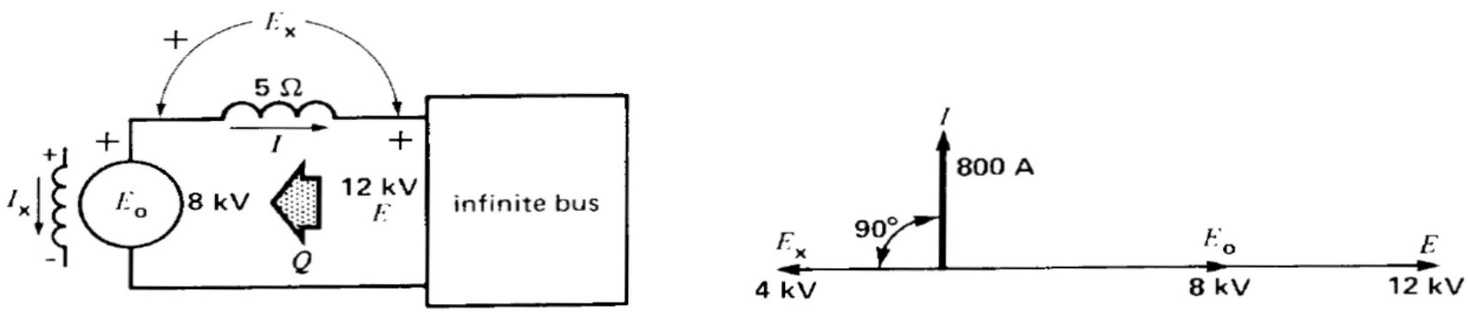
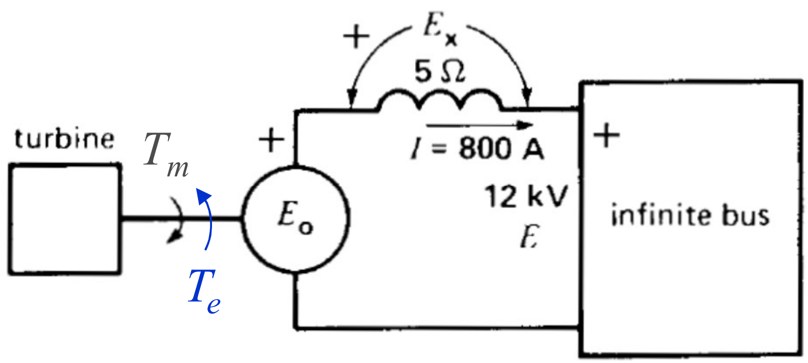


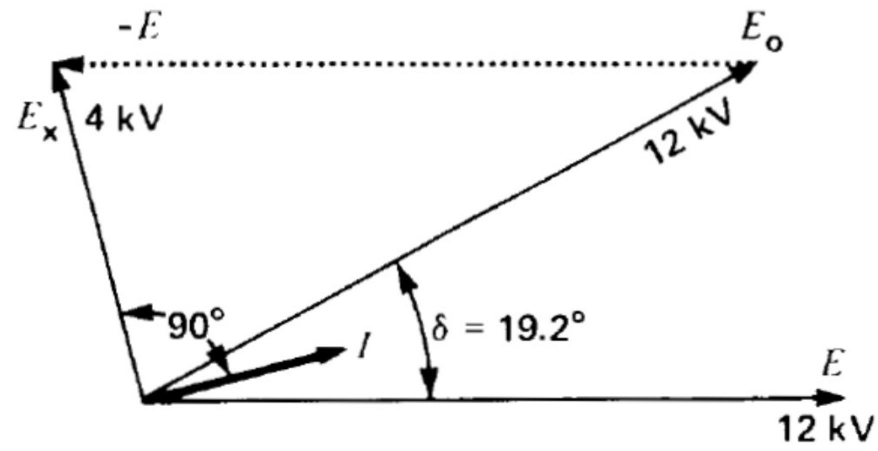
Figure 16.26c
Under-excited generator on an infinite bus.

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

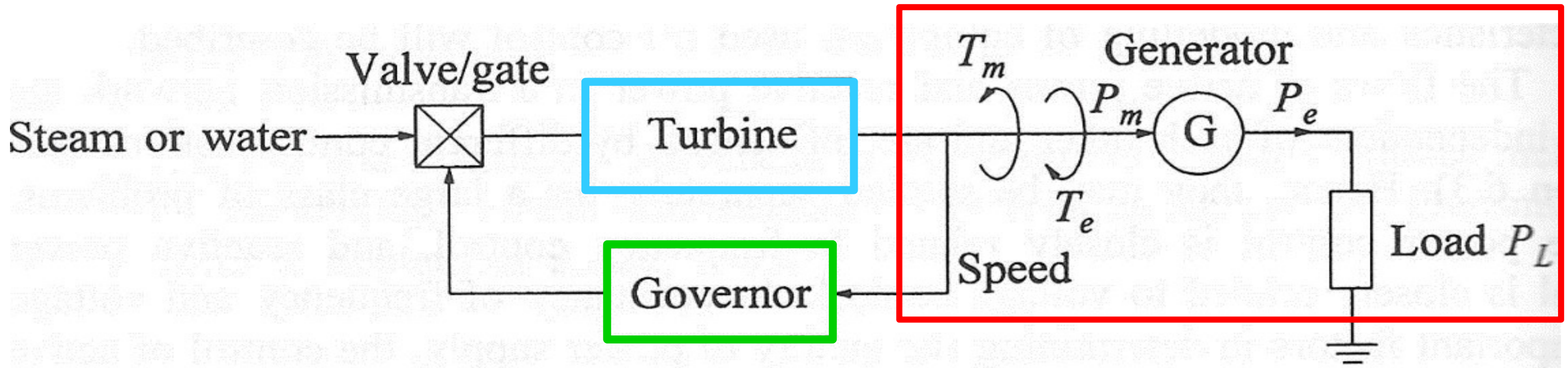




- Starting from E_o=E (the generator floats on the line) and keeping $|E_o|$=$|E|$
  - Open the steam valve of the turbine to increase the mechanical torque T_m
  - The rotor will accelerate, and phasor E_o will lead phasor E by $\delta>0$
  - With the increase of δ, power output of the generator $P=|E|^2\sin\delta/X_s$ 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? (coming from both E_o and E)
  - What is the angle of I? (leading E and lagging E_o by the same angle)

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

Control of active power



T_m = mechanical torque $\quad T_e$ = electrical torque

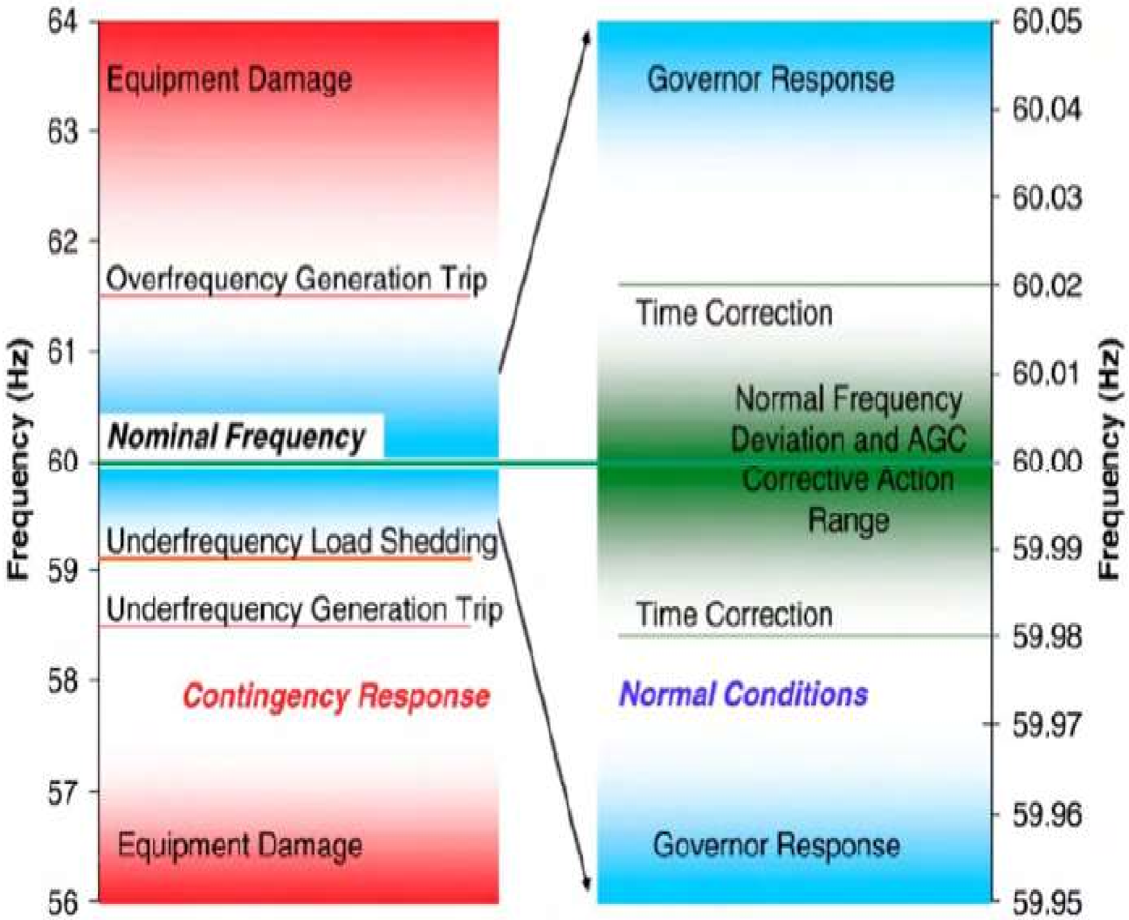
P_m = mechanical power $\quad P_e$ = electrical power $\quad P_L$ = load power

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

How much frequency deviates in a power grid

- Under normal conditions, frequency in a large Interconnected power system (e.g. the Eastern Interconnection) varies approximately ±0.03Hz from the scheduled value
- Under abnormal events, e.g. loss of a large generator unit, frequency experiences larger deviations.



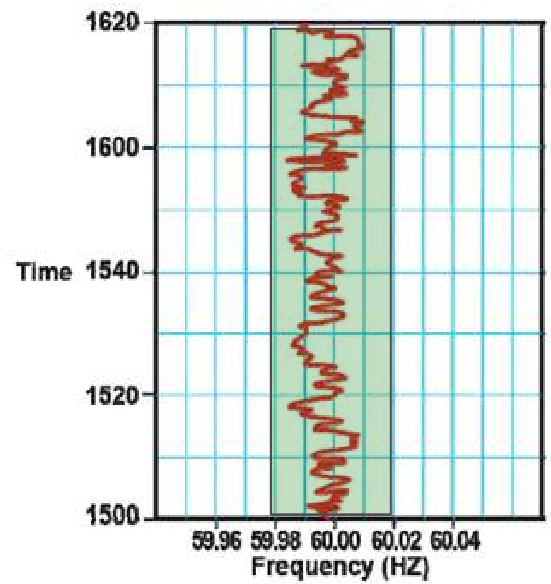


Figure 4-5. Normal Frequency Deviations

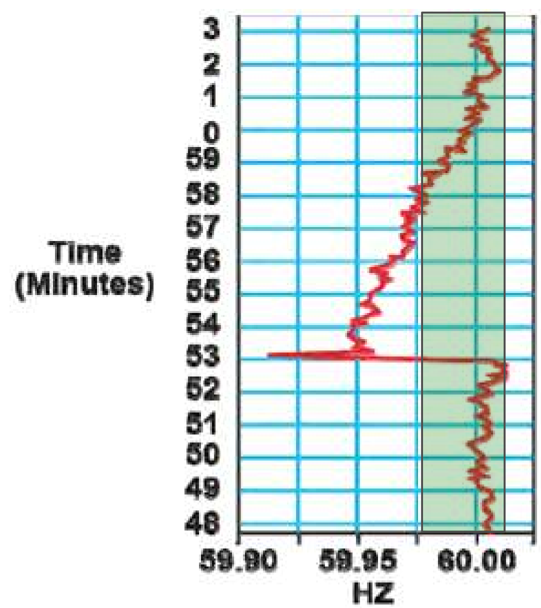


Figure 4-6. Abnormal Frequency Deviations

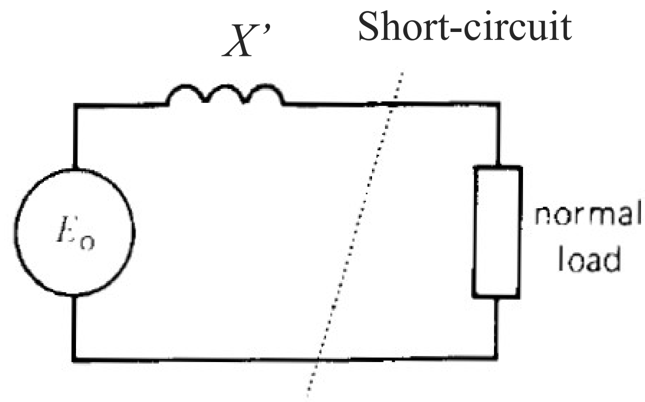
Transient reactance

- 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

  - **Learn Example 16-8**



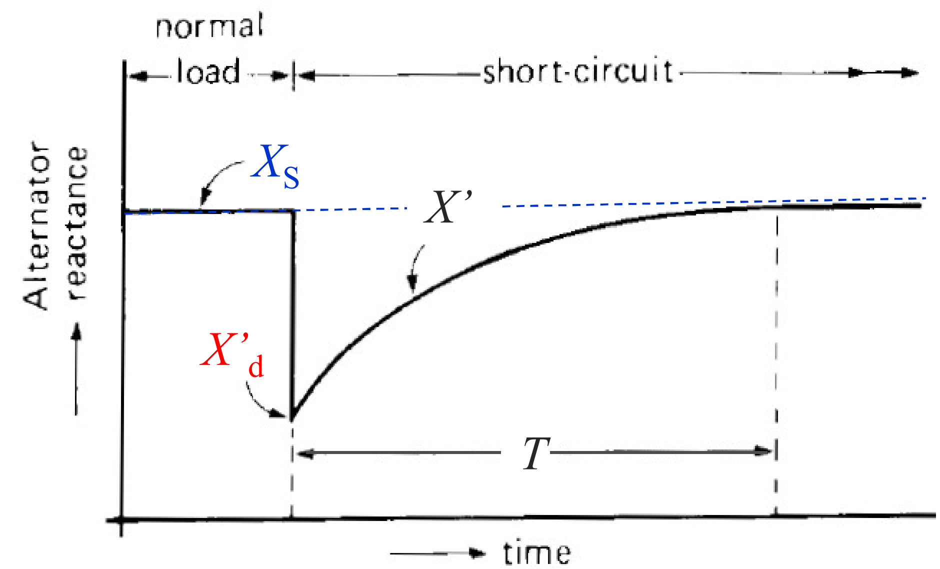


Figure 16.30
Variation of generator reactance following a short-circuit.