ECE 325 – Electric Energy System Components
5- Transmission Lines

Instructor:

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Content

(Materials are from Chapter 25)

- Overview of power lines
- Equivalent circuit of a line
- Voltage regulation and power transmission of transmission lines

Overview

Corona discharge on insulator string of a 500 kV line (source: wikipedia.org)

- Types of transmission lines
  - Overhead lines
  - Underground Cables (less than 1%)
- Properties
  - Series Resistance (stranding and skin effect)
  - Series Inductance (magnetic & electric fields; flux linkages within the conductor cross section and external flux linkages)
  - Shunt Capacitance (magnetic & electric fields; charge and discharge due to potential difference between conductors)
  - Shunt Conductance (due to leakage currents along insulators or corona discharge caused by ionization of air)
- Line-to-line voltage levels
  - 69kV, 115kV, 138kV and 161kV (sub-transmission)
  - 230kV, 345kV, and 500kV (EHV)
  - 765kV (UHV)

Overhead Transmission Lines

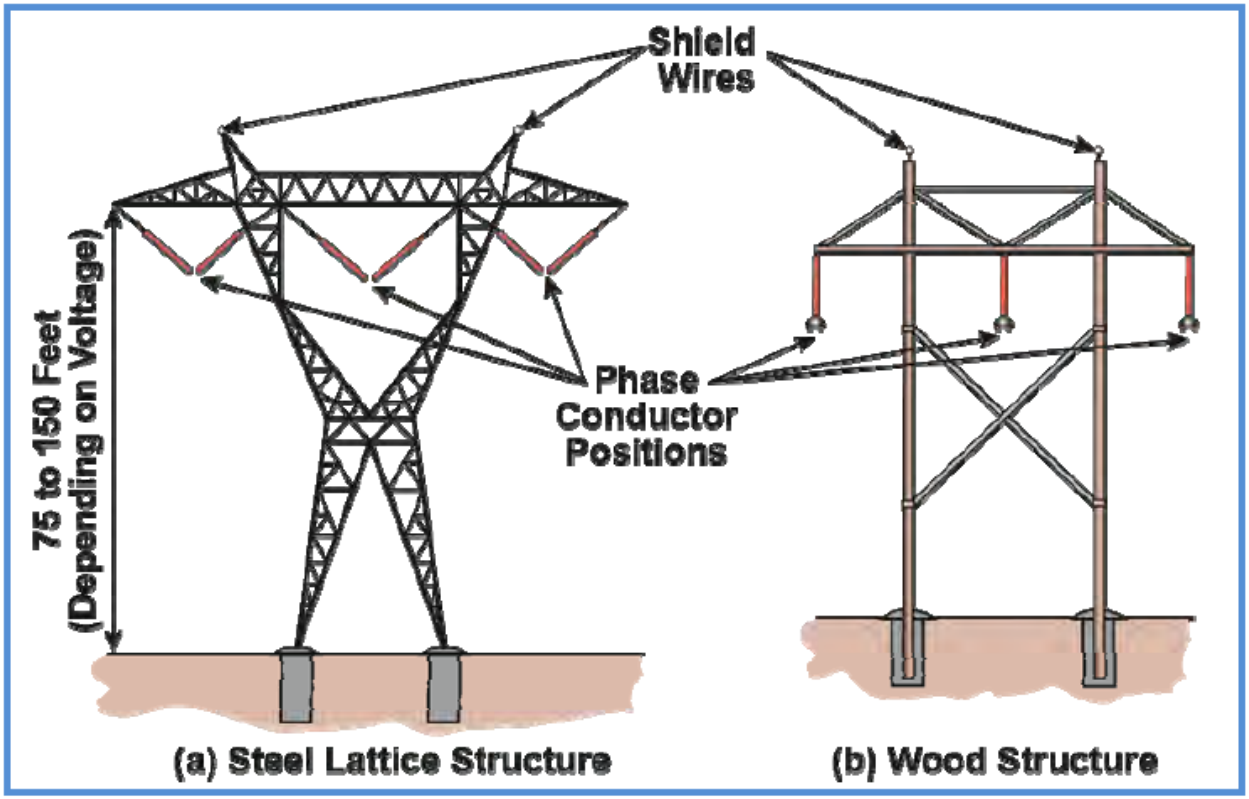
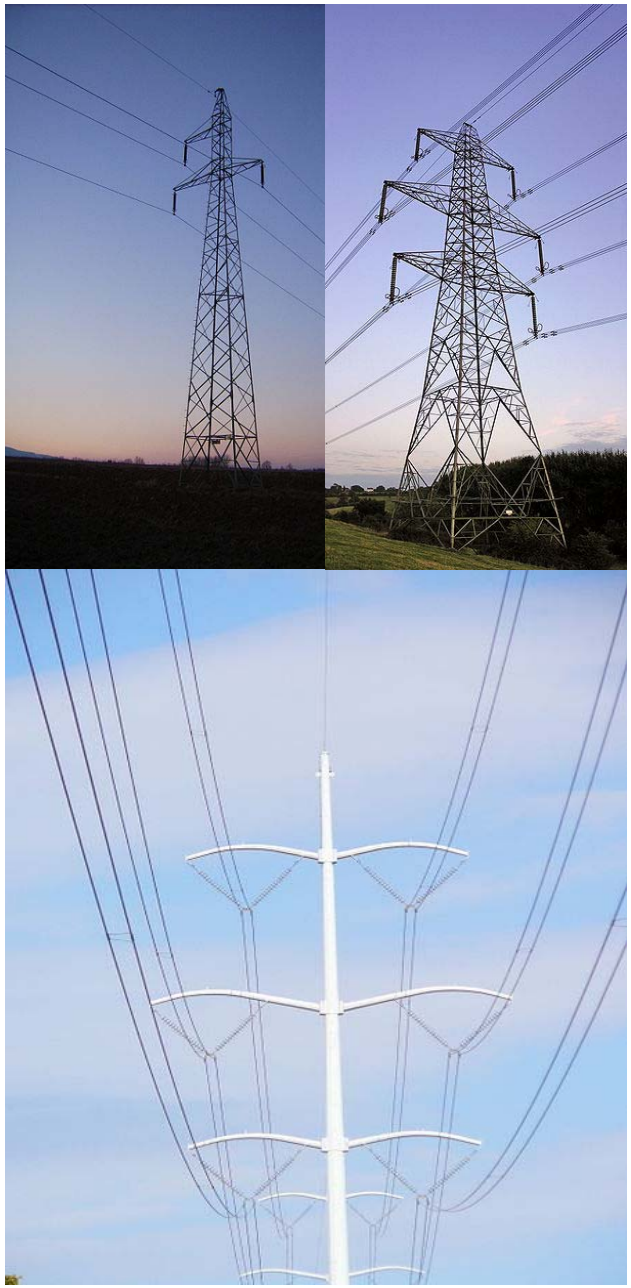


Figure 2-83. Transmission Line Structures

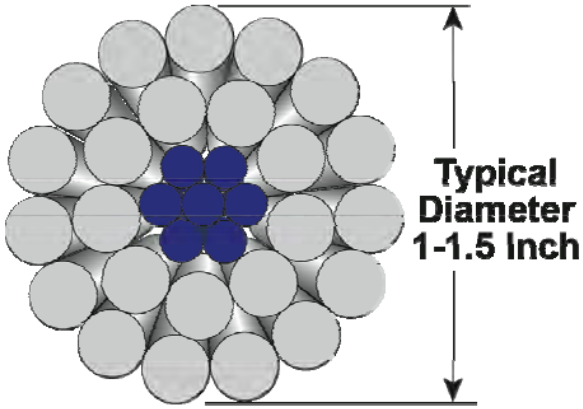
Shield wires (ground wires) are ground conductors used to protect the transmission lines from lightning strikes



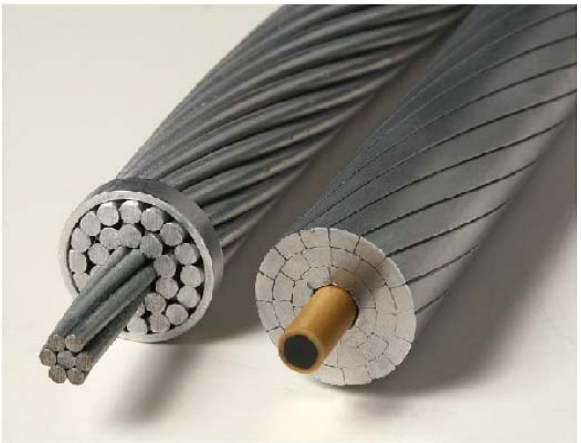
(Source: wikipedia.org and EPRI dynamic tutorial)

Overhead Transmission Lines

- Materials
  - AAC (All Aluminum Conductor),
  - AAAC (All Aluminum Alloy Conductor)
  - ACSR (Aluminum Conductor Steel Reinforced)
  - ACAR (Aluminum Conductor Alloy Reinforced)
  - ACCC (Aluminum Conductor Composite Core)
- Why not copper?
  - Relative lower costs and higher strength-to-weight ratios than copper
- Bundle conductors
  - Preferred for high voltages, e.g. 2-conductor bundles for 230kV, 3-4 for 345-500kV, and 6 for 765kV



ACSR (7 steel and 24 aluminum strands)



24/7 ACSR and modern ACCC conductors

A bundle of 4 conductor

Equivalent circuit of a transmission line

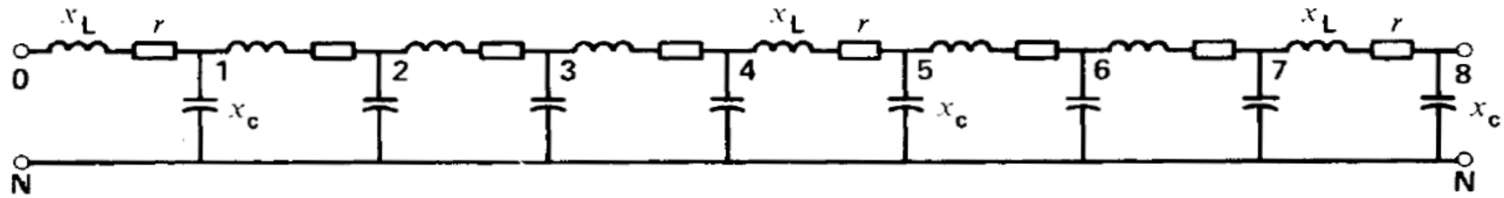


Figure 25.13
Distributed impedance of a transmission line.

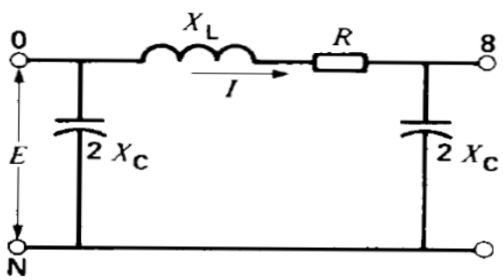
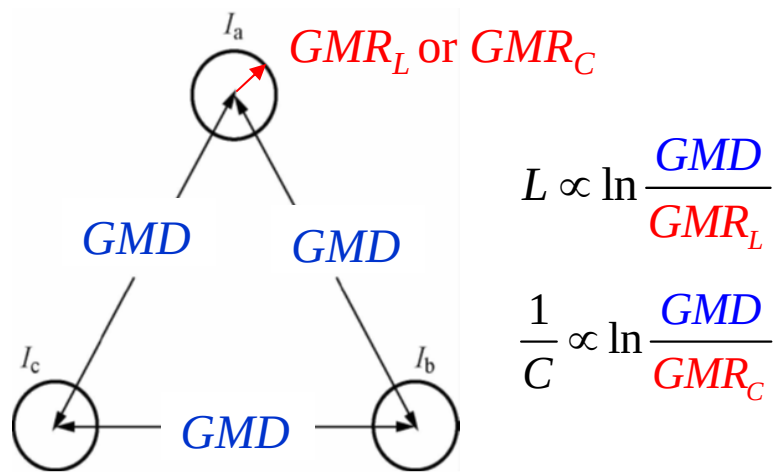


Figure 25.14
Equivalent lumped circuit of a transmission line.



$$L \propto \ln \frac{GMD}{GMR_L}$$

$$\frac{1}{C} \propto \ln \frac{GMD}{GMR_C}$$

- $R = r \times N$, $X_L = x_L \times N$, $X_C = x_C / N$
- With the increase of the length of the line, R and X_L increase but X_C decreases
- For transmission lines, $R << X_L$

TABLE 25C TYPICAL IMPEDANCE VALUES PER KILOMETER FOR 3-PHASE, 60 HZ LINES

Type of line	x_L [Ω]	x_C [Ω]
aerial line	0.5	300 000
underground cable	0.1	3 000

Simplifying the equivalent circuit

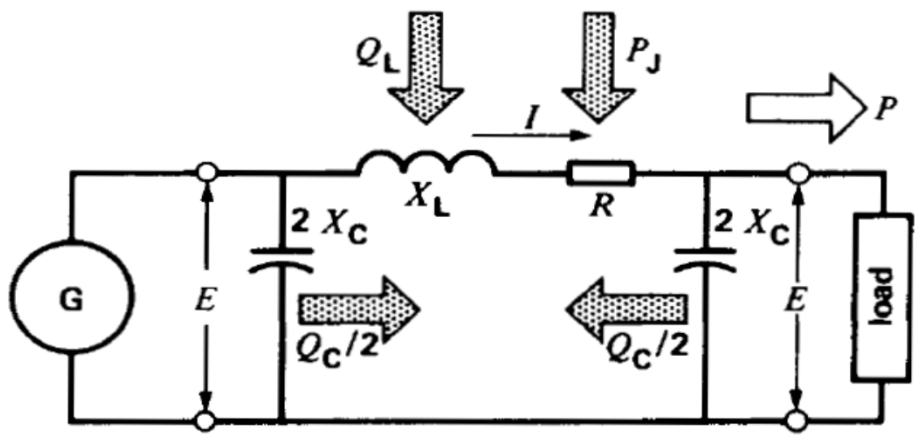


Figure 25.17
Active and reactive powers of a transmission line.

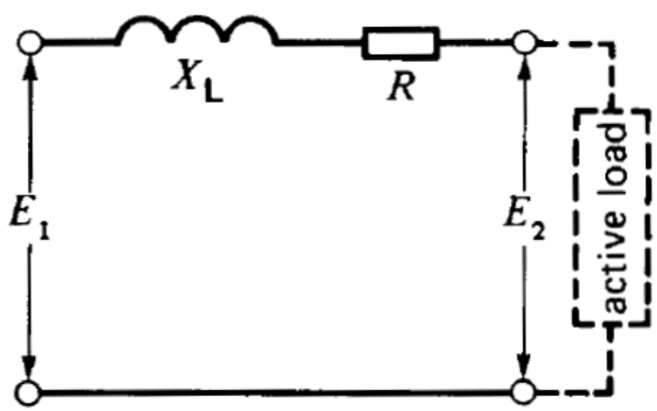


Figure 25.18
Equivalent circuit of a short LV line.

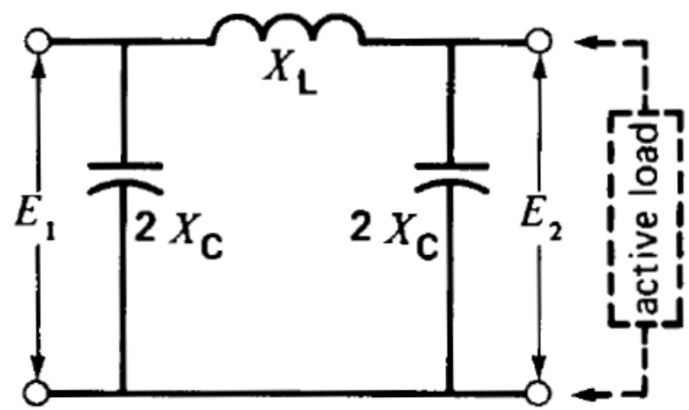
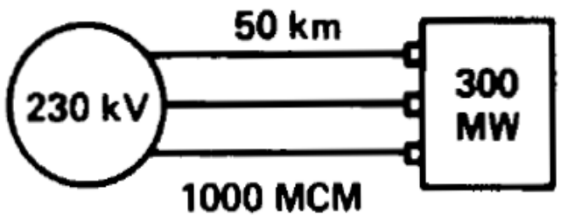


Figure 25.19
Equivalent circuit of a long HV line.

Example 25-3



$r = 0.065\ \Omega/\text{km}$

$X_L = 0.5\ \Omega/\text{km}$

$X_C = 300\ \text{k}\Omega\cdot\text{km}$

X_L=0.5 ×50=25Ω

X_C=300,000/50=6kΩ, so $2X_C$=12k Ω

R=0.065 ×50=3.25Ω

Note X_C=480X_L and X_L=7.7R

P=300/3=100MW

$|E|$=230/√3=133kV

$|I|$=100MW/133kV=750A

Loss $|I|^2R$=1.83MW=0.0183P

$Q_L=|I|^2X_L$=14.1Mvar

$Q_C=|E|^2/X_C$=3Mvar <<Q_L

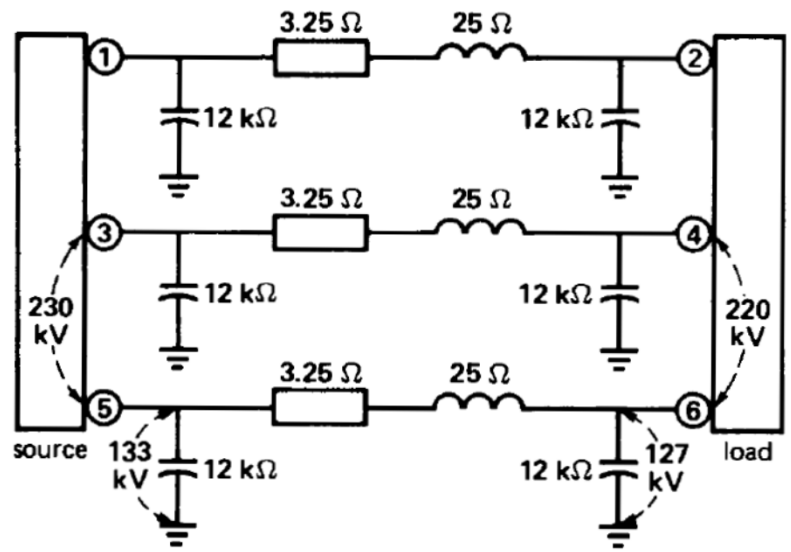
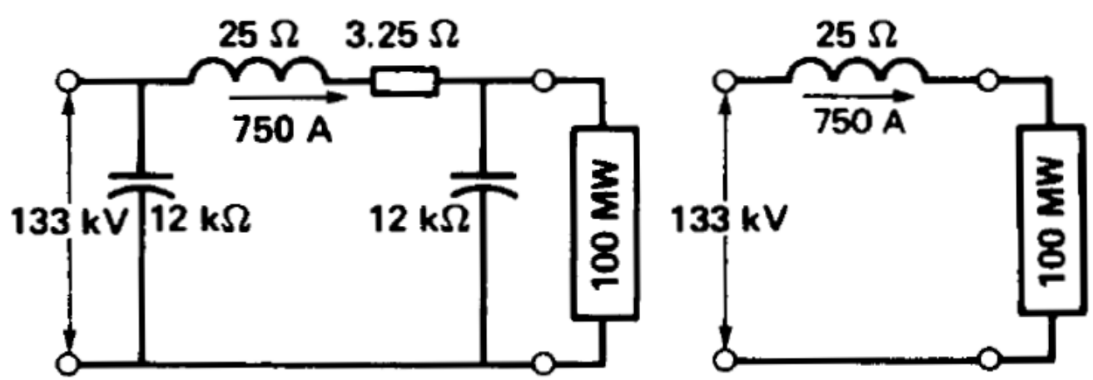


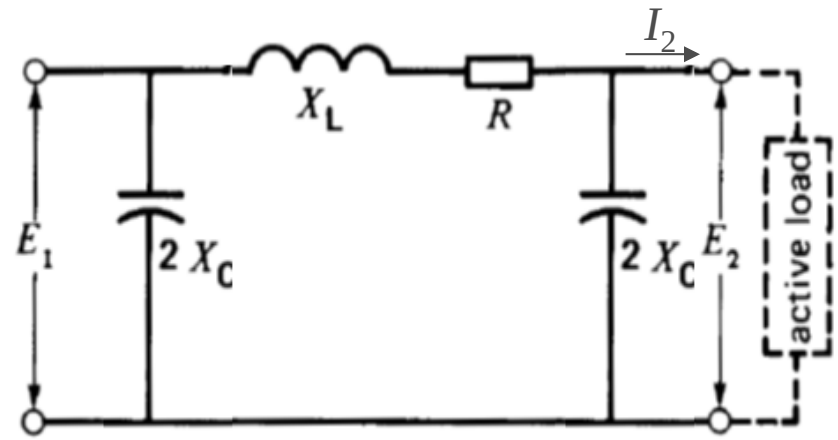
Figure 25.16
Equivalent circuit of a 3-phase line.



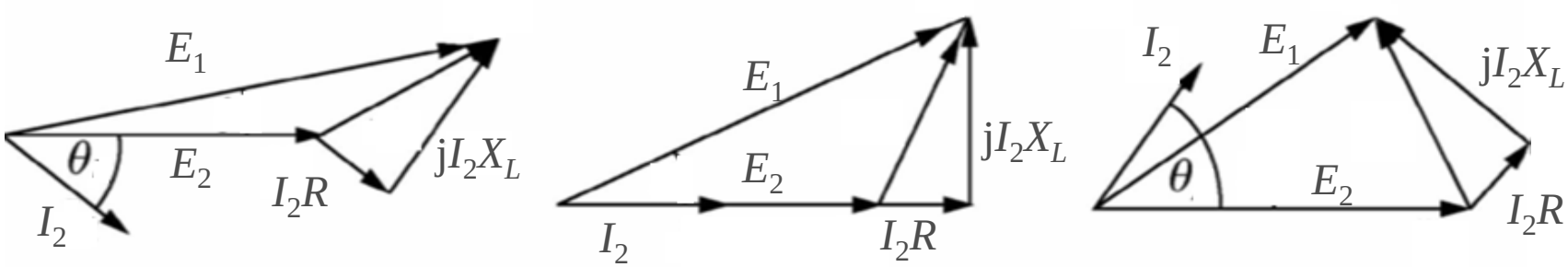
Voltage regulation

$$\text{Voltage Regulation} = \frac{|E_{2,NL}| - |E_{2,FL}|}{|E_{2,FL}|} \times 100\%$$

(if ignoring X_C) $$\approx \frac{|E_1| - |E_{2,FL}|}{|E_{2,FL}|} \times 100\%$$



- VR is a measure of line voltage drop and usually should not exceed ±5% (or ±10%)
- VR depends on the load power factor:
  - VR is low for a low lagging power factor
  - Perhaps, VR<0 for a leading power factor (i.e. $|E_1|<|E_2|$).
  - If ignore X_C, three typical loads with lagging, unity and leading power factors



Lagging PF Unity PF Leading PF

Resistive line

- There is an upper limit to the power the line can transmit to the load

$$P = |E_R| \cdot |I| = |I|^2 (kR) = \left| \frac{E_S}{R + kR} \right|^2 kR$$

$$= \frac{|E_S|^2}{R(1/k + k + 2)} \le \frac{|E_S|^2}{4R}$$

$P = P_{max} = |E_S|^2/4R$ when $k=1$, i.e. $E_R = E_S/2$

- If we allow a maximum VR of 5%, i.e. $E_R = 0.95E_S$, the line can support a load that is only 19% of P_{max}
- The total power from the sender is $P + |I|^2 R$
- VR is a key factor that limit the power transmission capacity

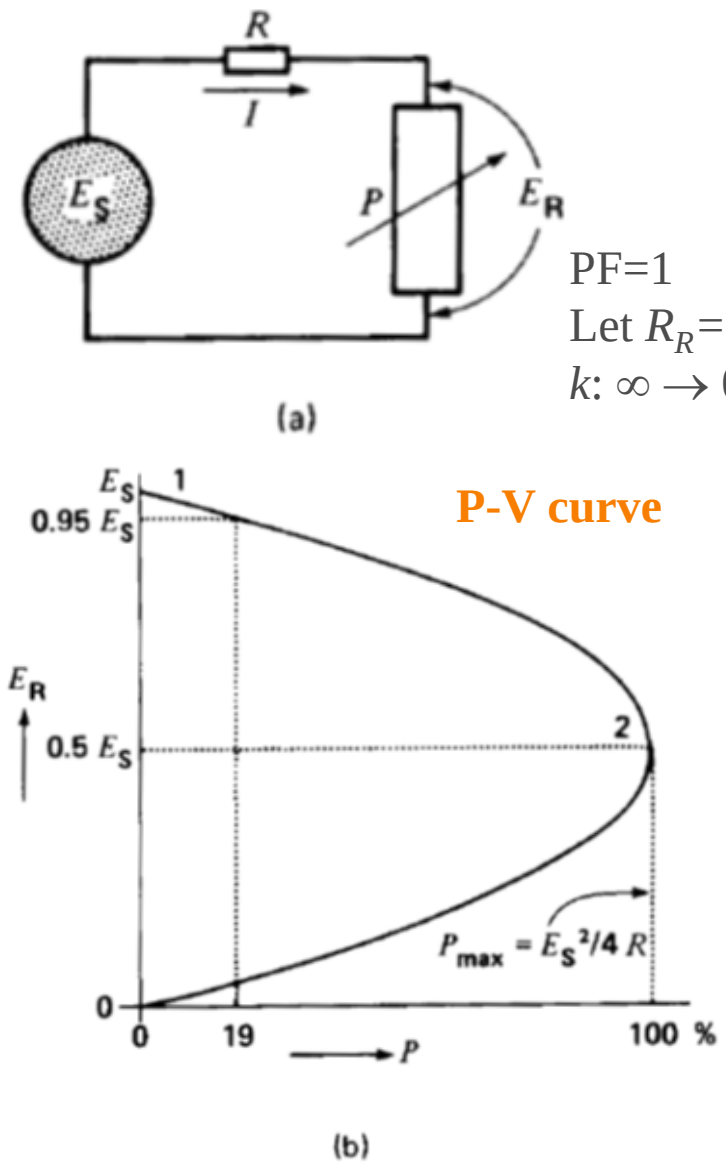


Figure 25.21
Characteristics of a resistive line.

PF=1
Let $R_R = kR$
k: $\infty \to 0$

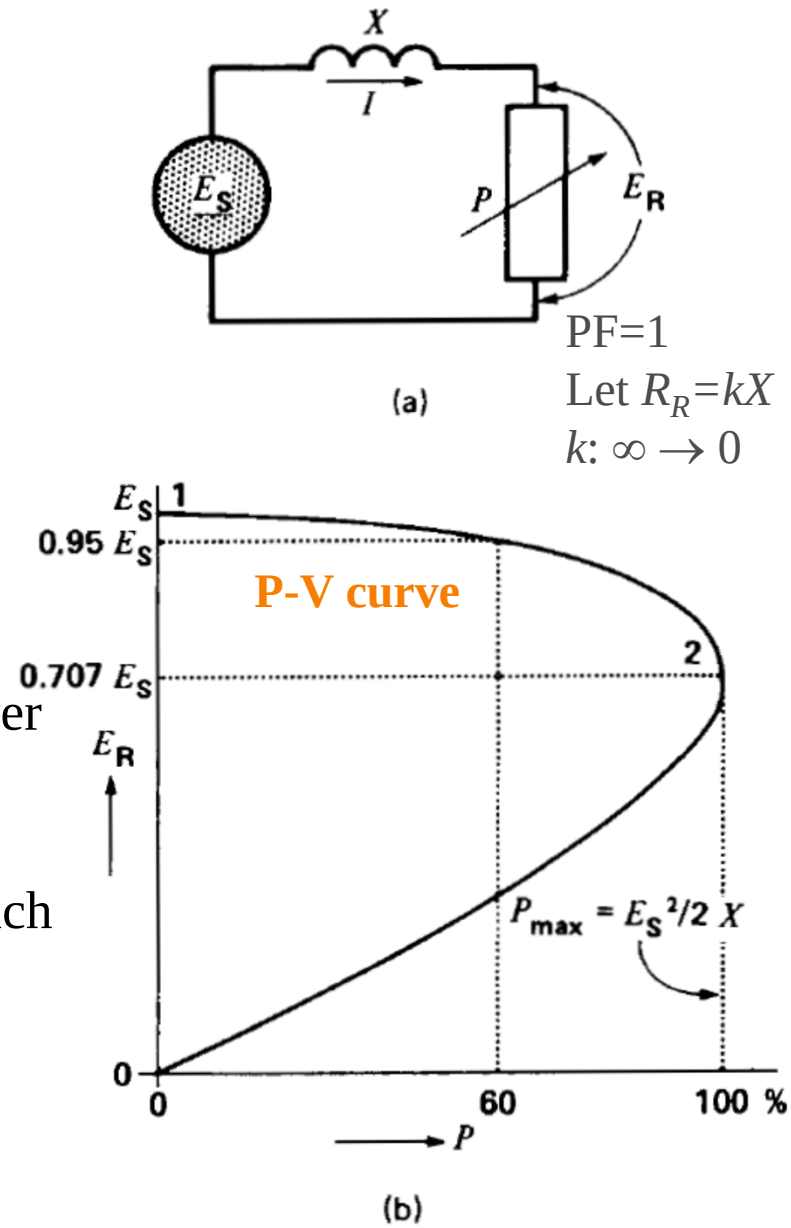
Inductive line

$$P = |I|^2 (kX) = \left| \frac{E_S}{jX + kX} \right|^2 kX$$

$$= \frac{|E_S|^2}{X\,|k - 1/k + 2j|} \le \frac{|E_S|^2}{2X}$$

$P_{max}=|E_S|^2/2X$ when k=1, $|E_R|=|E_S|/\sqrt{2}=0.707|E_S|$

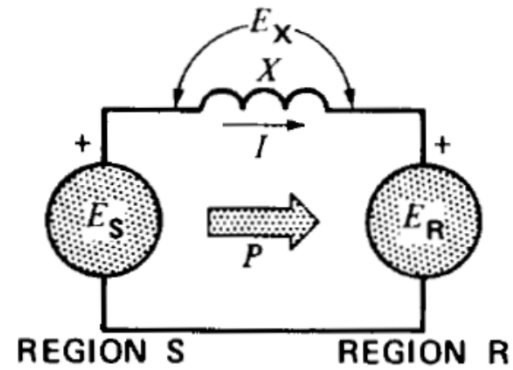
- A inductive line can deliver twice as much power as a resistive line (if X=R)
- If we allow a maximum VR of 5%, the line can support a load that is 60% of P_{max}, i.e. 6x as much as power as a resistive line
- VR is a key factor that limit the power transmission capacity
- The total power from the sender is $P+j|I|^2X$



PF=1
Let R_R=kX
k: $\infty \rightarrow 0$

Figure 25.22
Characteristics of an inductive line.

Inductive line connecting two systems

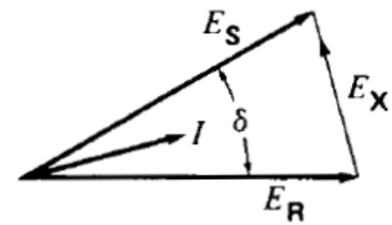


$$S = E_S I^* = E_S \left(\frac{E_S - E_R}{jX} \right)^* = |E_S| \angle \delta \left(\frac{|E_S| \angle -\delta - |E_R| \angle 0^\circ}{X \angle -90^\circ} \right)$$

$$= \frac{|E_S|^2}{X} \angle 90^\circ - \frac{|E_S||E_R|}{X} \angle(\delta + 90^\circ)$$

$$P = -\frac{|E_S||E_R|}{X} \cos(\delta + 90^\circ)$$

$$= \frac{|E_S||E_R|}{X} \sin\delta \quad \approx \frac{|E_S||E_R|}{X} \delta (\text{in rad})$$



$$Q = \frac{|E_S|^2}{X} - \frac{|E_S||E_R|}{X} \sin(\delta + 90^\circ) = \frac{|E_S|^2}{X} - \frac{|E_S||E_R|}{X} \cos\delta$$

$$= \frac{|E_S|}{X} \left(|E_S| - |E_R| \cos\delta \right) \approx \frac{|E_S|}{X} \left(|E_S| - |E_R| \right)$$

- If $|E_S| = |E_R| = E$, $Q \approx 0$, i.e. almost no reactive flow

$$\boxed{P = \frac{E^2}{X} \sin\delta \le \frac{E^2}{X}}$$

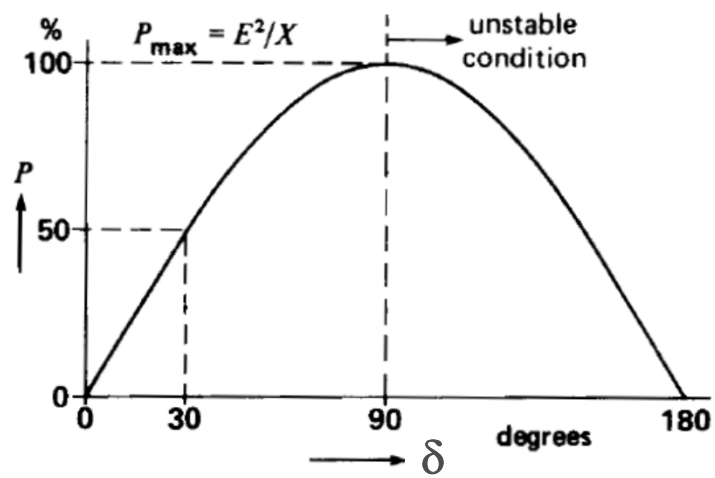
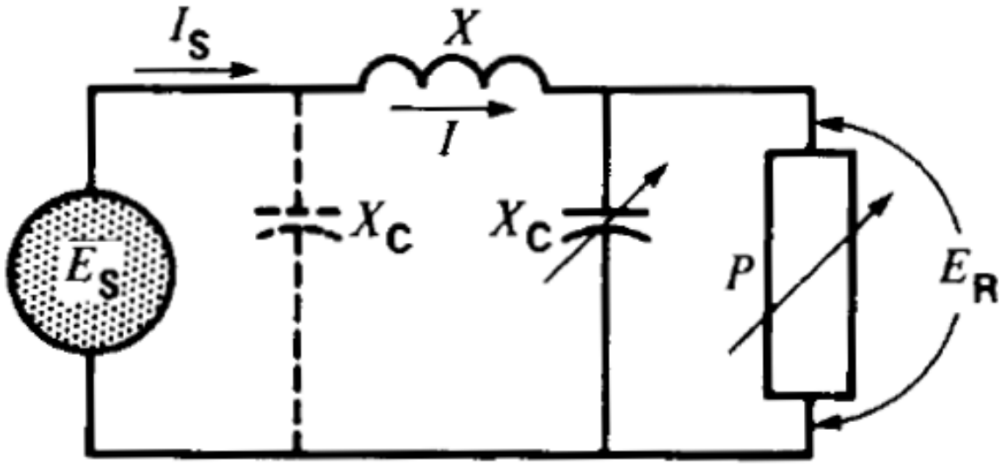


Figure 25.30a
Power versus angle characteristic.

Compensated inductive line



- To have $|E_R|=|E_S|$, the line can fully be compensated by adding a shunt capacitor to the receiving end whose X_C is adjustable so that

$$|E_S|^2/X_C=0.5|I|^2X$$

while the other $0.5|I|^2X$ is provided by the source or another capacitor with X_C at the sending end.

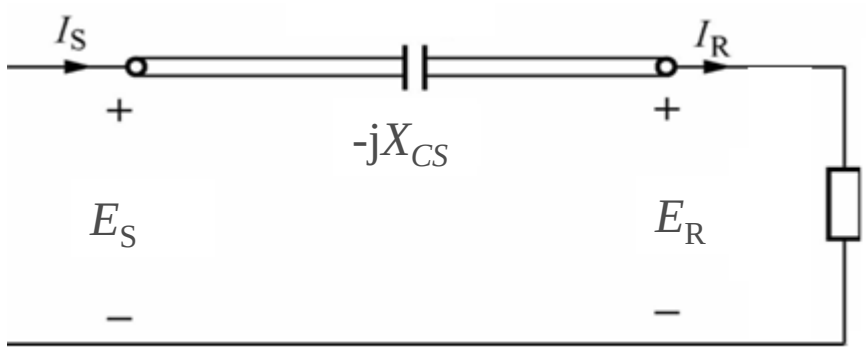
- Thus, $P_{max}=|E_S|^2/X$

Increasing the power transmission capacity

To increase $P_{max}=|E_S|^2/X$, an approach is to reduce line reactance X

- Use parallel lines:
  - $X \rightarrow X/2$ or X/n, so $P_{max} \rightarrow 2P_{max}$ or nP_{max}
  - Improving security against a line trip.
- Use a series capacitor

  $P_{max}=|E_S|^2/(X-X_{CS})$
  - It may cause sub-synchronous resonance (SSR)



$$f_{SSR} = f\sqrt{\frac{X_{CS}}{X}} = f\sqrt{\frac{1}{LC_S}}$$

If f=60Hz, f_{SSR}= 30Hz for 25% compensation (X_{CS}/X=1/4)

Voltage Regulation for EHV lines

A 3-phase 735kV 60Hz 600km line, operated at 727kV, has inductive reactance of 0.5 Ω/km and capacitive reactance of 300kΩ/km.

- At no-load (open-circuit) conditions,

  for each phase,

  $|E_S|=727/\sqrt{3}=420\text{kV}$,

  $X_L=0.5\times600=300\Omega$, $X_C=300\text{k}/600=500\Omega$,

  $X_{C1}=X_{C2}=2X_C=1000\ \Omega$

  $E_R=E_S\times(-jX_{C2})/(jX_L-jX_{C2})$
  $=420\angle0^o\times1000/(1000-300)=600\angle0^o$ kV

To bring $|E_R|$ back to $|E_S|$, add a shunt reactor of X_{L2} at the receiving end:

If $X_{L2}=X_{C2}$, then $-jX_{C2}//jX_{L2}=\infty$ and $|E_R|=|E_S|$.

The reactive power generated by X_{C2} is entirely absorbed by X_{L2} (cancelling each other)

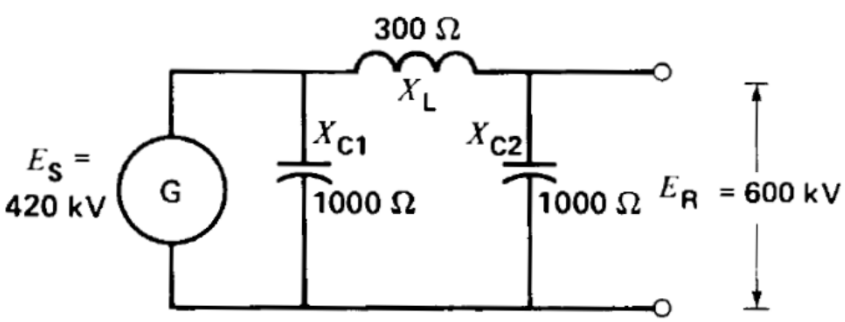


Figure 25.35
EHV transmission line at no-load.

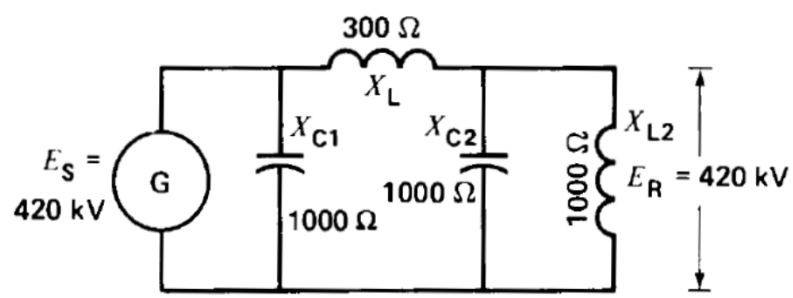
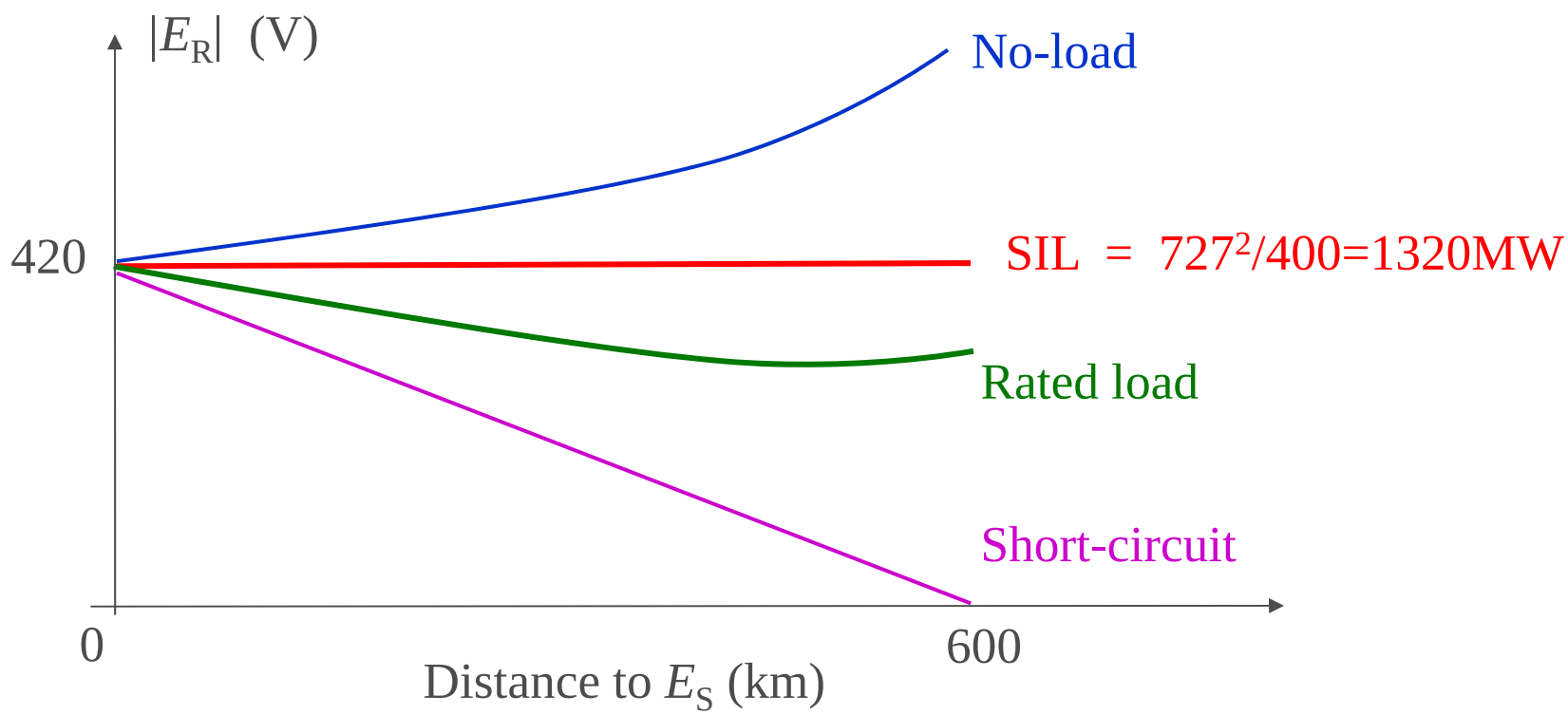


Figure 25.36
EHV reactor compensation.

Surge-impedance load (SIL)

- When connected to a gradually increasing load with PF=1, $|E_R|$ decreases from $|E_{R,NL}|$ (open-circuit) to 0 (short-circuit). When $|E_R|=|E_S|$, the amount of load is called the surge-impedance load (SIL) and the corresponding load impedance is called the surge impedance, which has $Z_Y \approx 400\Omega$ for aerial lines

$$\text{SIL} = E_L^2/Z_Y = E_L^2/400 \text{ (MW)} \qquad E_L\text{: 3-phase line voltage in kV}$$



Inter-region power exchange: Example 25-8

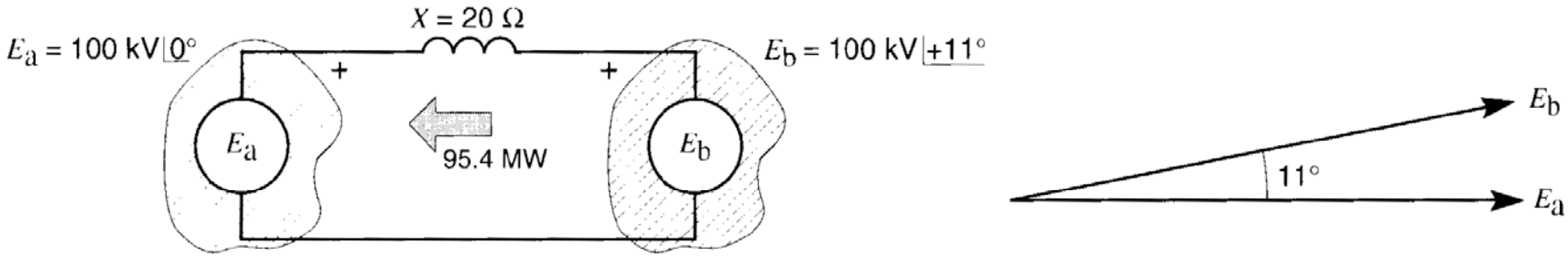


Figure 25.41a
An ordinary transmission line causes power to flow in the wrong direction.

- Calculate (1) the power transmitted by the line and (2) the required phase-shift enabling transmitting 70MW from E_a to E_b

(1) $P_{ab}=(E^2/X)\sin(\delta_a-\delta_b)=(100^2/20)\sin(-11^o)=-95.4\text{MW}$ $(E_a \leftarrow E_b)$

(2) $P_{ab}=70=(100^2/20)\sin(\delta_a-\delta_b)$, so $\delta_a-\delta_b=8^o$, i.e. 8-(-11)=19° phase-shift of E_a

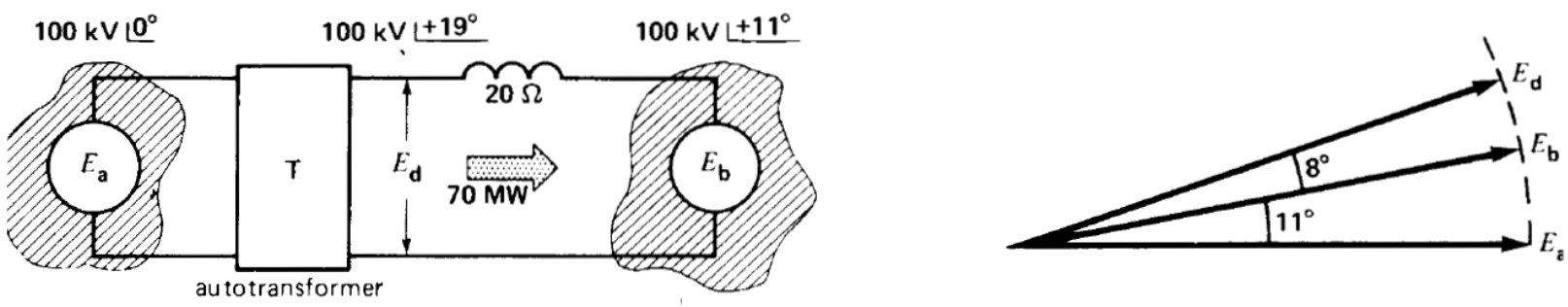


Figure 25.41b
A phase-shift autotransformer can force power to flow in the desired direction (Example 25-8).

Homework Assignment #4

- Read Chapters 11, 12 &25
- Questions:
  - 11-7, 11-8, 11-9, 12-2, 12-7, 12-8, 25-11, 25-12, 25-13, 25-14, 25-15, 25-16, 25-17, 25-18, 25-21
- Due date:
  - hand in your solution to Denis at MK 205 or by email (dosipov@vols.utk.edu) before the end of 10/14 (Wed)