TSTE26 Powergrid and technology for renewable production

Lecture 4
Power flow & Voltage stability

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Outline

Electric Power Systems, A first course by Ned Mohan

- Chapter 5 Power flow calculation
- Chapter 10 Voltage stability

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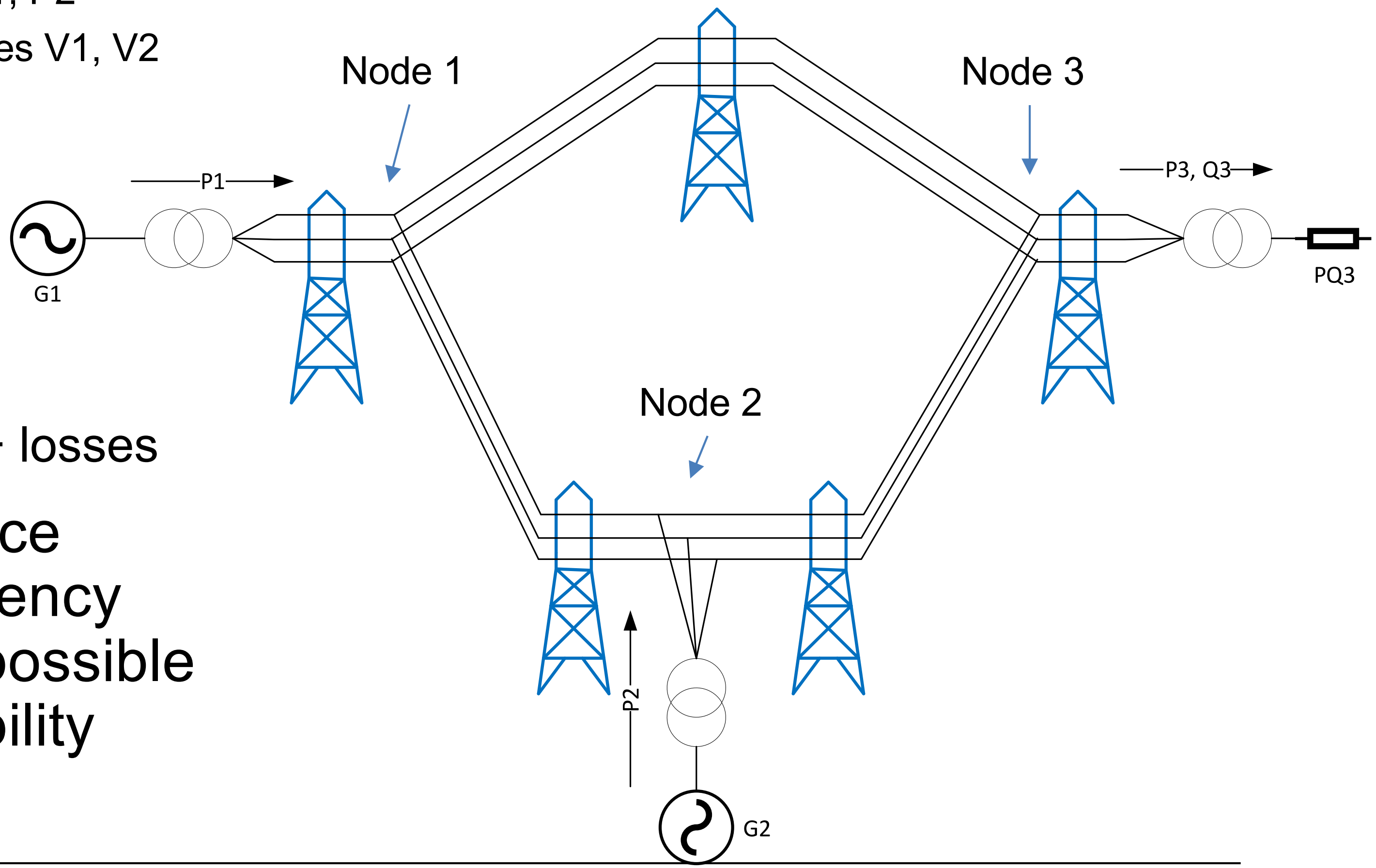
Power system example

- 3 nodes (bus), [1, 2, 3]
- Two generators: G1, G2
  - Feeding power P1, P2
  - Controlling voltages V1, V2
  - **PV-bus**
- Load R3
  - P3, Q3
  - **PQ-bus**
- Power balance
  - $P_1 + P_2 = P_3 + \text{losses}$
- Power imbalance results in frequency deviation and possible transient instability (Lecture 7)



Power balance

Power imbalance:

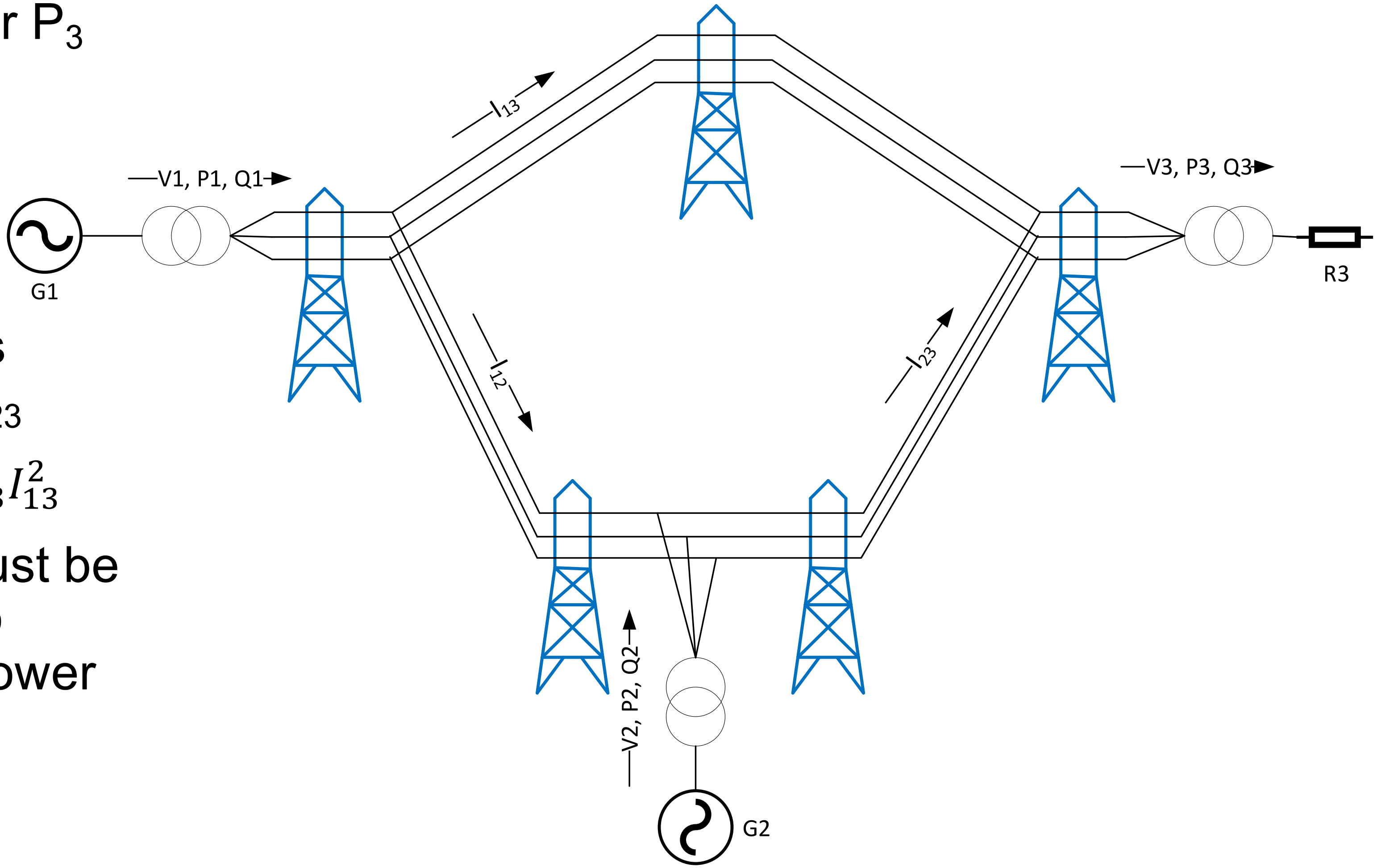
- Load variation
- Load power P_3 varies with voltage

$$P_3 = \frac{V_3^2}{R_3}$$

- Line losses P_{12}, P_{13}, P_{23}

$$P_{13} = 3 \cdot R_{13} I_{13}^2$$

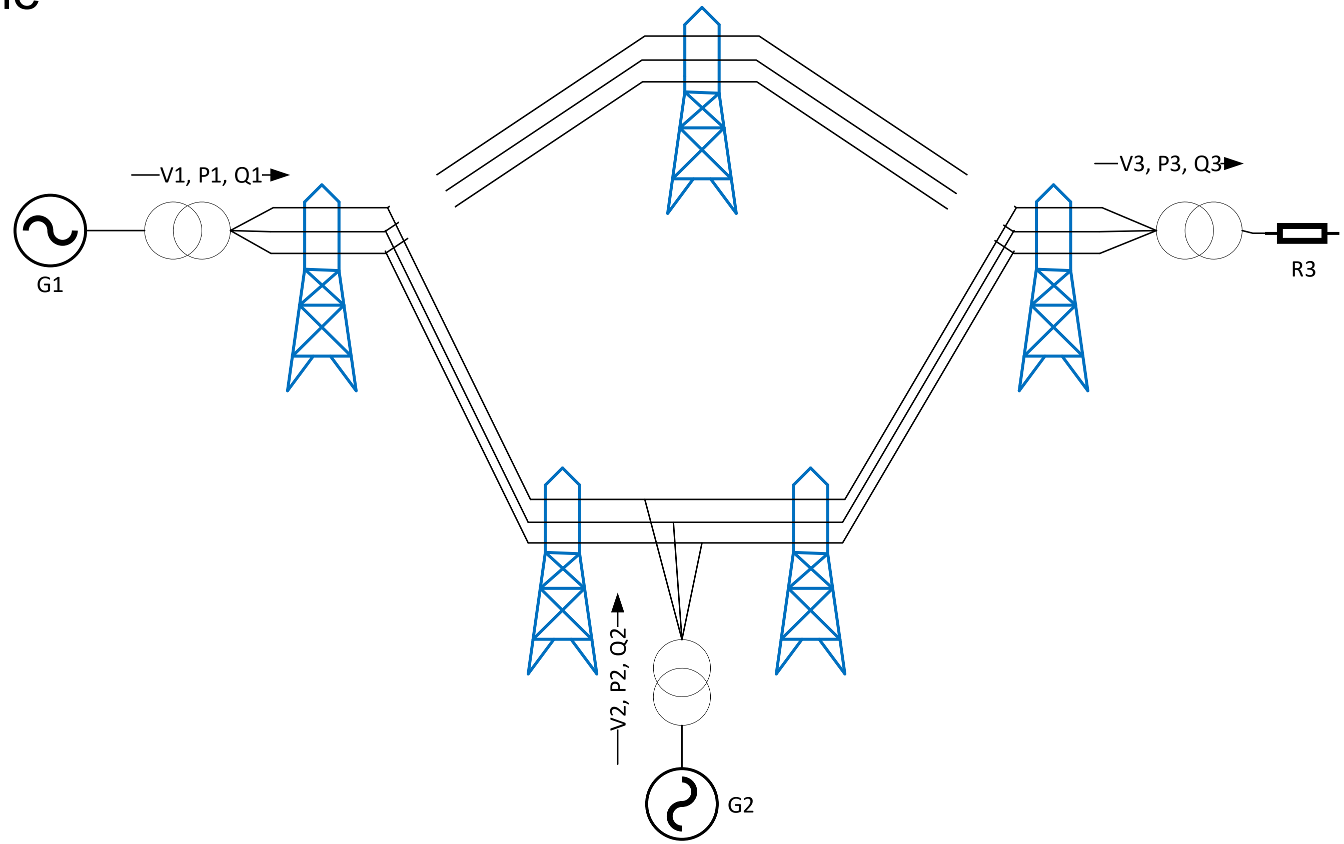
- P_1 or P_2 must be changed to maintain power balance



Line outage

Line disconnection

- All current on one line
- Higher losses



Slack bus, infinite bus

Load = PQ Buses

- Active and reactive power load

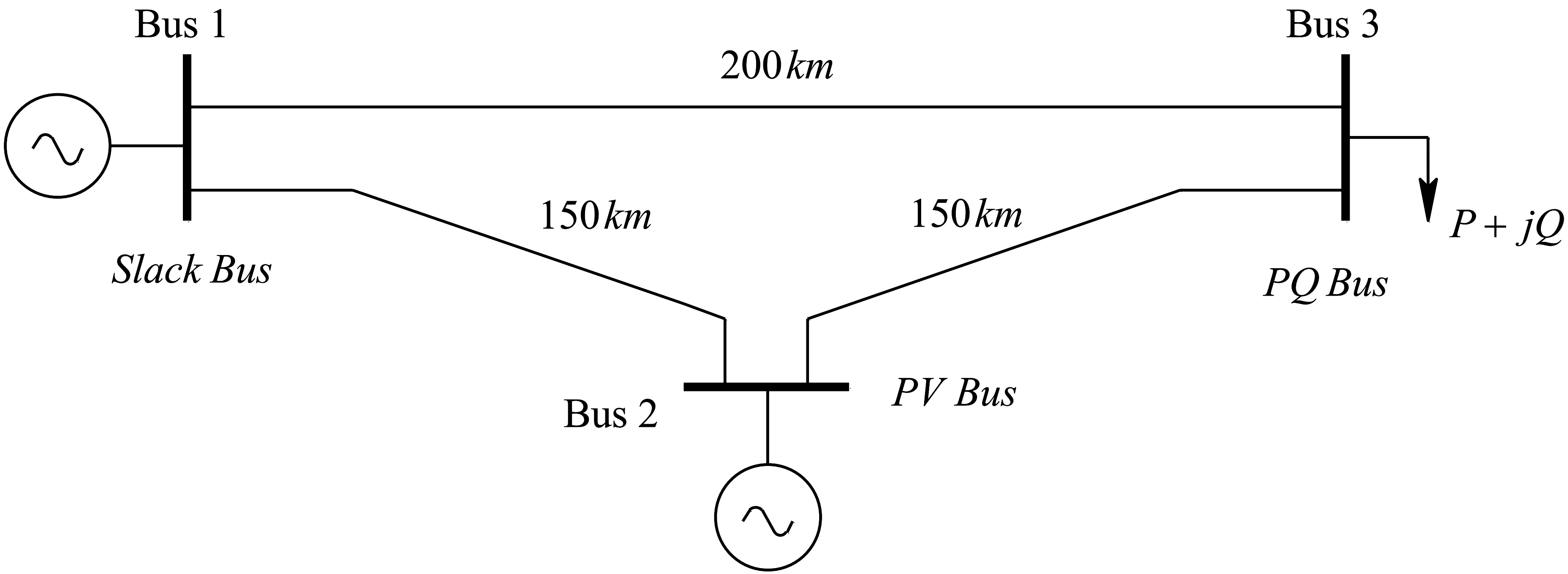
Generator = PV Bus

- Constant active power
- Constant voltage magnitude

One generator changed to Slack Bus

- Fixed voltage source (magnitude and angle)
- Active power defined by the power imbalance: $P_{1(\text{slack bus})} = P_3 + \text{losses} - P_2$

345-kV Three-Bus Example Power System



Line-line voltage: $V_{LL} = 345\ kV$

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Chapter 10

Voltage stability

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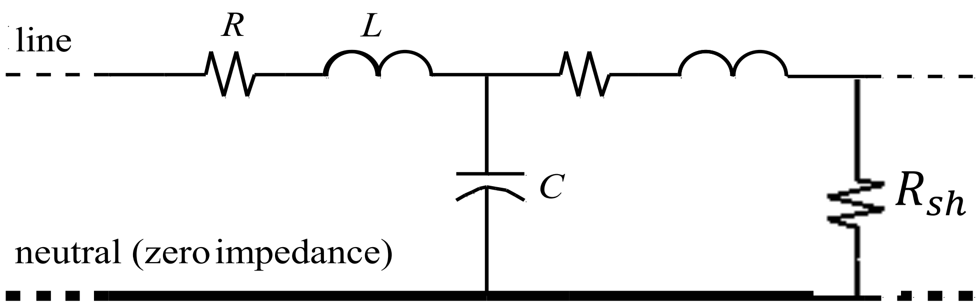
Repetition of the Cousins of Resistance

- Resistance *R* [Ω]
- Capacitance C $[F]$ Farad
- Inductance L $[H]$ Henry
- Reaktance $X = \omega L,\ X = \frac{1}{\omega C}$ $[\Omega]$
- Impedance $Z = R + i\,X$ $[\Omega]$
- Conduktance *G*=$\frac{1}{R}$ $[\Omega^{-1}] = [mho] = [S]$ Siemens
- Susceptance B $[S]$
- Admittance $\frac{1}{Z} = Y = G + j\,B$ $[S]$

Transmission Line Parameters:

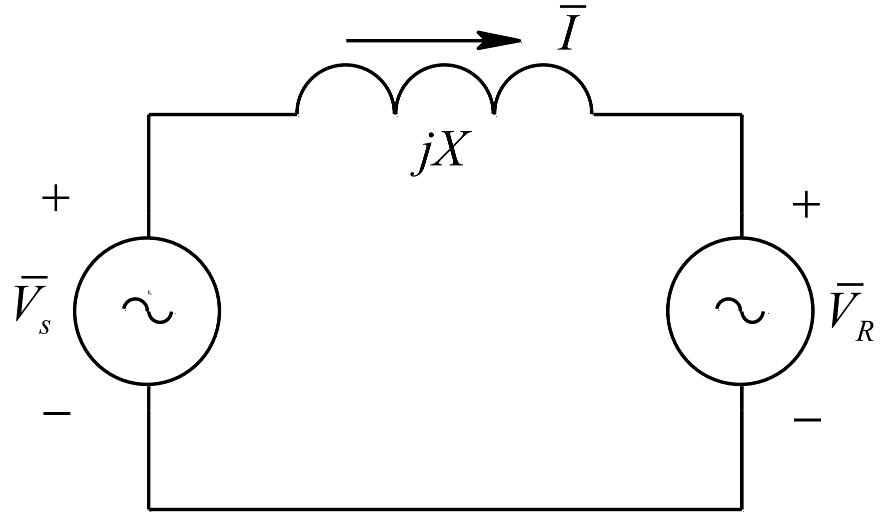


Distributed Parameters per km
Analyzed on a per-phase basis

Nominal Voltage	$R(\Omega/km)$	$\omega L(\Omega/km)$	ωC (μmho/km
230 kV	0.055	0.489	3.373
345 kV	0.037	0.376	4.518
500 kV	0.029	0.326	5.220
765 kV	0.013	0.339	4.988

$Reactance\ (ind)\!: X_L = \omega L$ $\quad$ $Susceptance\!: B = \frac{1}{X_C} = \omega C$

Power Flow in AC Systems



(a)

- In long power lines the inductance dominates
- Inductance ”eats” reactive power
- Need to supply reactive power to maintain voltage stability at high power transfers

Power Flow in AC Systems

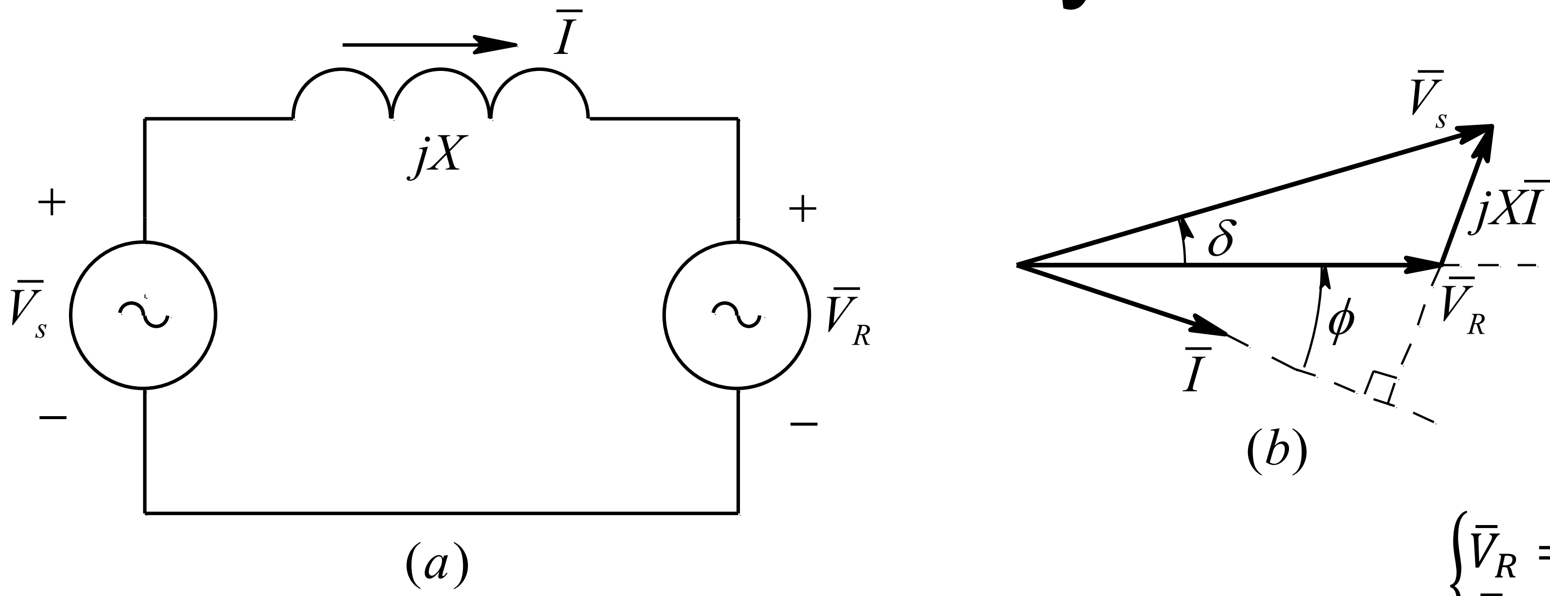


Fig. 2-17 Power transfer between two ac systems.

$$\begin{cases}\bar{V}_R = V_R\angle 0 \\ \bar{V}_S = V_S\angle\delta\end{cases}$$

$$P_R + jQ_R = \sqrt{3}\cdot\bar{V}_R\cdot\bar{I}^* = \sqrt{3}\cdot\bar{V}_R\left(\frac{\bar{V}_S-\bar{V}_R}{jX\sqrt{3}}\right)^* = \bar{V}_R\left(\frac{\bar{V}_S-\bar{V}_R}{jX}\right)^*$$

Note $\sqrt{3}$ in the denominator since the voltages are ph-ph

$$P_R + \mathrm{j}Q_R = V_R\left(\frac{V_S\angle(-\delta)-V_R}{-jX_L}\right) = \frac{V_SV_R\sin\delta}{X_L} + j\left(\frac{V_SV_R\cos\delta - V_R^2}{X_L}\right)$$

Power-Angle Diagram

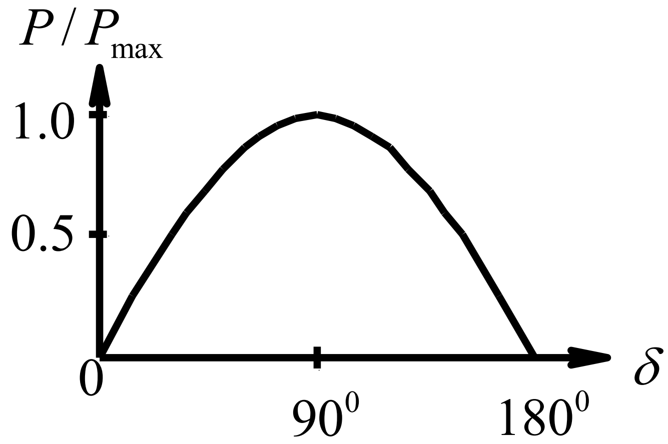


Fig. 2-18 Power as a function of δ.

$$P_R = \underbrace{\frac{V_S V_R}{X}}_{(=P_{max})} \sin\delta$$

Reactive Power

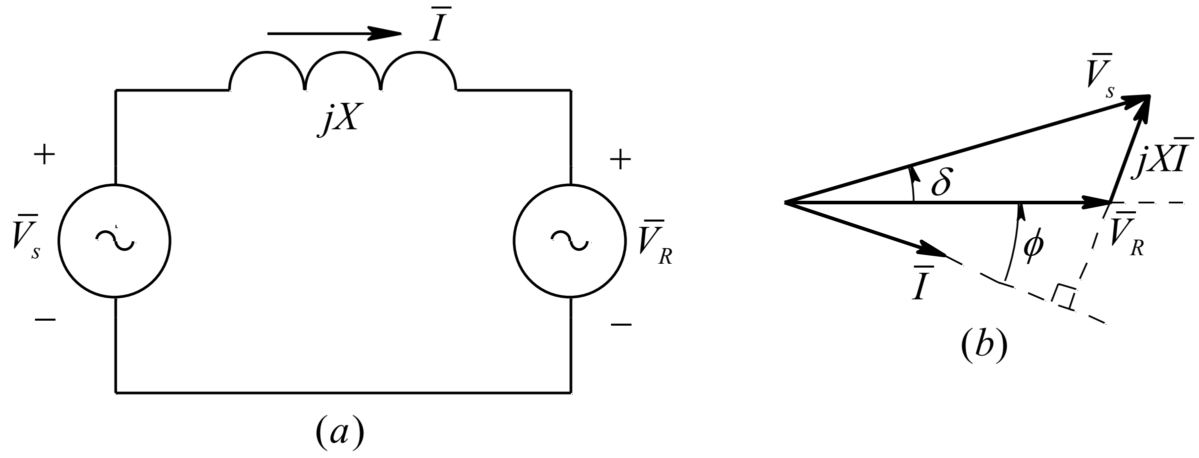


Fig. 2-17 Power transfer between two ac systems.

$$Q_R = \frac{V_S V_R \cos\delta}{X} - \frac{V_R^2}{X}$$

For small δ

$\cos\delta \approx 1$

$$Q_R = V_R \frac{V_S - V_R}{X}$$

Q_R defined by the voltage difference. Q flows from high to low voltage

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A Radial System

$$\begin{cases} \bar{V}_R = V_R \angle 0 \\ \bar{V}_S = V_S \angle \delta \end{cases}$$

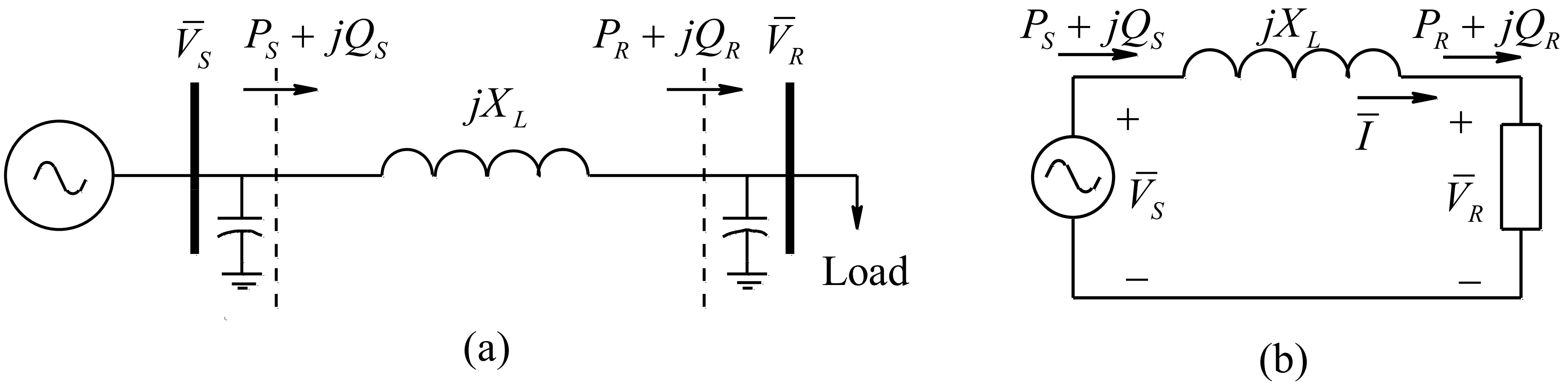

Fig. 10-1 A radial system.

Line B combined with load

$$\bar{I} = \frac{\bar{V}_S - \bar{V}_R}{jX_L\sqrt{3}}$$

$$S_R = P_R + \text{j } Q_R = \sqrt{3}\bar{V}_R \bar{I}^*$$

$$P_R + \text{j}Q_R = V_R\left(\frac{V_S\angle(-\delta) - V_R}{-jX_L}\right) = \frac{V_S V_R \sin\delta}{X_L} + j\left(\frac{V_S V_R \cos\delta - V_R^2}{X_L}\right)$$

Voltages and Current Phasors with Both-Side Voltages at 1 PU

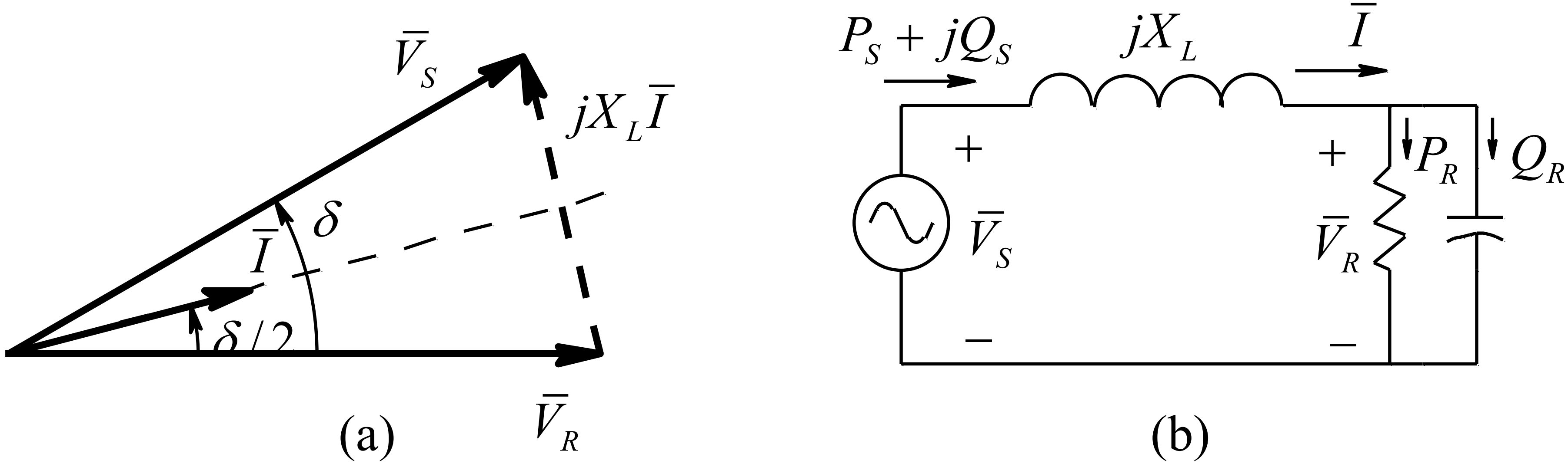

Fig. 10-2 Phasor diagram and the equivalent circuit with $V_S = V_R = 1\,\text{pu}$.

$$\bar{V}_S = \bar{V}_R + jX_L\bar{I} \qquad Q_{Line} = I^2 X_L$$

$$Q_s = -Q_R \qquad Q_S = Q_R + \underbrace{I^2 X_L}_{Q_{Line}} \qquad I^2 X_L = Q_{Line} = 2|Q_R|$$

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Reactive Power Need at Higher Loading:

$$P_R = \frac{V_S V_R}{X_L} \sin\delta \qquad \frac{V_R}{V_S} = \cos\delta\left(\frac{1}{1 + \frac{Q_R}{V_R^2 / X_L}}\right)$$

- Both voltages close to 1 per unit
- Large power transfer means larger angle, $\cos\delta \ll 1$
- Q_R must be negative for $\frac{V_R}{V_S} = 1$

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Voltage Profile for Three Values of SIL

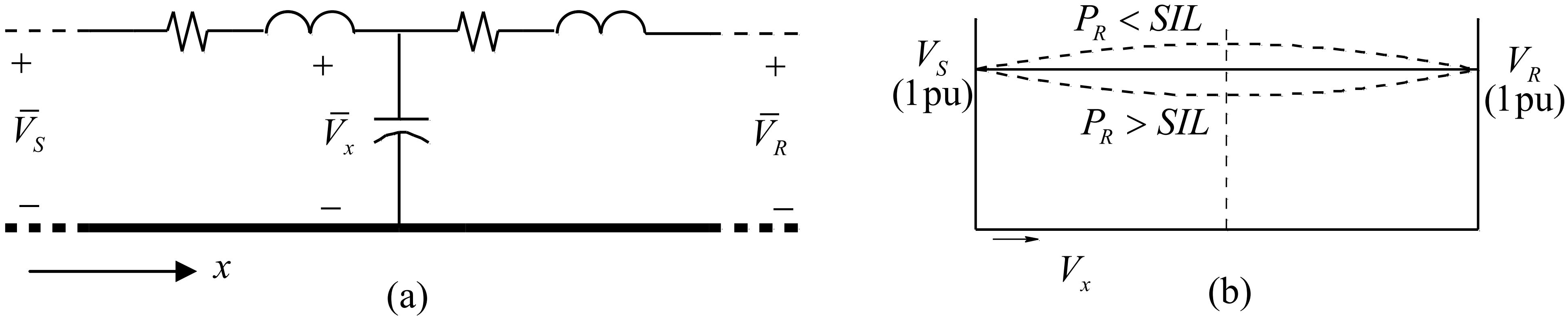


Fig. 10-3 Voltage profile along the transmission line.

Surge Impedance Loading (SIL)

$$Z_c = \sqrt{\frac{L}{C}} = \sqrt{\frac{\omega L}{\omega C}} = \sqrt{\frac{Z}{B}} \qquad SIL = \frac{V_{LL}^2}{Z_c}$$

345 kV example:

$$Z_c = \sqrt{\frac{0.376\ ohm/km}{4.5\ \mu\ mho/km}} = 289\ ohm$$

$$SIL = \frac{345^2}{289} = 413\ MW$$

Voltage versus active power

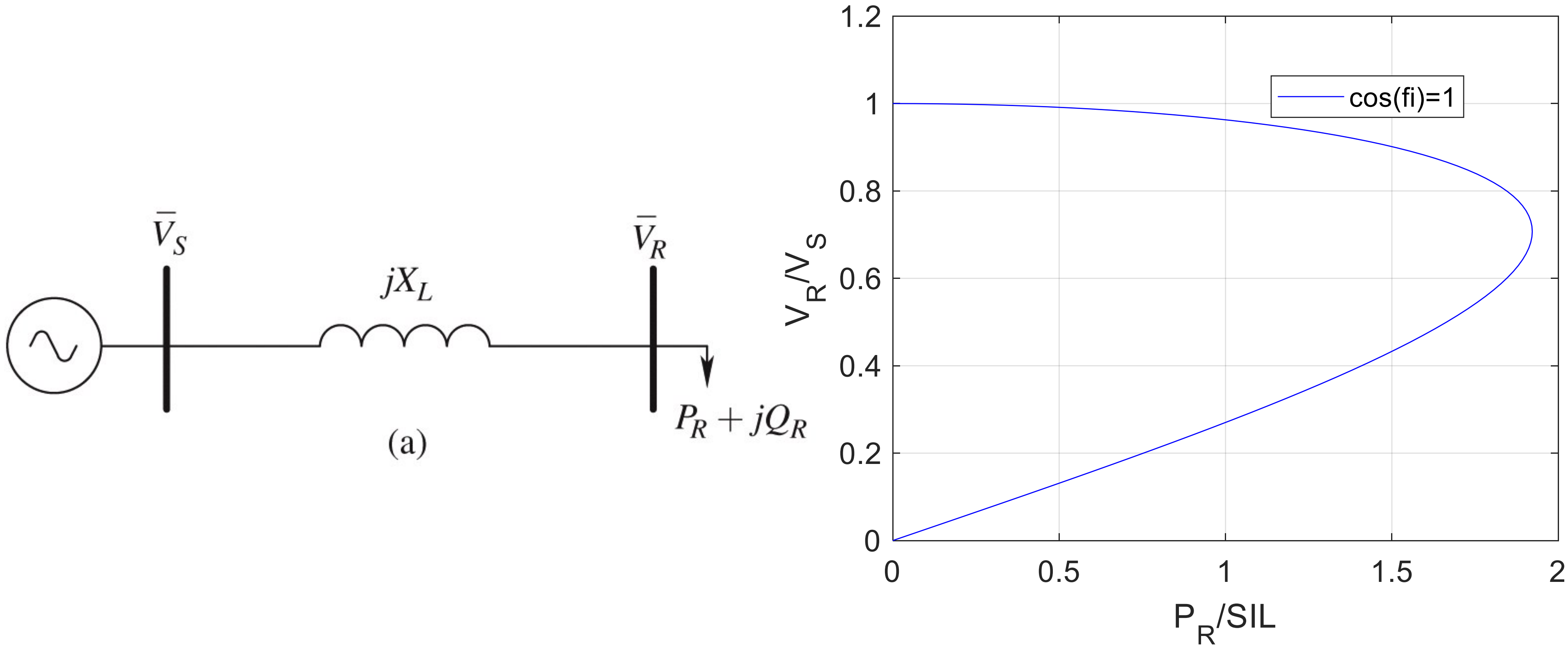
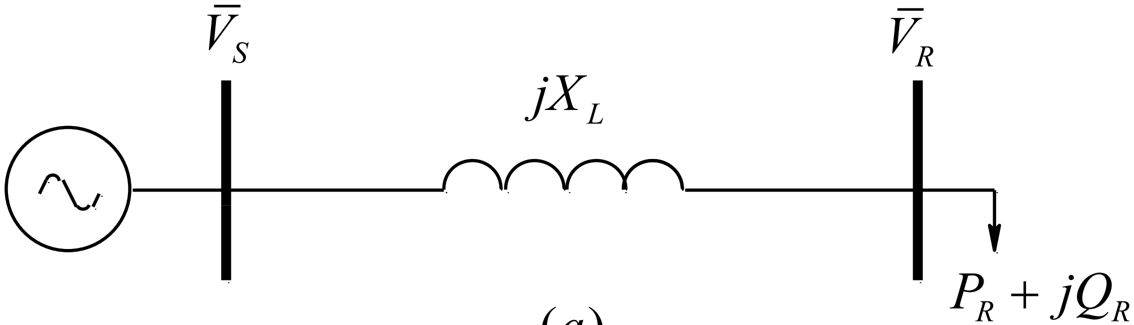
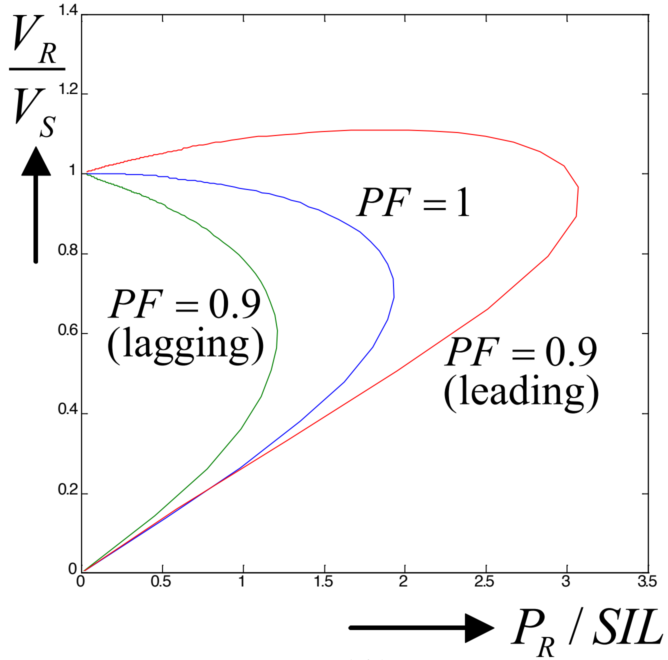


Figure 10.4

“Nose” Curves at Three Power Factors as a function of Loading



(a)



(b)

Leading PF implies capacitive load. R+C or R//C

Lagging PF implies inductive load. R+L or R//L

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Prevention of Voltage Instability

- Voltage (excitation) Control of Synchronous Generators
- Shunt (Parallel) Reactive Power Compensation
- Series Reactive Power Compensation
  - Reduction of line X

Thevenin equivalent

Thevenin (2-pole) equivalent of dashed area equals

Voltage source

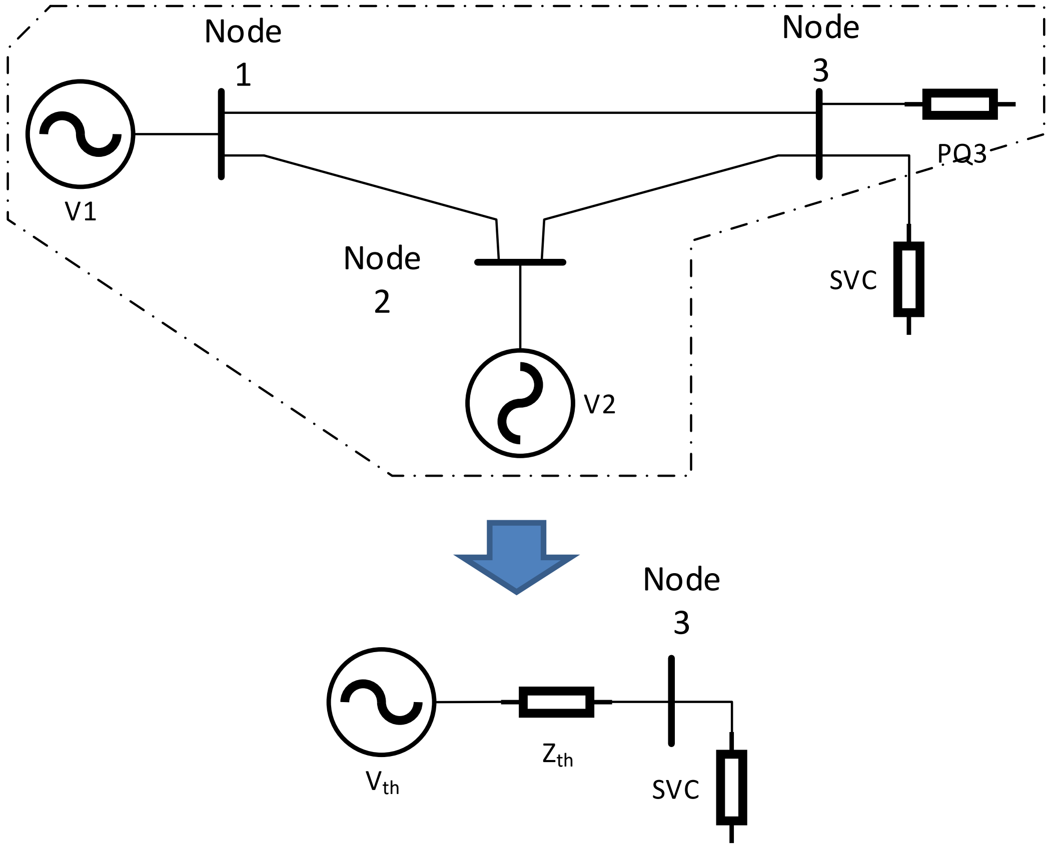
$$V_{th} = V_{oc}$$

$$V_{oc} = Open\ circuit\ voltage$$

Series impedance

$$Z_{th} = \frac{V_{oc}}{I_{sc}}$$

$$I_{sc} = Short\ circuit\ current$$



Effect of Shunt Q compensation on Bus Voltage

$$\bar{V}_{bus} = \bar{V}_{Th} - jX_{Th}\bar{I}$$

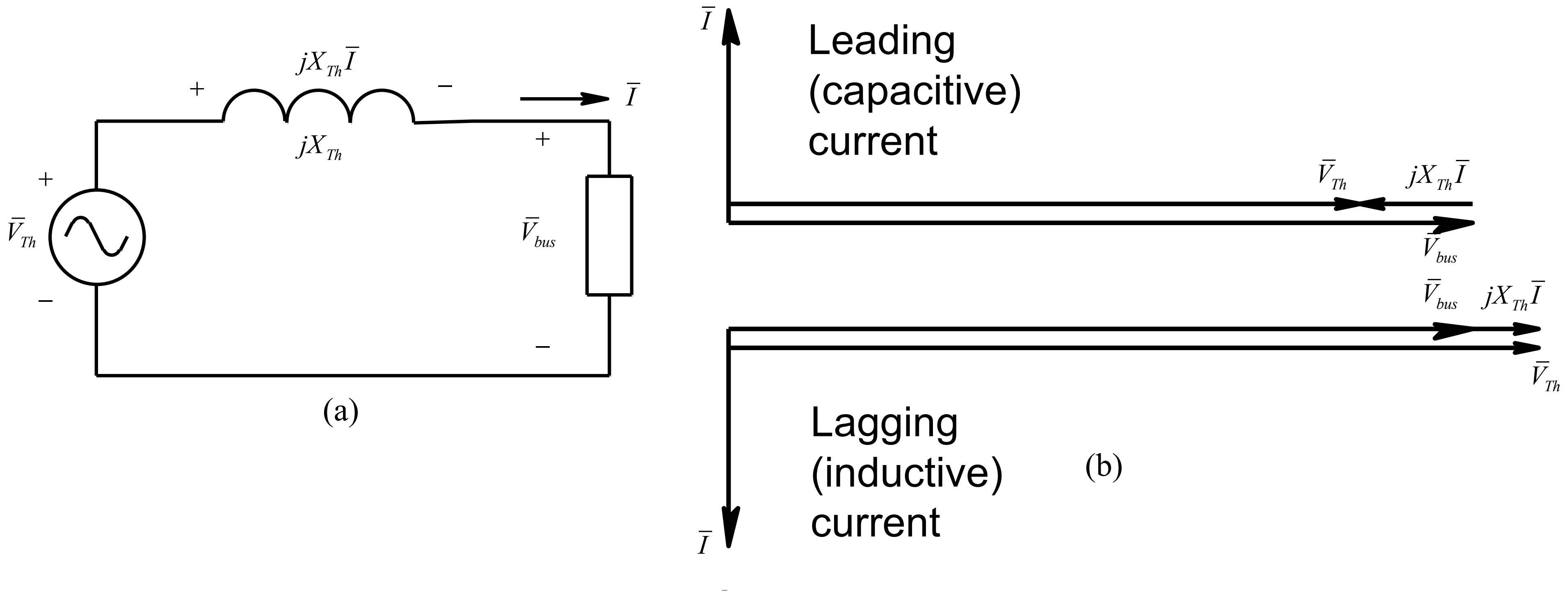
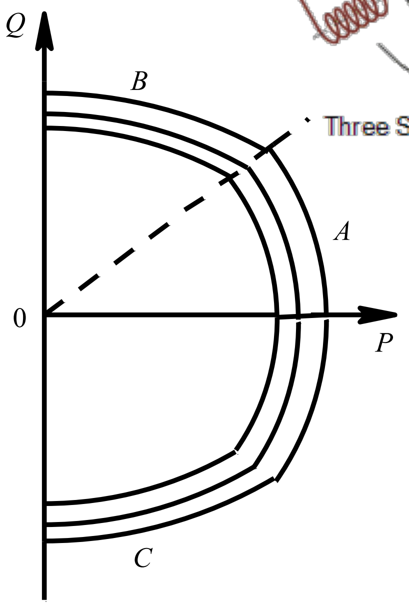


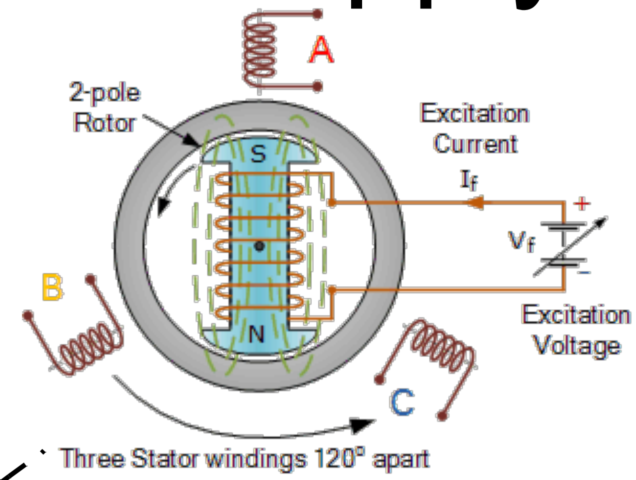
Fig. 10-6 Effect of leading and lagging currents due to the shunt compensating device.

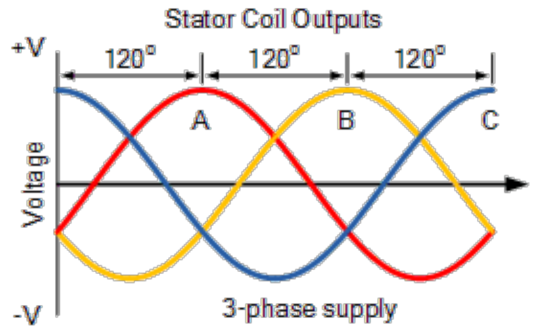
Synchronous Generator Reactive Power Supply

Wound rotor synchronous generator

- Rotor magnetisation control by excitation current
- Internal voltage defined by magnetisation







Available in power stations. (Hydro, Nuclear, Fossil fuel)

$$|S|(=\sqrt{P^2+Q^2})$$

Fig. 10-5 Reactive power supply capability of synchronous generators.

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Static Var Compensators (SVC)

- **SVC**
  - **Static**. A static (non-rotating) device
    - Controlled capacitor (**TSC**)
    - Controlled inductor (**TCR**)
    - Converter (**STATCOM**)
  - **Var**: Generates or consumes reactive power (unit VAr)
  - **Compensator**: Controlled system for compensation of large active power loading or generation

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Thyristor switched capacitor (TSC)

- **Switched capacitor**
  - Connected when thyristors are on
  - Disconnected when thyristors are off
- Gives leading current $I_c = V_{bus} \cdot \omega C$
- Inductor for reducing transients

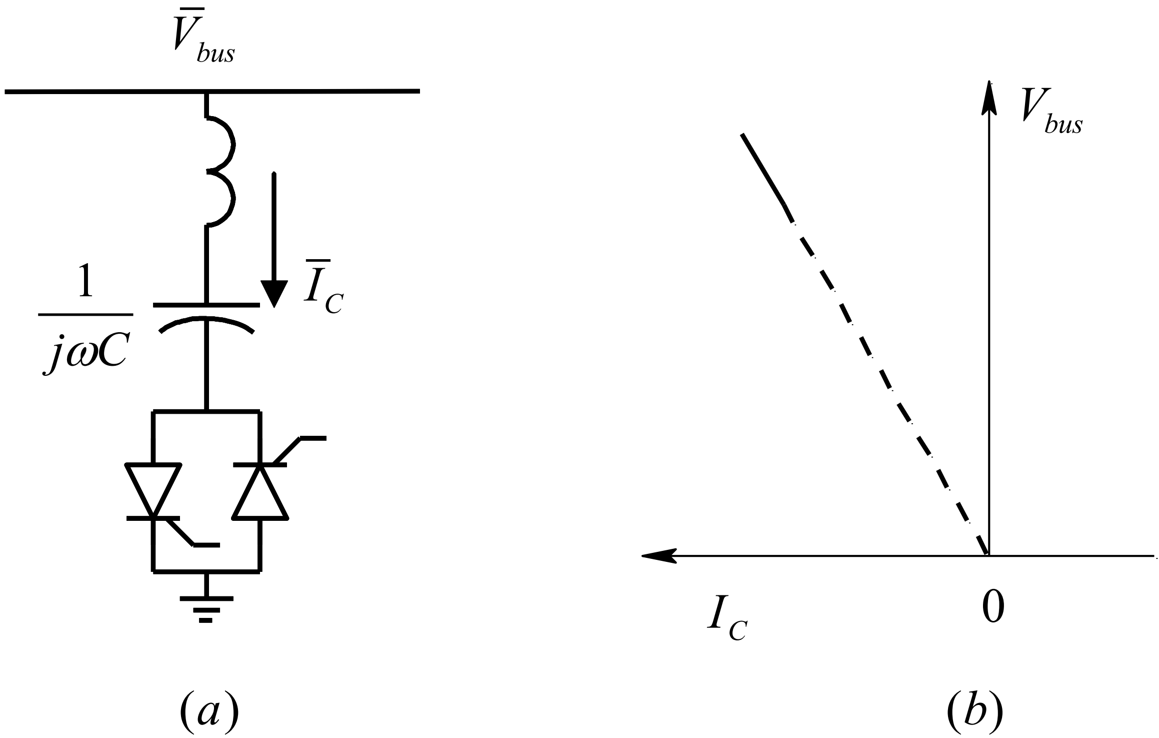


Fig. 10-7 V-I characteristic of SVC.

Thyristor Controlled Reactors (TCR)

- Reactor = Inductor
- Thyristor turn-on delayed by angle α
- Gives lagging current $I_L = \left[0..\frac{V_{bus}}{\omega L}\right]$

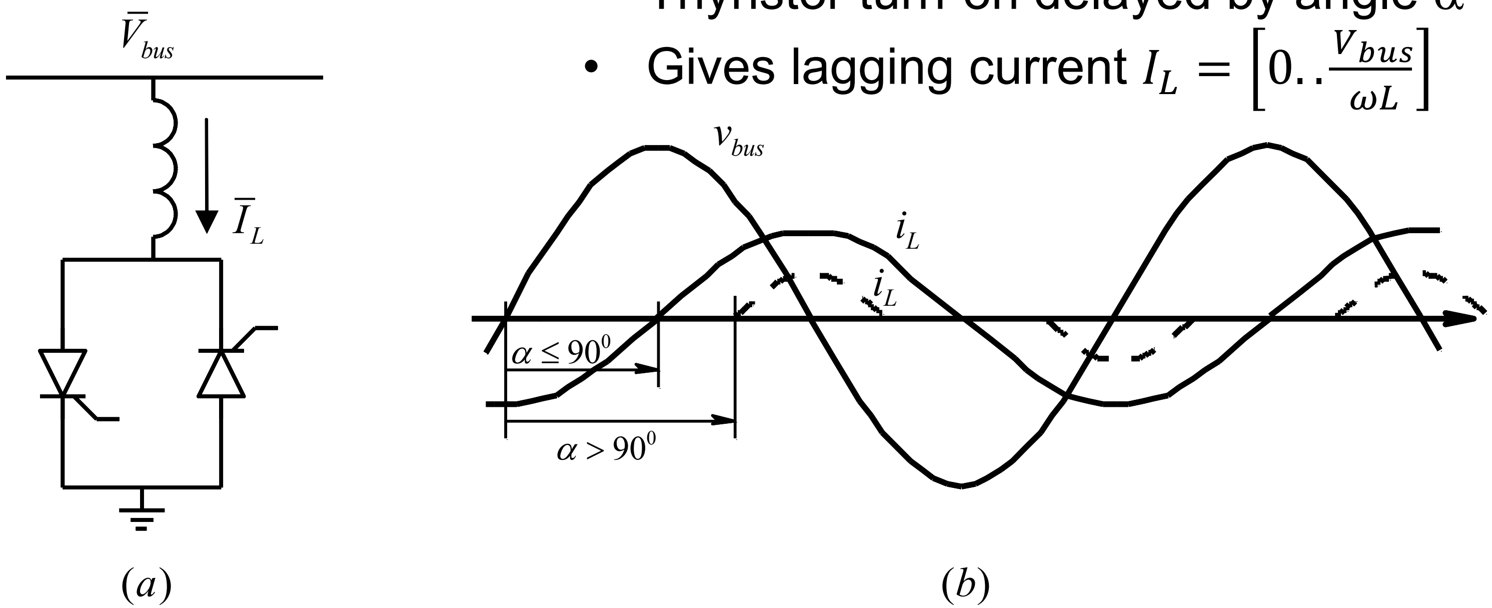
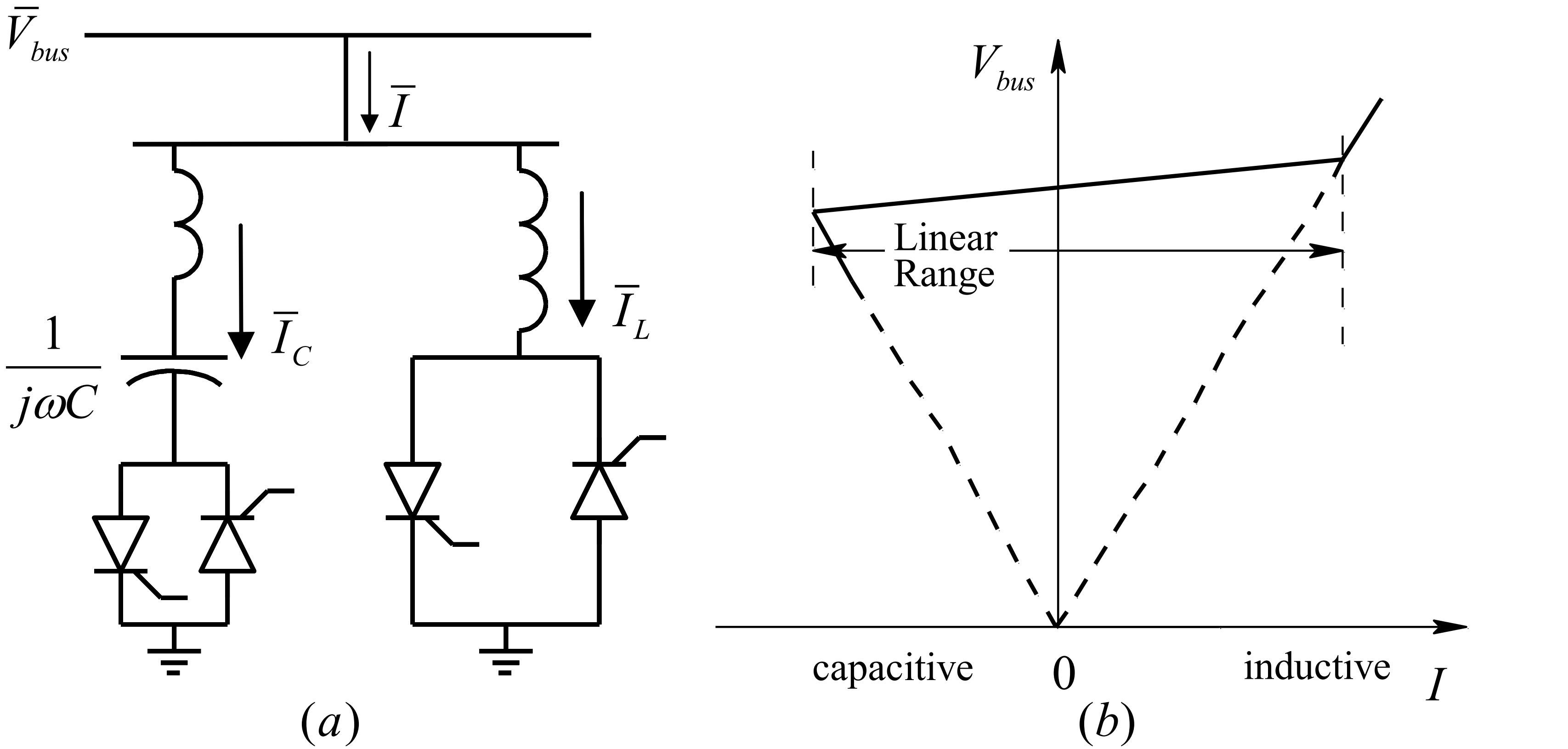


Fig. 10-8 Thyristor-Controlled Reactor (TCR).

Voltage Control by TSC and TCR Combination



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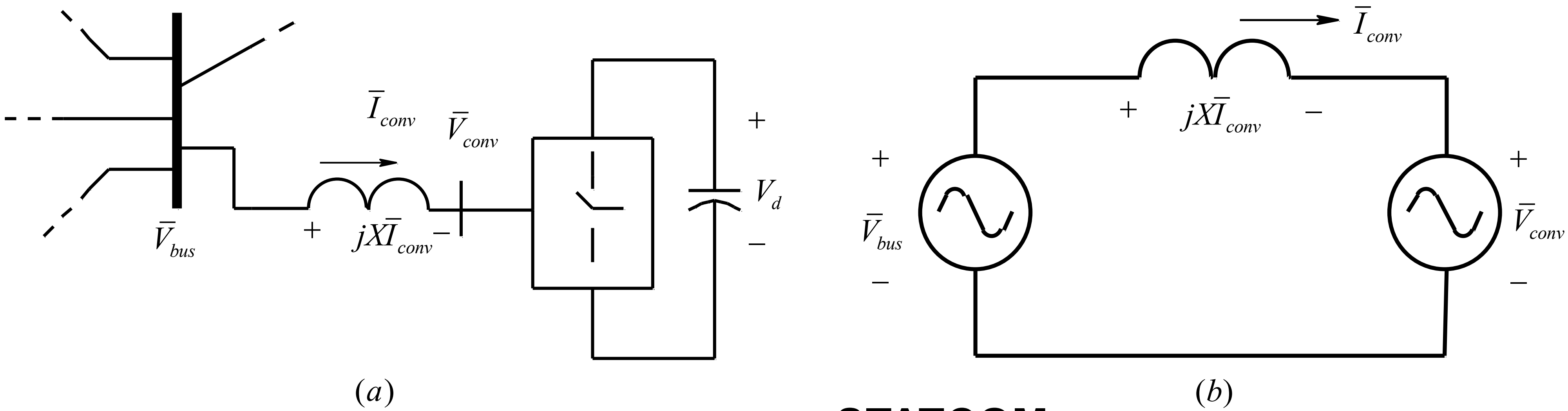
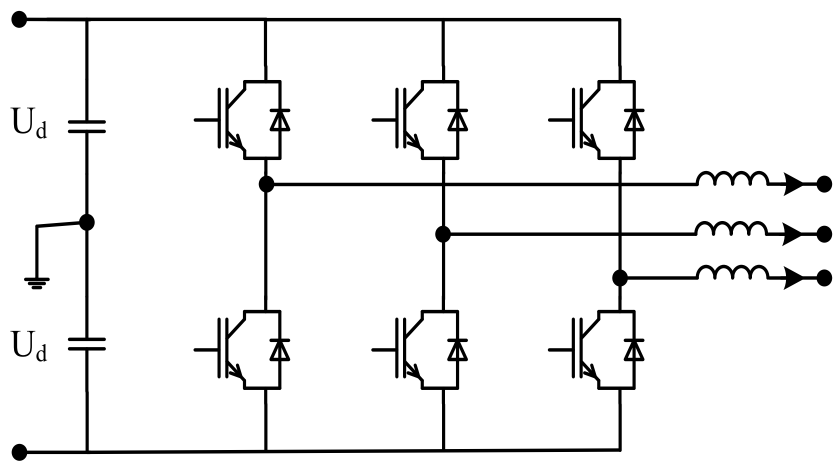
SVC Installation

STATCOM





STATCOM

STATic **COM**pensator, same characteristic as synchronous machine, but static

Converter giving fully controlled capacitive or inductive current

Capacitive current limited by U_d

STATCOM V-I Characteristic

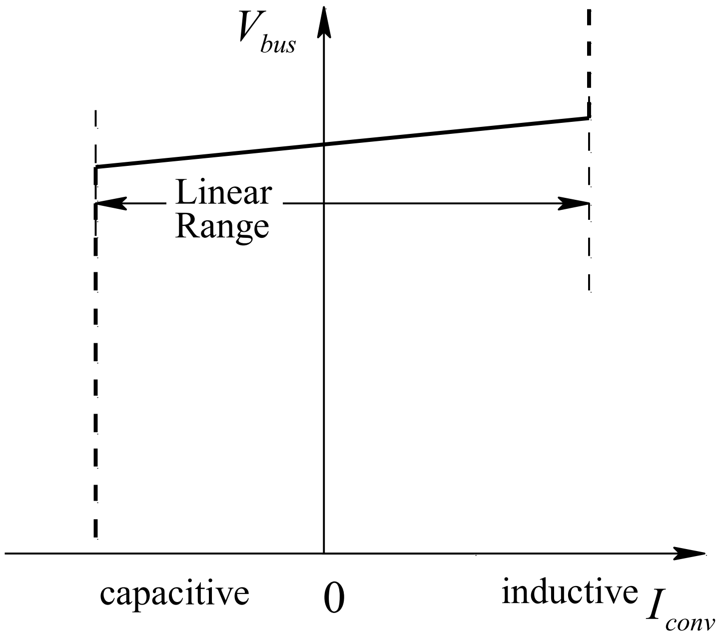
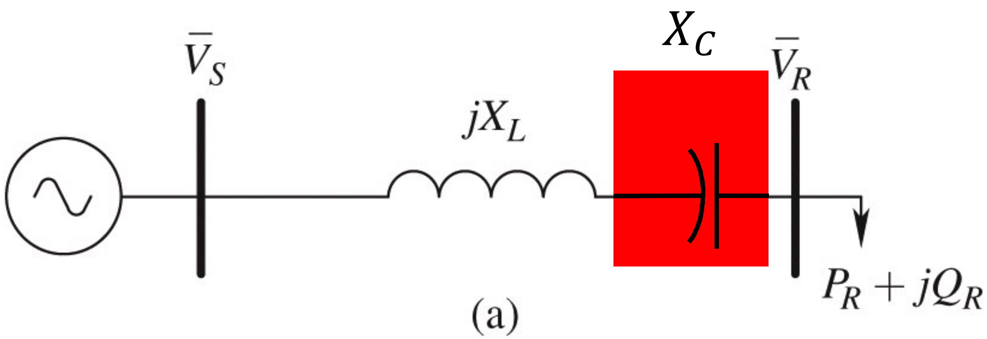


Fig. 10-11 STATCOM VI characteristic.

Series compensation

Reactive power consumption of line inductance is compensated



$\bar{Z} = R + j(X_L - X_C)$

Surge impedance: $Z_C = \sqrt{\frac{X_L - X_C}{B}}$

SIL increased

Figure 10.4

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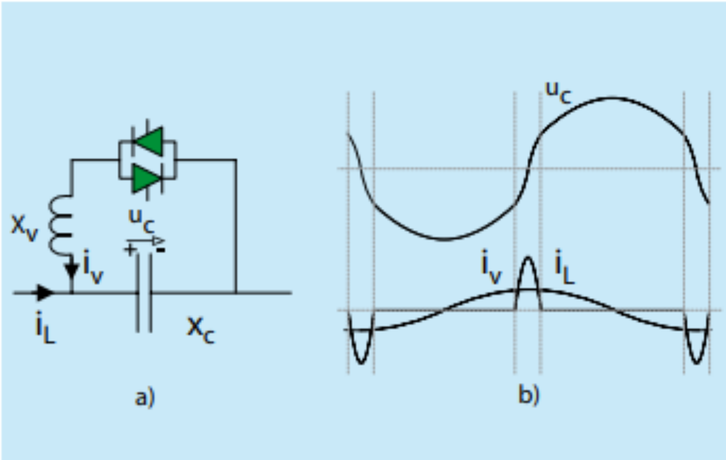
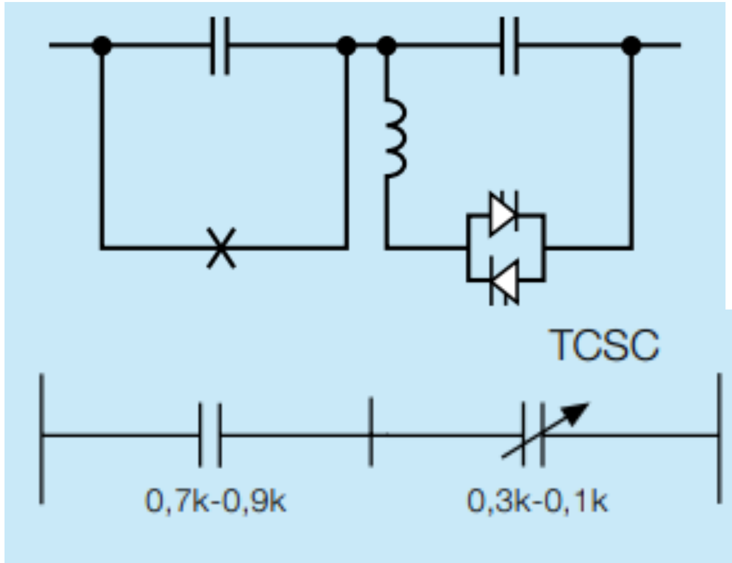
Thyristor-Controlled Series Capacitor (TCSC)





Controlled capacitance
Boosting of the voltage

$$V_c = \frac{I_c}{B} = \frac{I_c}{\omega C}$$

C appear smaller

Power flow control
Damping of oscillations

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TCSC Installation

Summary

- Load flow calculation principles
- Radial System Example
- Voltage Collapse at reactive power deficit
- Management of Voltage Stability
    - Synchronous Generators
    - Shunt Reactive Power Compensators, SVC
    - STATCOM
- Power flow control
    - Series compensation

Chapter 5 Power flow calculation

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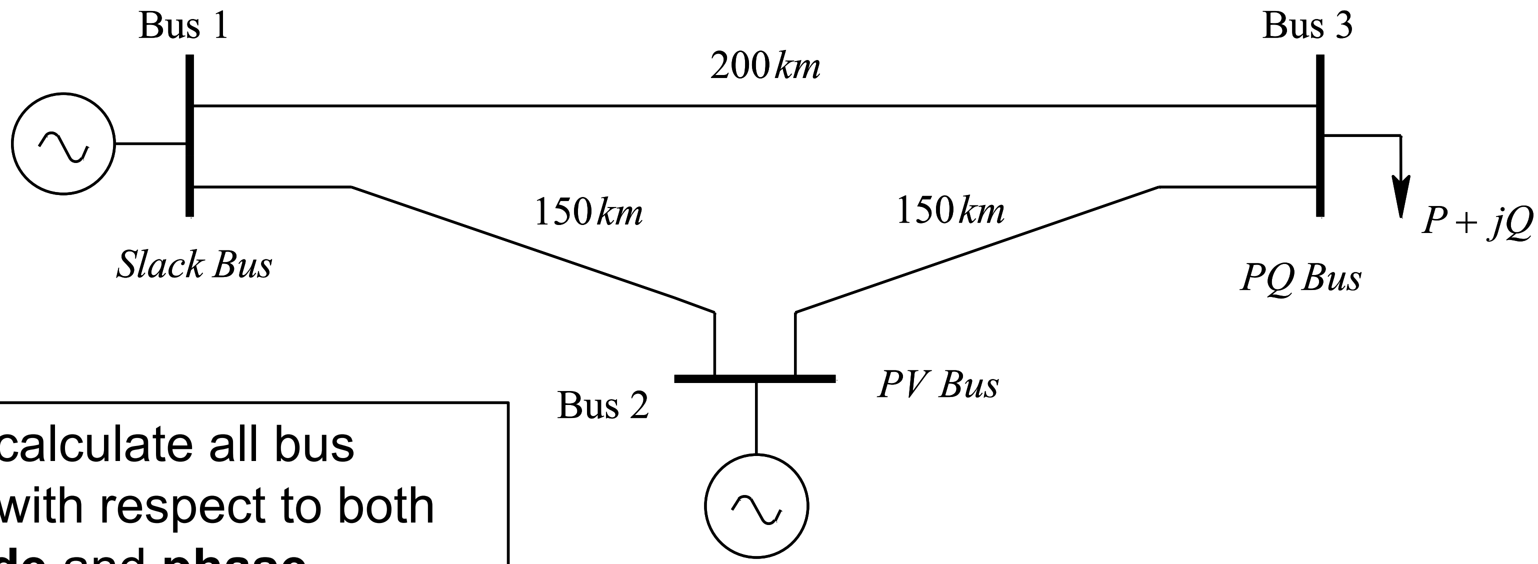
Power flow calculation for 3-Bus Example:

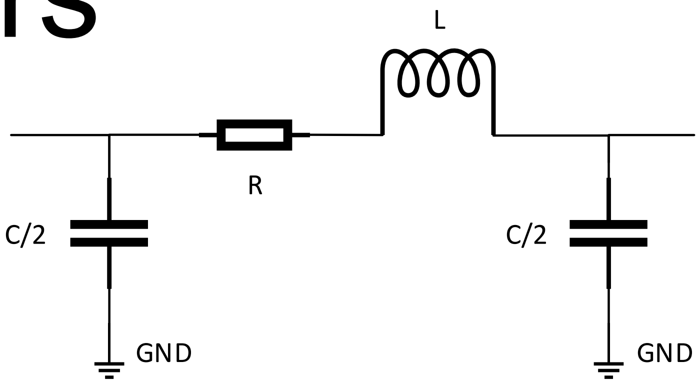


Goal: To calculate all bus voltages with respect to both **magnitude** and **phase**

Example 5-4

1. Bus1, slack bus: $V_1 = 1.0\angle 0° \; pu$ — Fully defined
2. Bus2, PV-bus: $V_2 = 1.05 \; pu, P_2^{sp} = 2.0 \; pu$ — Unknown: angle(V_2)
3. Bus3, PQ-bus: $P_3^{sp} = -5.0 \; pu, Q_3^{sp} = -1.0 \; pu$ — Unknown: magnitude(V_3) and angle(V_3)

Line parameters



Line parameters defined based on per km data for the given length

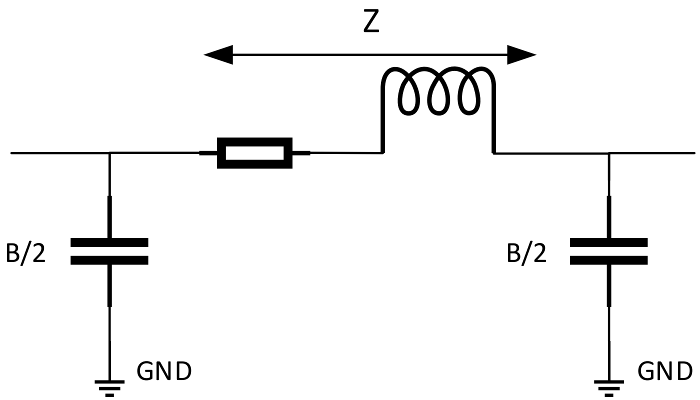
$$Impedance\text{: } \bar{Z} = R + jX\ [ohm]$$

$$\text{Admittance: } \bar{Y} = \frac{1}{\bar{Z}} = G + jB\ [mho]$$

$$Susceptance\text{: } B = \frac{1}{X_C} = \omega C\ [mho]$$

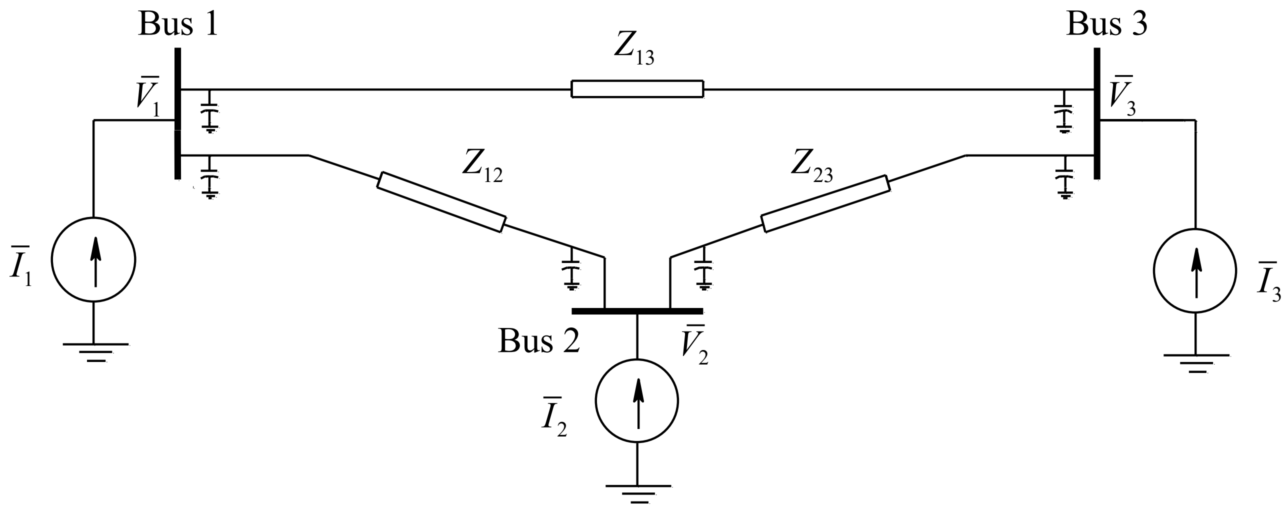
$$\bar{U} = \bar{Z} \cdot \bar{I}$$

$$\bar{I} = \bar{Y} \cdot \bar{U}$$



Building the Admittance Matrix

- $\bar{I}_k, \bar{V}_k$ is the current and voltage at bus (node) k
- $\bar{V}_m$ is the voltage in other end of line connected to node k



- Y_{kG} is the total admittance to ground at bus (node) k
- For each line, total B is split equally between the ends of the line

$$\bar{I}_k = \bar{V}_k Y_{kG} + \sum_{\substack{m \\ m \neq k}} \frac{\bar{V}_k - \bar{V}_m}{Z_{km}}$$

$$\bar{I}_k = \bar{V}_k \left(Y_{kG} + \sum_{\substack{m \\ m \neq k}} \frac{1}{Z_{km}} \right) - \sum_{\substack{m \\ m \neq k}} \frac{\bar{V}_m}{Z_{km}}$$

$$Y_{kG} = j \sum_{\substack{m \\ m \neq k}} \frac{B_{km}}{2}$$

Admittance Matrix

Symmetrical matrix with no of rows and columns equal to no of nodes

$$Y_{kk} = Y_{kG} + \sum_{\substack{m \\ m \neq k}} \frac{1}{Z_{km}}$$

$$\begin{bmatrix} \bar{I}_1 \\ \bar{I}_2 \\ .. \\ .. \\ .. \\ \bar{I}_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & .. & .. & .. & Y_{1n} \\ Y_{21} & Y_{22} & .. & .. & .. & Y_{2n} \\ .. & .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. & .. \\ Y_{n1} & Y_{n2} & .. & .. & .. & Y_{nn} \end{bmatrix} \begin{bmatrix} \bar{V}_1 \\ \bar{V}_2 \\ .. \\ .. \\ .. \\ \bar{V}_n \end{bmatrix}$$

$$Y_{km} = -\frac{1}{Z_{km}}$$

$$\bar{V}_m = V_m e^{j\theta_m}$$

$$\bar{I}_k = \sum_{m=1}^{n} Y_{km} \bar{V}_m$$

Basic Power Flow Equations

$$\bar{V}_m = V_m e^{j\theta_m}$$

Bus k conditions given by a row of the Y matrix

$$\bar{I}_k = \sum_{m=1}^{n} Y_{km} \bar{V}_m$$

$$P_k + jQ_k = \bar{V}_k \bar{I}_k^*$$

Nonlinear system equations

$$P_R = \frac{V_S V_R}{X} \sin\delta \qquad Q_R = \frac{V_S V_R \cos\delta}{X} - \frac{V_R^2}{X}$$

MATLAB function fsolve for solving nonlinear system of equations

fsolve

Solve system of nonlinear equations

Nonlinear system solver

Solves a problem specified by

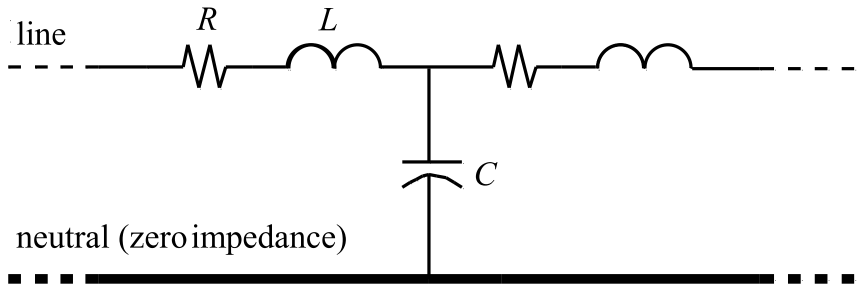
$$F(x) = 0$$

for x, where $F(x)$ is a function that returns a vector value.

x is a vector or a matrix; see Matrix Arguments.

Transmission lines in 345 kV example system

From Table 4-1:
series reactance = $0.376\ \Omega/km$,
series resistance = $0.037\ \Omega/km$,
shunt susceptance $B(=\omega C) = 4.5\,\mu\mho/km$



$$Z_{12} = (0.037 + j0.376) \cdot Length_{(1-2)}\ ohm$$

$$B_{12} = 4.5 \cdot Length_{(1-2)}\ \mu ohm$$

Line	Series Impedance Z in Ω (pu)	Total Susceptance B in $\mu\mho$ (pu)
1-2	$Z_{12} = (5.55 + j56.4)\Omega = (0.0047 + j0.0474)$ pu	$B_{Total} = 675\mu\mho = (0.8034)$ pu
1-3	$Z_{13} = (7.40 + j75.2)\Omega = (0.0062 + j0.0632)$ pu	$B_{Total} = 900\mu\mho = (1.0712)$ pu
2-3	$Z_{23} = (5.55 + j56.4)\Omega = (0.0047 + j0.0474)$ pu	$B_{Total} = 675\mu\mho = (0.8034)$ pu

$$Z_{base} = \frac{U_{ph}^2}{S_{ph}} = \frac{U_{LL}^2}{S_{3ph}} = \frac{345kV^2}{100MVA} = 1190\ ohm \qquad Y_{base} = 1/Z_{base}$$

Fsolve equation setup

```
function [ dpq,pq,vk,ik ] = PFsolve( x,y,vref,pqref )
%PFsolve Summary of this function goes here
%   x: variables for solution
%   y: admittance matrix
%   vref: voltage references for slack-bus or PV-busses.
%       Complex value if angle is defined for slack-bus.
%   pqref: p-references for PV-busses and p+jq for PQ-busses.

% Node voltages
vk(1,1)=vref(1);
vk(2,1)=vref(2)*exp(1j*x(1));
vk(3,1)=x(2)*exp(1j*x(3));

% Injected currents into nodes
ik=y*vk;

% Injected power into nodes
pq=vk.*conj(ik);

% Equations to solve for zero through variables in x
dpq(1)=real(pqref(2)-pq(2));
dpq(2)=real(pqref(3)-pq(3));
dpq(3)=imag(pqref(3)-pq(3));
end
```

$V_1 = 1.0\angle 0°\ pu$ → vk(1,1)=vref(1);

$V_2 = 1.05\ pu$ → vk(2,1)=vref(2)*exp(1j*x(1));

x(1): Unknown: angle(V_2)

x(2): Unknown: magnitude(V_3)

x(3): Unknown angle(V_3)

$P_2 = P_2^{sp}$ → dpq(1)

$P_3 = P_3^{sp}$ → dpq(2)

$Q_3 = Q_3^{sp}$ → dpq(3)

Power Flow Results in the Example Power System

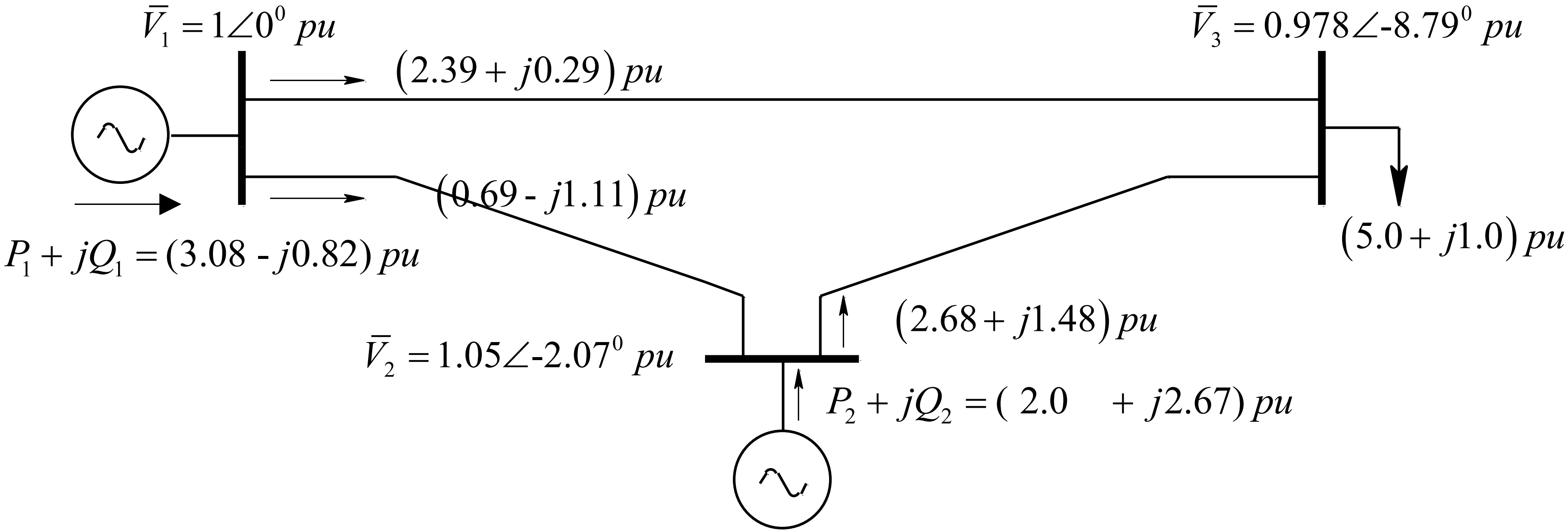


Fig. 5-4 Power-Flow results of Example 5-4.

```
x=fsolve(@PFsolve,x0,[],y,vref,pqref)
```

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