ECE 522 - Power Systems Analysis II
Spring 2021

Voltage Stability

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Instructor: Kai Sun

THE UNIVERSITY OF TENNESSEE KNOXVILLE

Content

- Basic concepts
  - Voltage collapse, Saddle-node and limit-induced bifurcations, P-V and V-Q curves
- Voltage Stability Analysis (VSA)
  - Dynamic and Static Analyses, Modal analysis and Continuation Power-Flow
- Causes and prevention of voltage instability
- References:

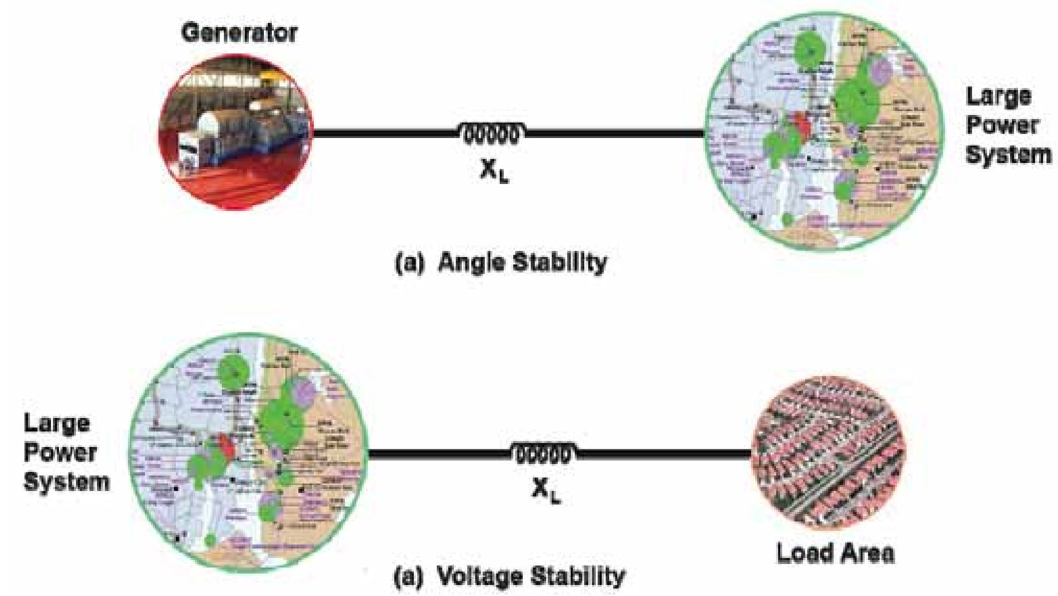
1. Chapter 14 of Kundur's book
2. Carson W. Taylor, "Power System Voltage Stability" McGraw Hil, 1994
3. "Survey of the voltage collapse phenomenon", NERC Interconnection Dynamics Task Force Report, Aug. 1991
4. EPRI Tutorial's Chapter 6
5. "Voltage Stability Assessment: Concepts, Practices and Tools", IEEE-PES Power Systems Stability Subcommittee Special Publication, Aug. 2002
6. V. Ajjarapu, C. Christy, "The continuation power flow: a tool for steady state voltage stability analysis", *IEEE Trans Power Syst.*, vol. 7, no. 1, Feb, 1992

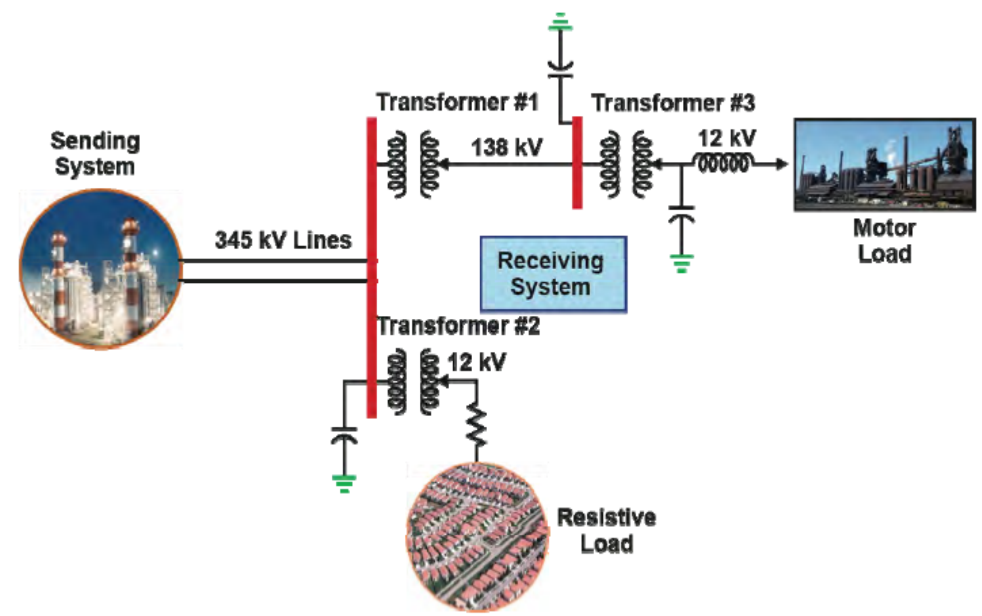
Voltage Stability

- Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all buses in the system under normal conditions and after being subjected to a disturbance.
- A system enters a state of voltage instability (or voltage collapse) when a disturbance, e.g. an increase in load demand, or change in the system condition, causes a progressive and uncontrollable decline in voltage
- The main factor causing instability is the inability of the power system to meet the demand for reactive power
- Voltage stability problems normally occur in heavily stressed (loaded) areas.

Voltage Stability vs. Rotor Angle stability

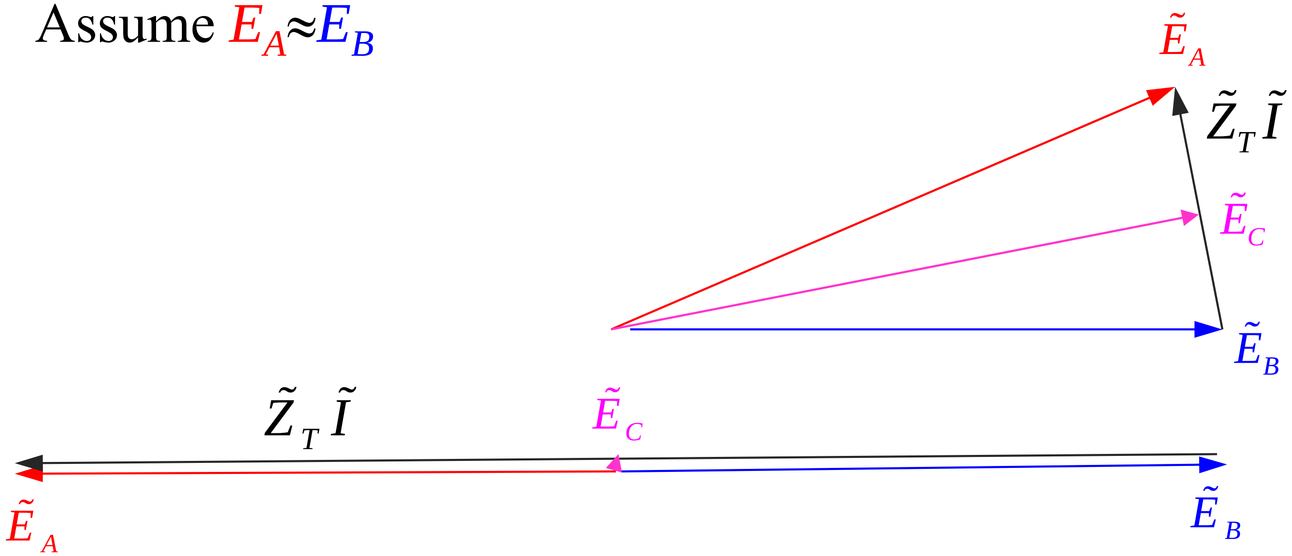
- Rotor angle stability is stability with generators while voltage stability is basically stability with loads
  - **Rotor angle stability** is often concerned with remote power plants connected to a large system over long transmission lines. If voltage collapse is observed at a point (e.g. the center of oscillation) in a transmission system remote from loads, it is, in nature, rotor angle instability.
  - **Voltage stability** is concerned with load areas and load characteristics. In a large interconnected system, voltage collapse of a load area is possible without loss of synchronism of any generators.
- Use of term "transient voltage instability", which often refers to FIDVR (fault-induced delayed voltage recovery), has recently been discouraged by IEEE Power & Energy Society to avoid a confusion with transient instability.





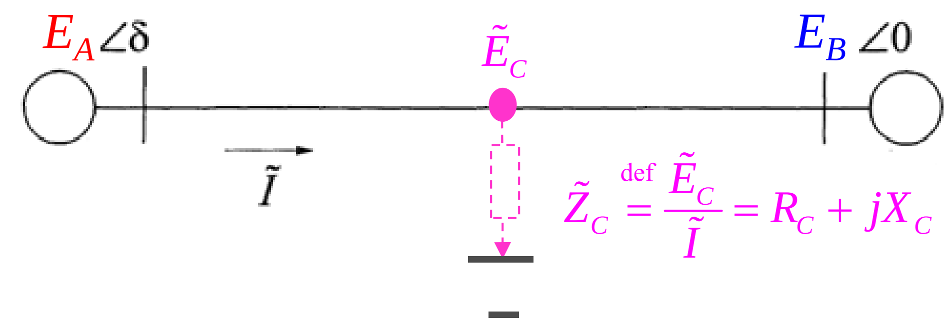
Voltage at the Electrical Center

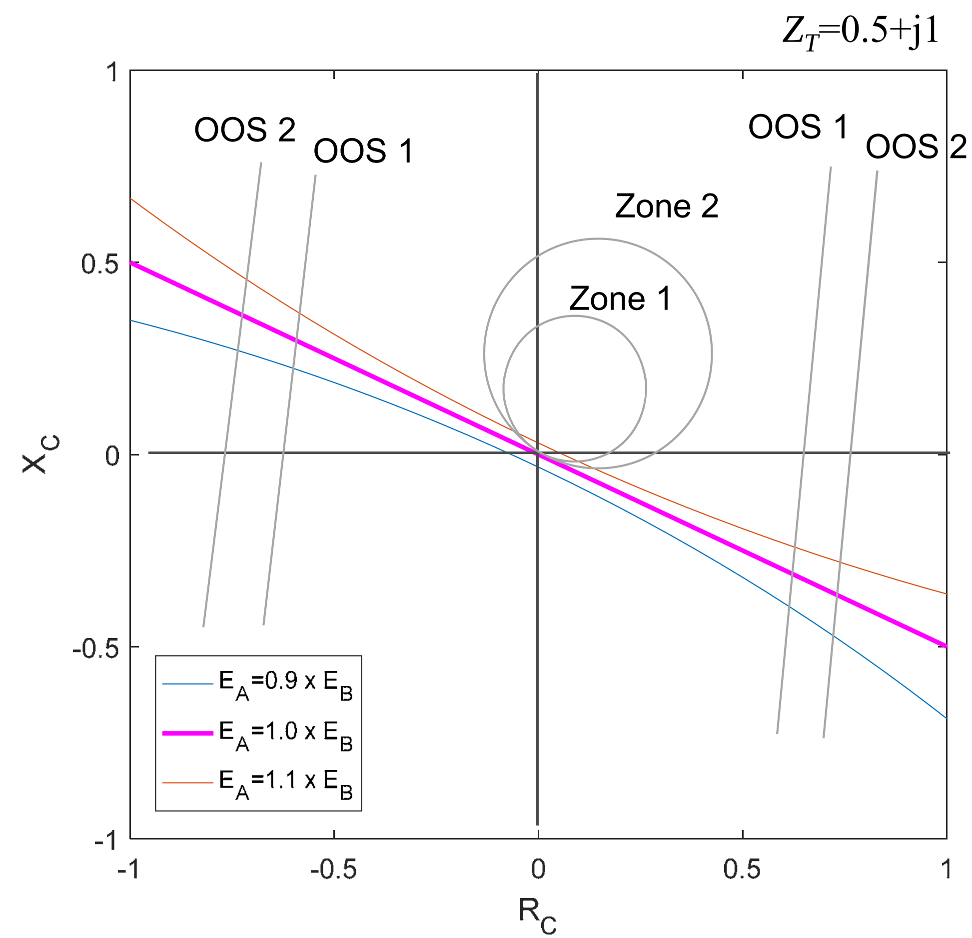
Assume $E_A \approx E_B$



δ (deg)	30	45	60	90	120	180
E_C/E_A (pu)	0.97	0.92	0.87	0.71	0.50	0.00

When a power system is experiencing a large oscillation, large voltage variations are observed at the buses near the oscillation center of the mode.





Out of step protection is trigger if the time required to cross OOS2 and OOS1 exceeds a threshold (See Kundur's 13.5.3)

Simple radial system

How does V_R change as P_R increases?

$$V_R = Z_{LD} I \qquad P_R = V_R I \cos\phi$$

$$\tilde{I} = \frac{\tilde{E}_S}{\tilde{Z}_{LN} + \tilde{Z}_{LD}}$$

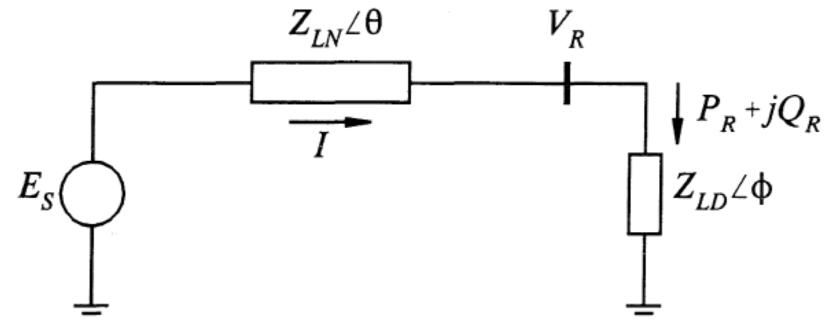
$$I = \frac{E_S}{\sqrt{(Z_{LN}\cos\theta + Z_{LD}\cos\phi)^2 + (Z_{LN}\sin\theta + Z_{LD}\sin\phi)^2}}$$

$$I = \frac{1}{\sqrt{F}}\frac{E_S}{Z_{LN}}$$

where $F = 1 + \left(\frac{Z_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z_{LD}}{Z_{LN}}\right)\cos(\theta - \phi)$

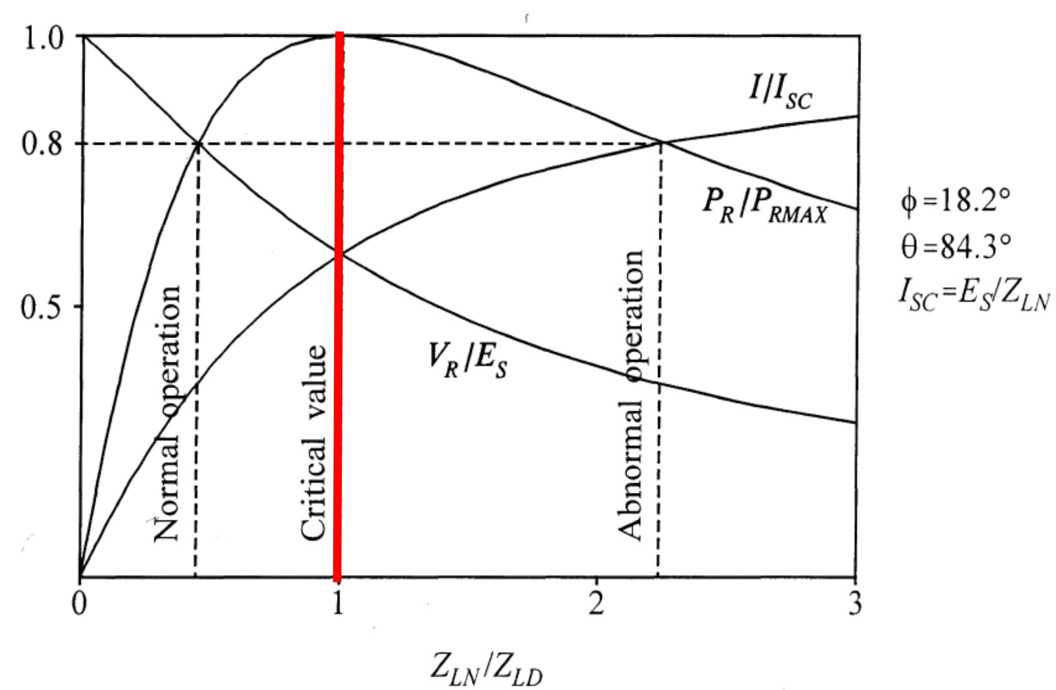
$$V_R = Z_{LD} I = \frac{1}{\sqrt{F}}\frac{Z_{LD}}{Z_{LN}} E_S$$

$$P_R = V_R I \cos\phi = \frac{Z_{LD}}{F}\left(\frac{E_S}{Z_{LN}}\right)^2 \cos\phi$$



(a) Schematic diagram

Z_{LD} decreases (assume constant Z_{LN})

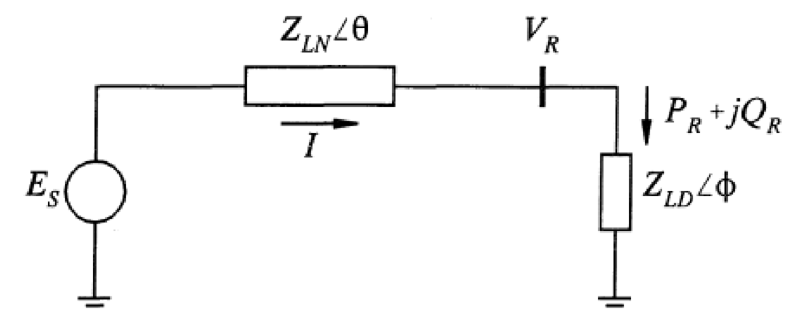


(b) Receiving end voltage, current and power as a function of load demand

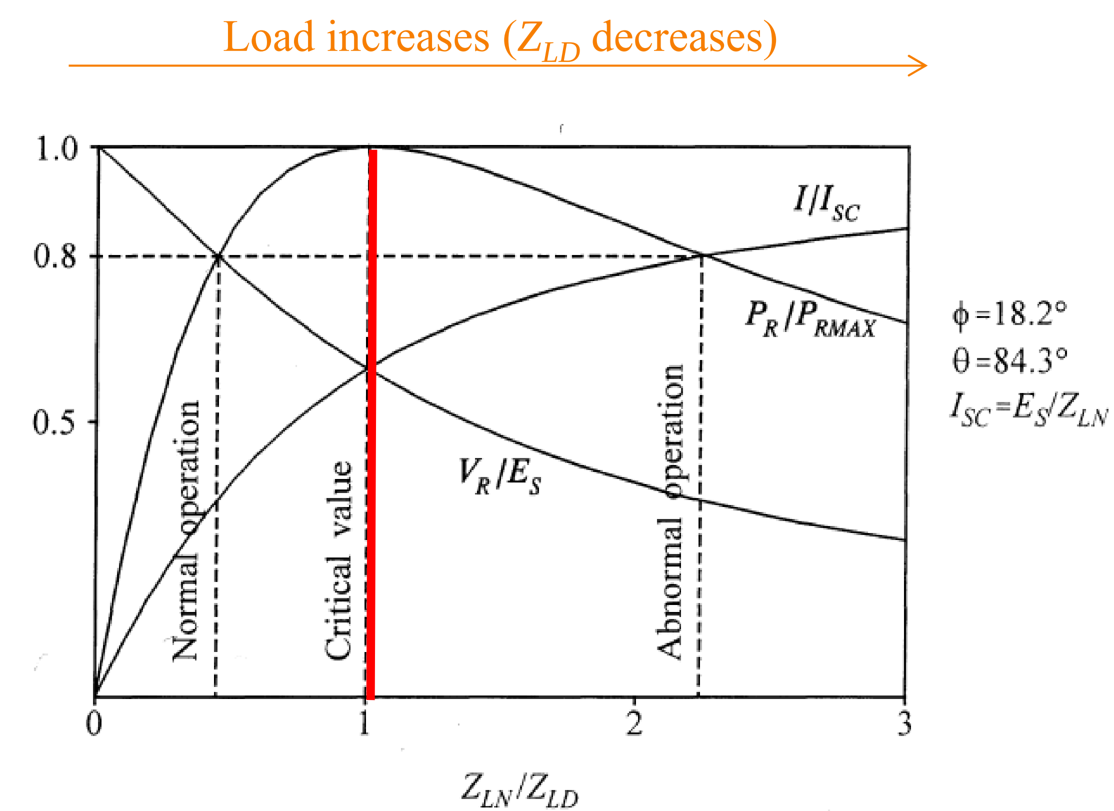
Figure 14.1 Characteristics of a simple radial system

How does voltage collapse happen?

- Voltage stability depends on the dynamics or controls with loads.
- Voltage collapse is caused when the control of a load cannot maintain the load at a low voltage and has an effect to reduce the voltage.
- Under normal conditions, $Z_{LD} >> Z_{LN}$ and an increase in active load P_R usually comes with a decrease in Z_{LD}
- However, when $Z_{LD} < Z_{LN}$ (heavily loaded), P_R decreases with a decrease in Z_{LD}, so a control that maintains the load by decreasing Z_{LD} becomes unstable
- A typical example is a load supplied through an ULTC transformer:
  - When the tap-changer tries to raise LV side load voltage (absorbing more Mvar from the HV side),
  - this control has an effect of reducing Z_{LD} and in turn further lowers V_R seen from the HV side.
  - If the HV side does not have enough reactive power to raise V_R, the control by ULTC will not stop and a progressive reduction of voltage can be caused.



(a) Schematic diagram



(b) Receiving end voltage, current and power as a function of load demand

Figure 14.1 Characteristics of a simple radial system

Load supplied through an ULTC transformer

$$V_R = Z'_{LD} I = \frac{1}{\sqrt{F'}} \frac{Z'_{LD}}{Z_{LN}} E_S$$

$$F' = 1 + \left(\frac{Z'_{LD}}{Z_{LN}}\right)^2 + 2\left(\frac{Z'_{LD}}{Z_{LN}}\right)\cos(\theta - \phi') \approx 1 + a^4 \frac{Z_{LD}^{\ 2}}{Z_{LN}^{\ 2}}$$

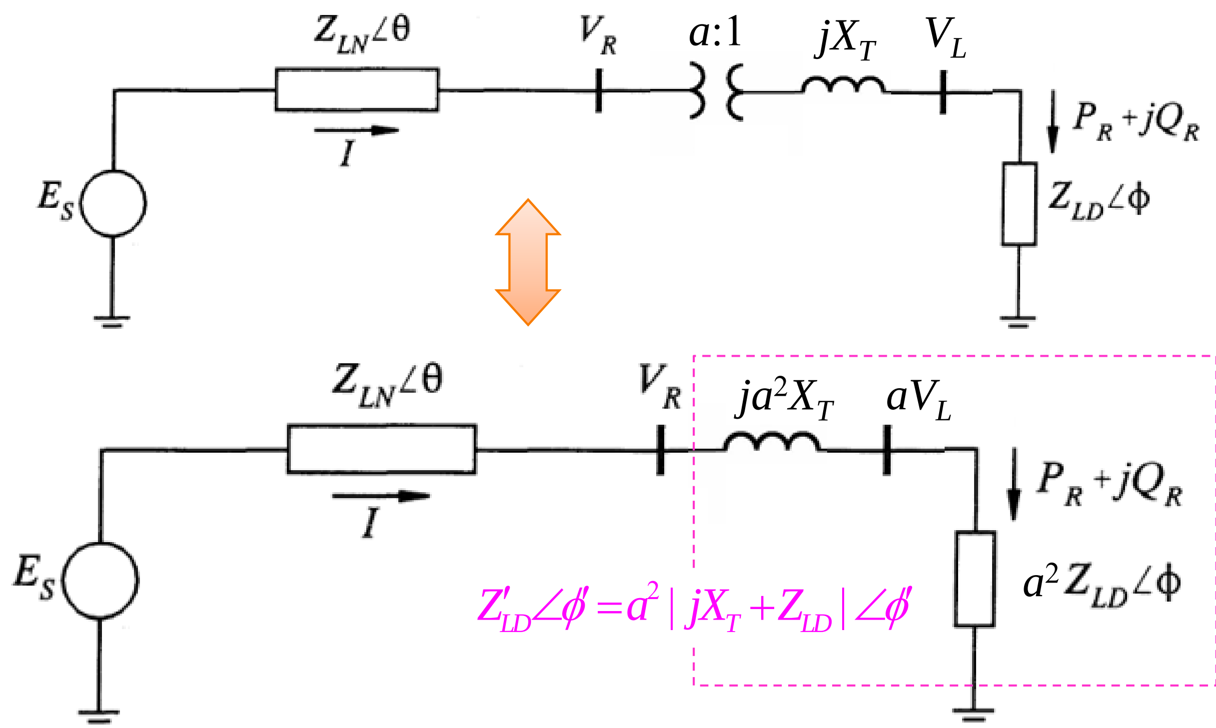
If $\theta \approx 90^o$, $\phi' \approx 0^o$, $X_T << Z_{LD}$

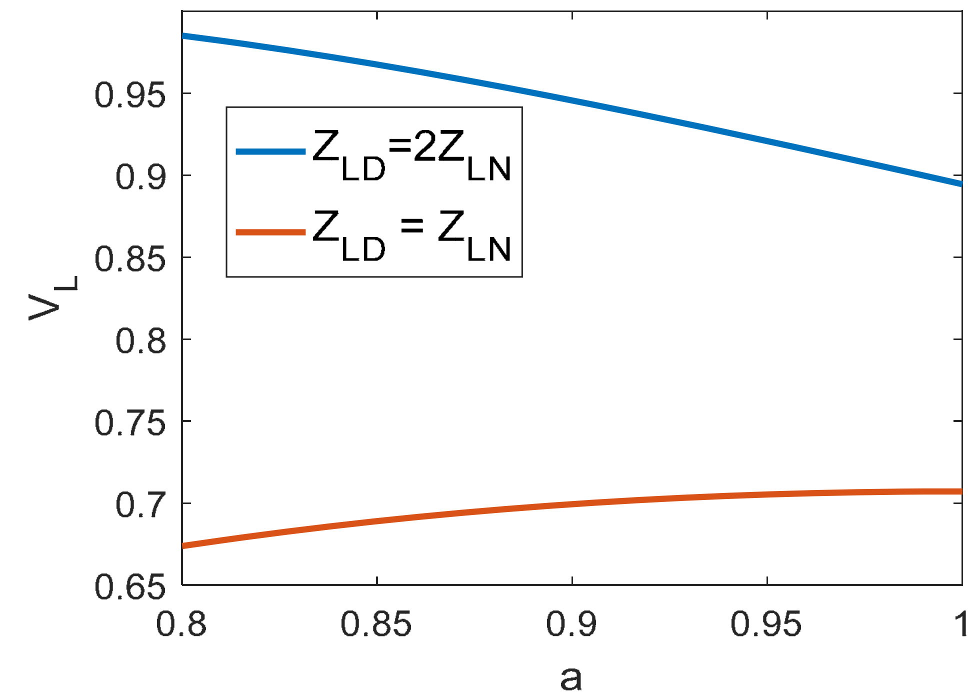
$$V_L = \frac{Z_{LD}}{Z_{LD} + jX_T} \cdot \frac{1}{a} V_R$$

$$= \frac{Z_{LD}}{Z_{LD} + jX_T} \cdot \frac{1}{a} \frac{1}{\sqrt{F'}} \frac{Z'_{LD}}{Z_{LN}} E_S \approx \frac{Z_{LD}}{Z_{LN}} \frac{E_S}{\sqrt{\frac{1}{a^2} + a^2 \frac{Z_{LD}^{\ 2}}{Z_{LN}^{\ 2}}}}$$

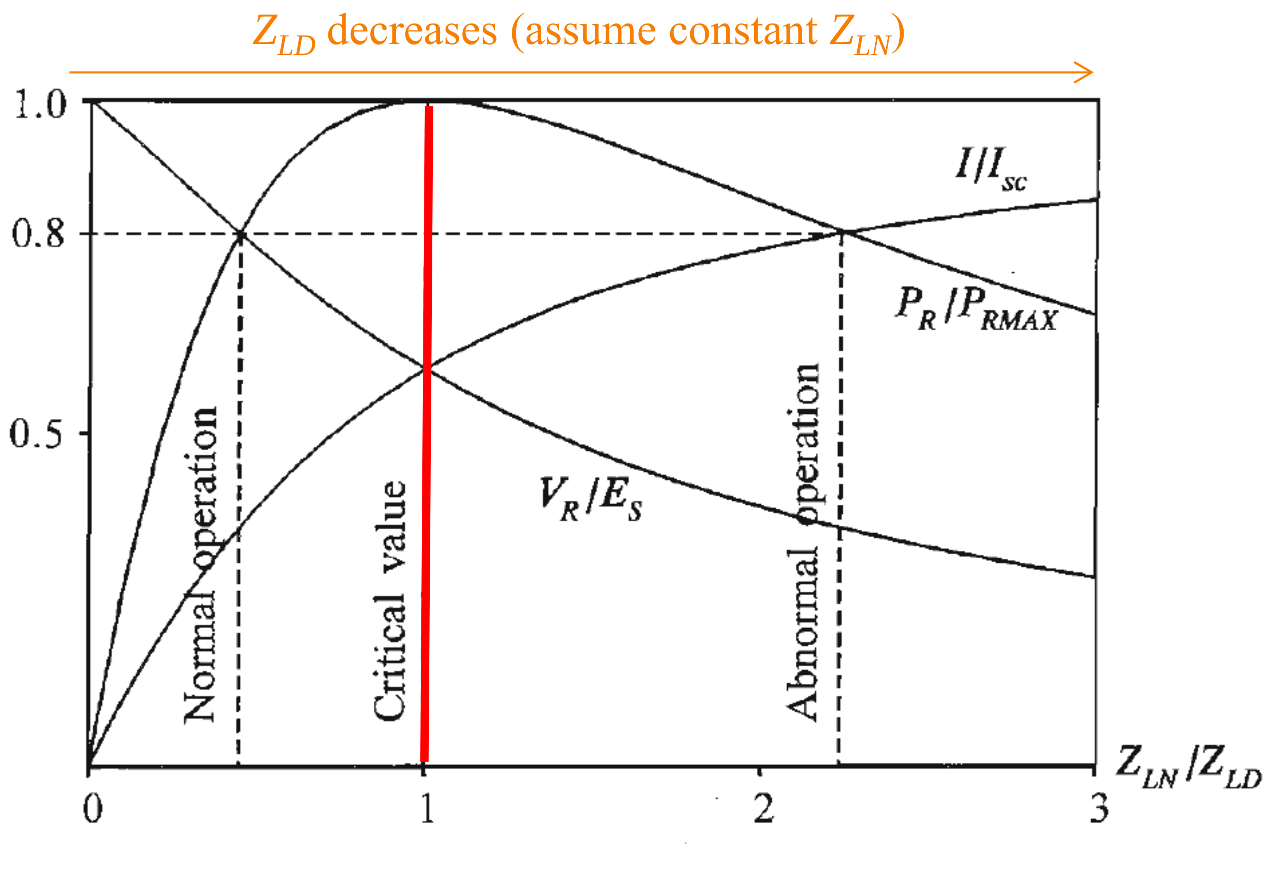
Tap↑ → a↓ → Z'_{LD}↓ → V_R↓ →

$V_L \sim V_R/a$ ↑ (light load) or ↓ (heavy load)

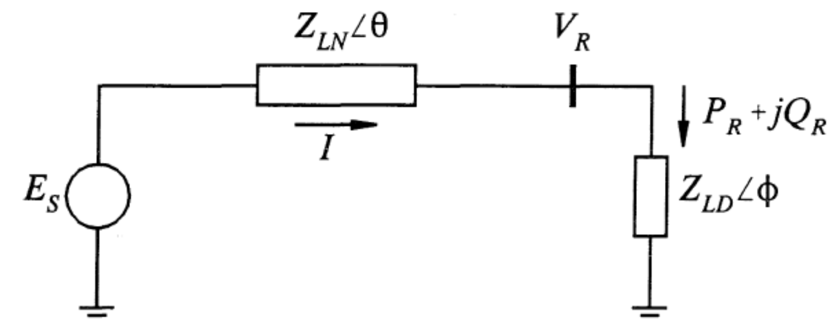




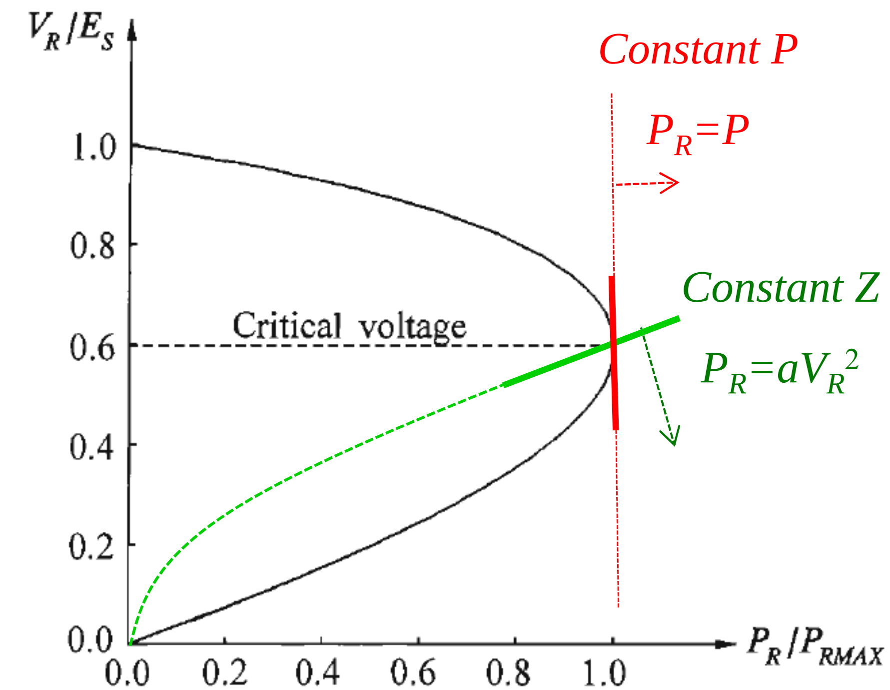
P-V Curve (distance to voltage collapse)



($I_{sc}=E_S/Z_{LN}$; $\cos\phi=0.95$ lag; $\tan\theta=10.0$)



(a) Schematic diagram



- The voltage collapse at the critical point (also called the "nose" or "knee" point) is referred to as "saddle-point bifurcation"
- Does voltage collapse always occur when the system passes the critical point?

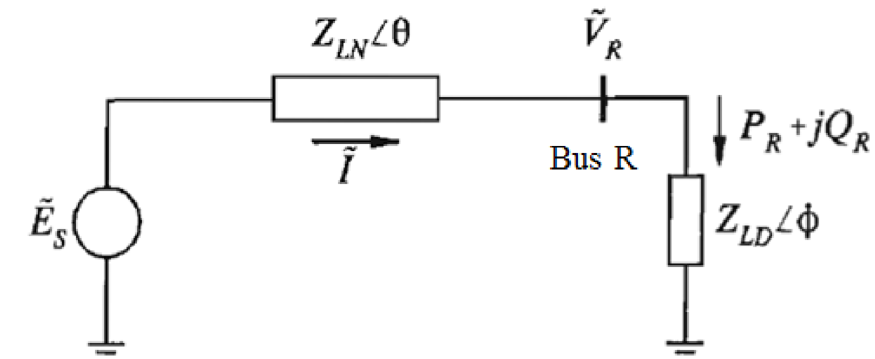
Example: P-V Curve with ZIP Load

Assume E_S=1.0pu, $Z_{LN}\angle\theta$=j0.5pu, cosϕ=0.97.

1. Draw the P_R-V_R curve at bus R and find P_R and V_R at the critical point
2. If the real power load is modeled as a ZIP load

$$P_R=P_0(V_R^2+0.9V_R+4.0) \qquad (1)$$

where P_0 depends on the load level. Estimate the lowest $|V_R|$ before voltage collapse happens.



Solution: Voltage collapse happens when load curve (1) does not intersect P-V curve (2).

$$V_R=\frac{1}{\sqrt{F}}\frac{Z_{LD}}{Z_{LN}}E_S \qquad P_R=\frac{Z_{LD}}{F}\left(\frac{E_S}{Z_{LN}}\right)^2\cos\phi \qquad (2)$$

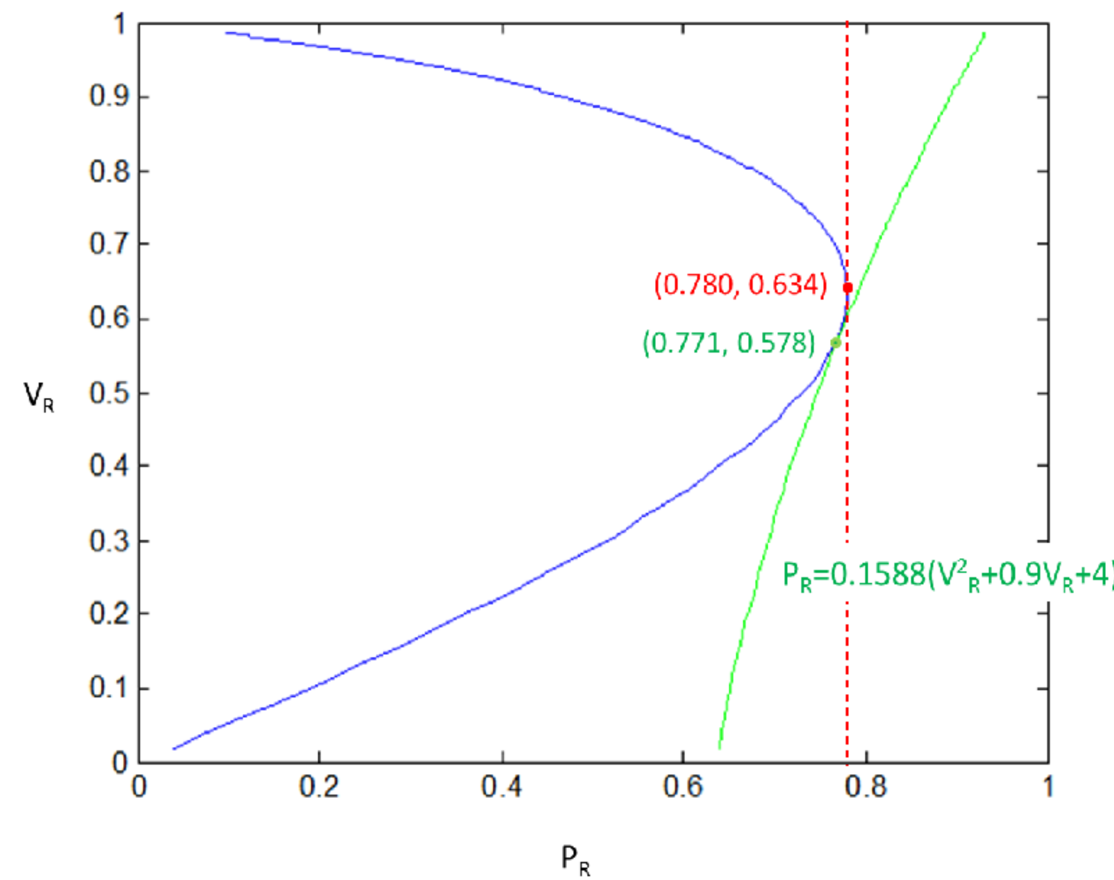
$$F=1+\left(\frac{Z_{LD}}{Z_{LN}}\right)^2+2\left(\frac{Z_{LD}}{Z_{LN}}\right)\cos(\theta-\phi)$$

1. At the nose point, Z_{LD}=Z_{LN}: $\quad F=2+2\cos(\theta-\phi)=2.486$

$$V_R=0.634 \text{ pu} \qquad P_R=0.780 \text{ pu}$$

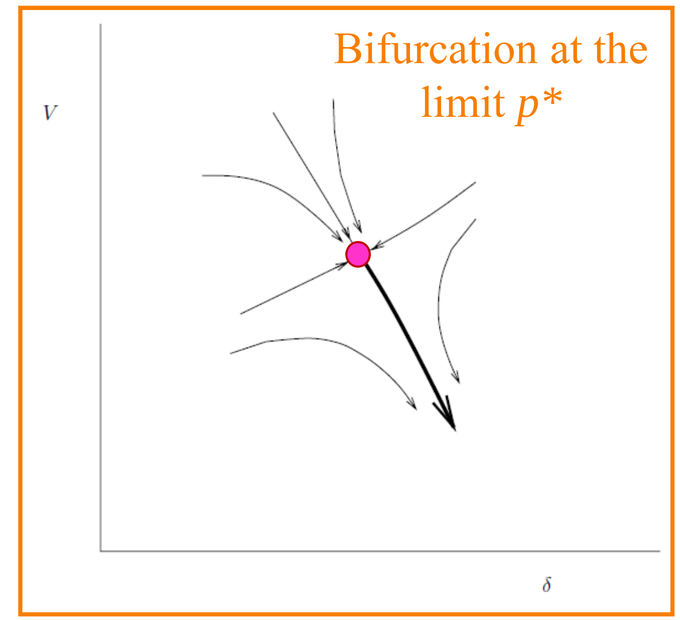
2. Find the tangent point of the P-V curve and the load curve, i.e. when (1) and (2) have a single solution of P_0.

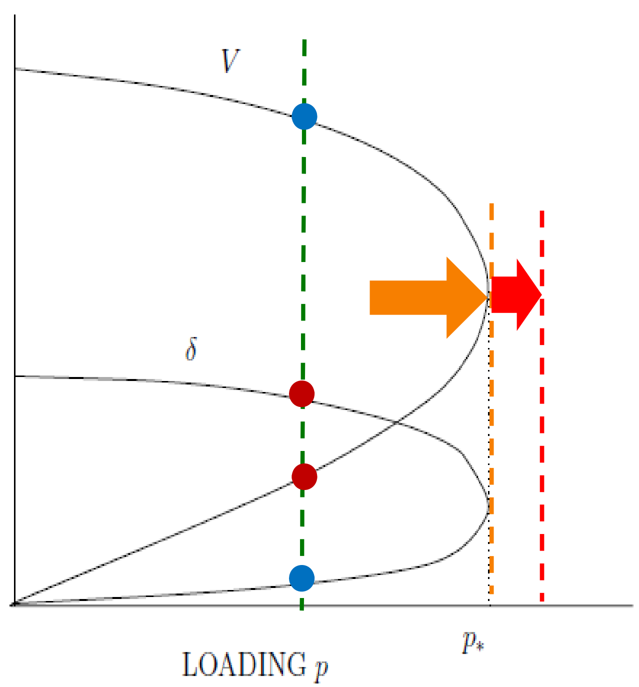
The tangent point is (0.771, 0.578), not the critical point, so the lowest voltage is 0. 771 pu (<0.780).

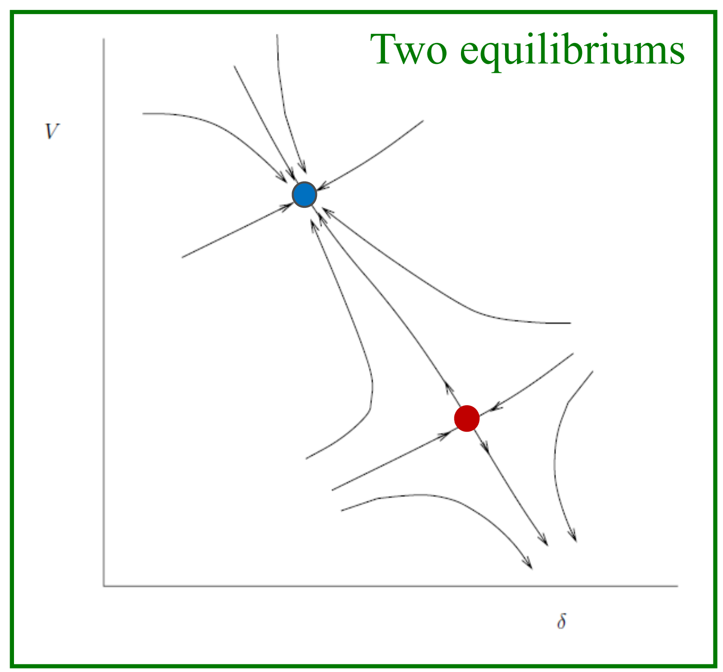


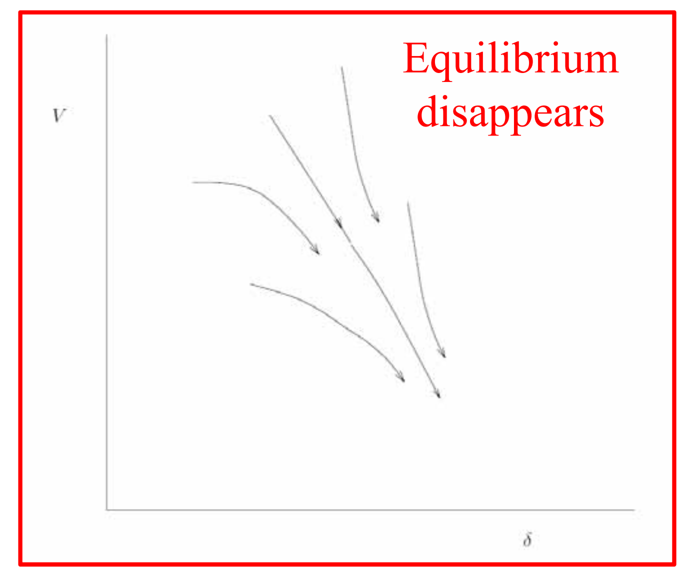
Saddle-node bifurcation

- A saddle-node bifurcation is the disappearance of a system's equilibrium as parameters change slowly (system dynamics can be ignored).
- This is an inherently nonlinear phenomenon and cannot occur in a linear model.
- In theory, voltage instability happens when the SEP and UEP merge or the SEP disappears. In reality, when they are too close, transient instability can happen even under a small disturbance. Thus, realistic voltage instability often involve transient instability.









Normalized P-V curves (various power factors)

- Normally, only the operating points above the critical points represent satisfactory operating conditions

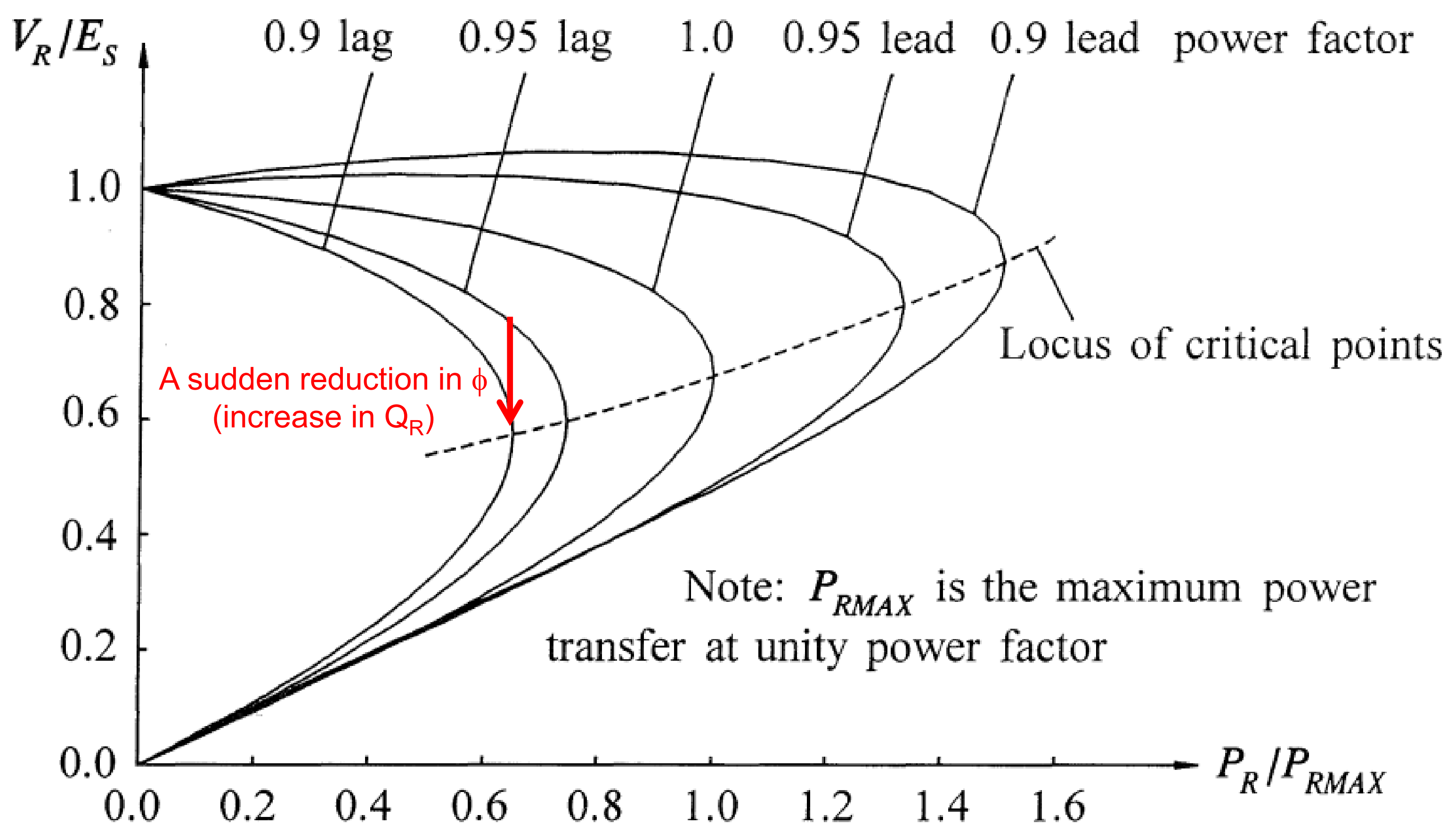
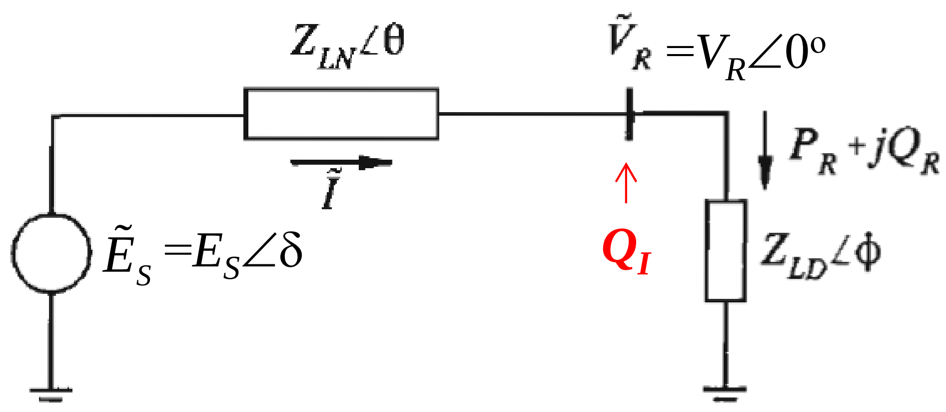


Figure 14.2 The V_R-P_R characteristics of the system of Figure 14.1

V-Q Curve (effectiveness of voltage control)

How does V_R change with Q_I injected by a var source?



$$Z_{LN} \approx jX_{LN}$$

$$P_R + j(Q_R - Q_I) = \tilde{V}_R \tilde{I}^* = \tilde{V}_R \left(\frac{\tilde{E}_S - \tilde{V}_R}{jX_{LN}} \right)^*$$

$$P_R = E_S V_R \sin\delta / X_{LN}$$

$$Q_R - Q_I = \frac{E_S V_R \cos\delta - V_R^2}{X_{LN}}$$

$$\sin\delta = \frac{P_R X_{LN}}{E_S V_R}$$

$$\cos\delta = \frac{(Q_R - Q_I) X_{LN} + V_R^2}{E_S V_R}$$

Eliminate δ by

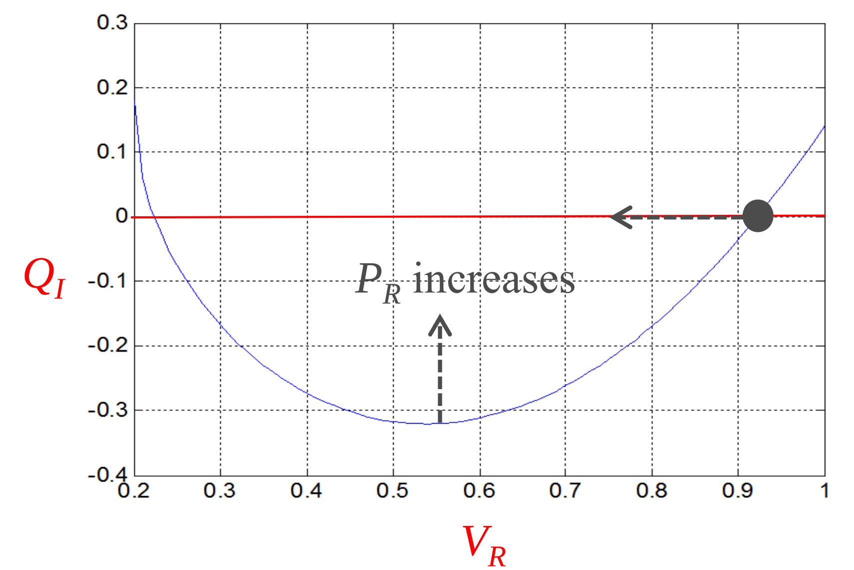
$\cos^2\delta + \sin^2\delta = 1$

$$Q_I = Q_R + \frac{V_R^2}{X_{LN}} - \sqrt{\frac{E_S^2 V_R^2}{X_{LN}^2} - P_R^2}$$

$$\boxed{Q_I = P_R \tan\phi + \frac{V_R^2}{X_{LN}} - \sqrt{\frac{E_S^2 V_R^2}{X_{LN}^2} - P_R^2}}$$

V-Q curve for specific P_R and ϕ

(one loading condition)



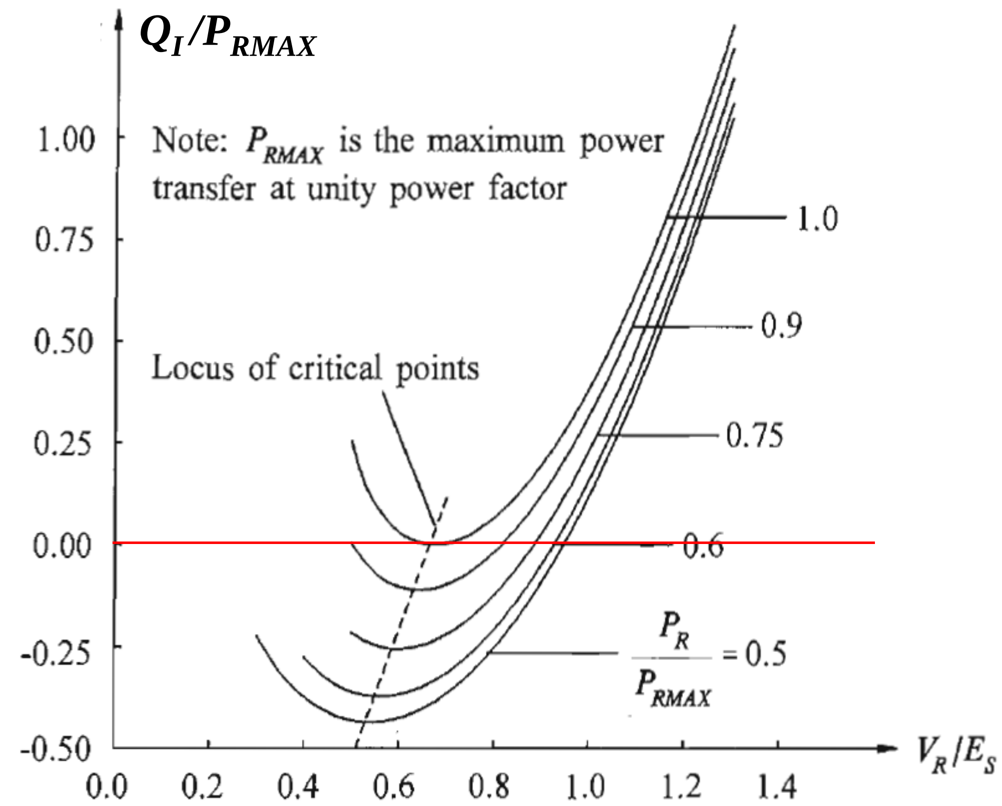
Normalized V-Q curves (P_R varies)

- A V-Q curve shows sensitivity and variation of a bus voltage with respect to Q injected at the bus. It indicates the Q_I required in order to maintain the bus voltage at desired value V_R

- A V-Q curve is generated by applying a fictitious var source, e.g. synchronous condenser, at the test bus, i.e. converting the bus to a PV bus with open var limits, so it can be used to examine needs for var compensation

- **Voltage is stable only when $dQ_I/dV_R>0$** since all var control devices are designed to operate when an increase in Q is accompanied by an increase in V

- Voltage stability limit is reached when $dQ_I/dV_R=0$



Example on a 39-bus system

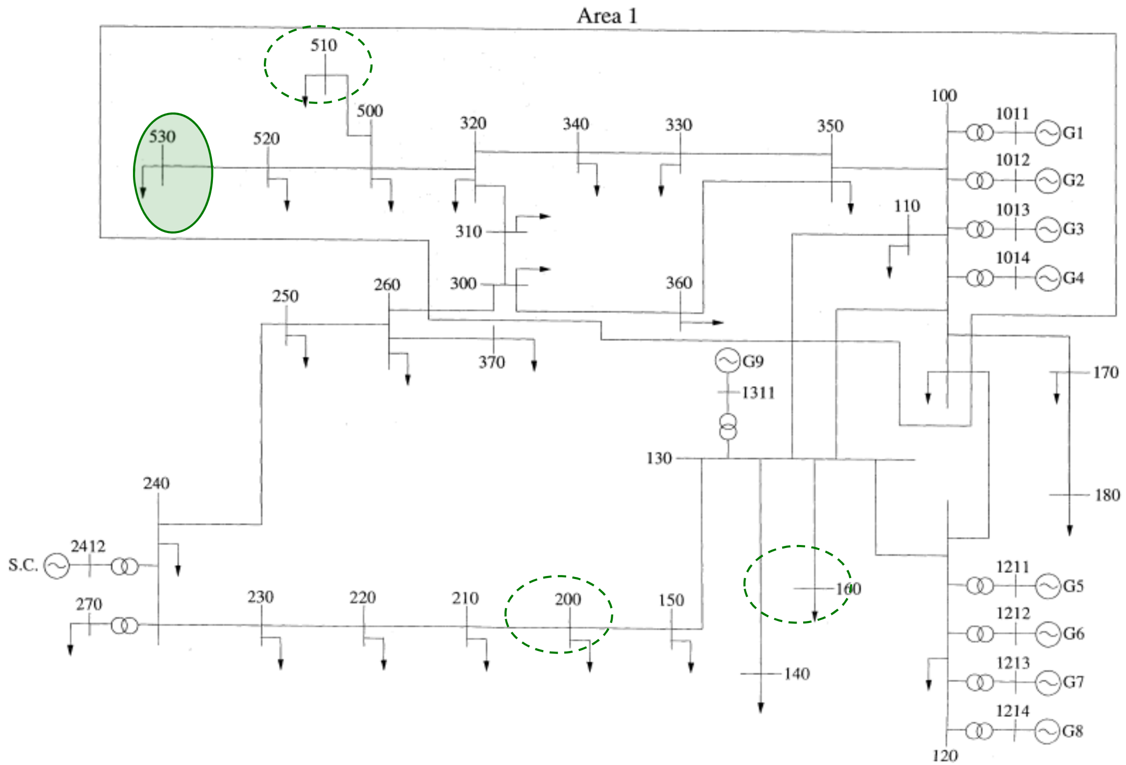
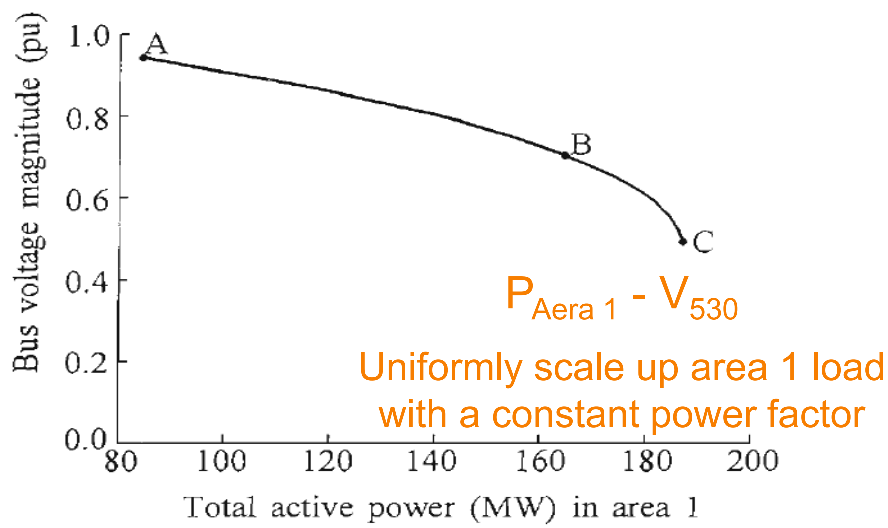
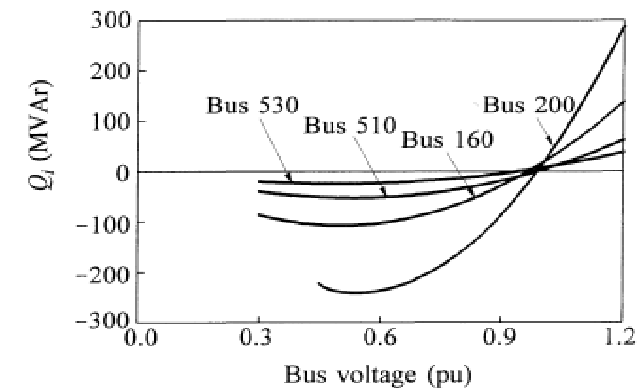


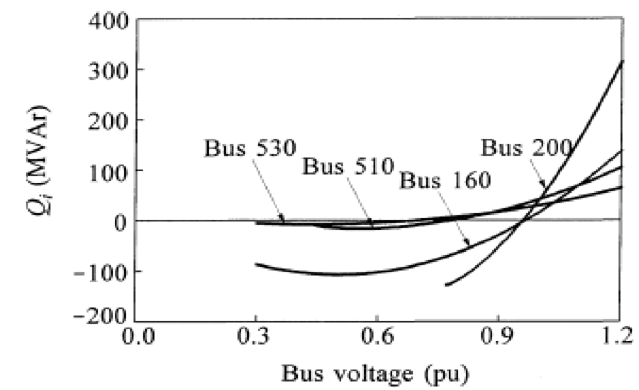
Figure 14.3 A 39-bus, 10-machine test system





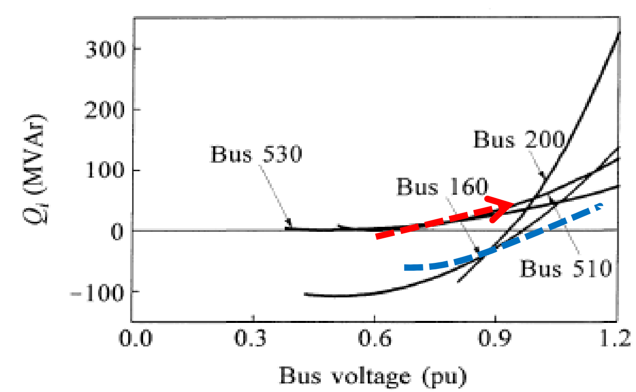
A

(a) Base case, with a load of 84.5 MW, 53.3 MVAr in area



B

(b) Operating condition near the critical operating point, with a load of 164.4 MW, 103.7 MVAr in area 1



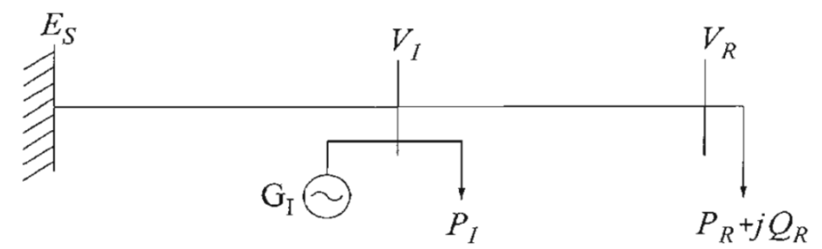
C

(c) Operating condition at the critical operating point, with a load of 186.9 MW, 117.9 MVAr in area 1

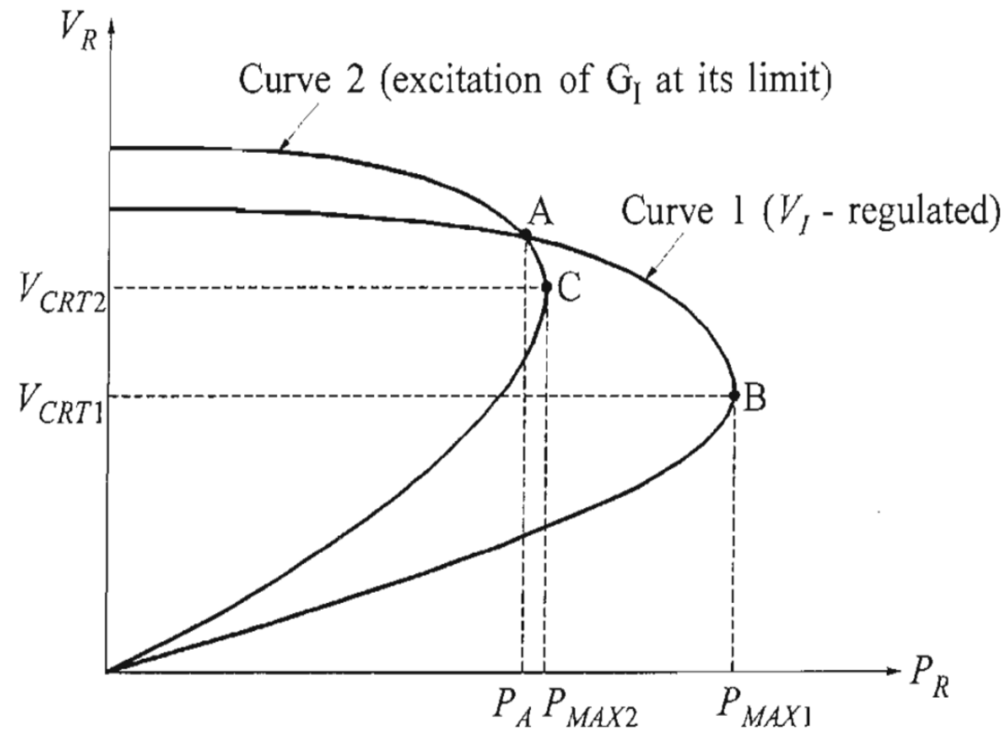
- Probable remedial actions before C is reached
  - Inject Q at Bus 530 to increase V
  - Reduce load near Bus 530

Influence of Generation Characteristics

- Actions of generator AVRs provide the primary sources of voltage support
- Under normal conditions, generator terminal voltages (e.g. V_I) are maintained constant
- During conditions of low/high voltages, the var output of a generator may reach its limit. Consequently, the terminal voltage V_I is not longer maintained constant
- Then, with constant field current, the point of constant voltage is now E_q of the generator behind its synchronous reactance $X_S \approx X_d$. That increases the network reactance significantly to further aggravate the voltage collapse condition
- It is important to maintain voltage control capabilities of generators
- The degree of voltage stability cannot be judged based only on how close the bus voltage is to the normal voltage level.
- Voltage collapse due to the reactive power/current limit being reached is referred to as "limit-induced bifurcation".



(a) Schematic diagram



(b) The V_R-P_R characteristics

Influence of Reactive Compensator Characteristics: Kundur's Example 14.1

- A reactive compensator is designed to increase compensation (ΔQ) in order to increase voltage (ΔV)
- However, for a passive compensator, Q_I is voltage-dependent, e.g. $Q_I=V_2^2/X_C$ with a shunt capacitor:
  - At Point A (low compensation): voltage is **stable**
    - The slope ΔQ/ΔV of the system is greater than that of the shunt capacitor
    - With the increase of compensation, A→ A', V_2 is increased, and then compensation can stop.
  - At Point B (high compensation): voltage is **unstable**
    - The slope ΔQ/ΔV of the system is smaller than that of the shunt capacitor
    - With the increase of compensation, B→ B', V_2 is decreased, so compensation cannot stop until the critical point.

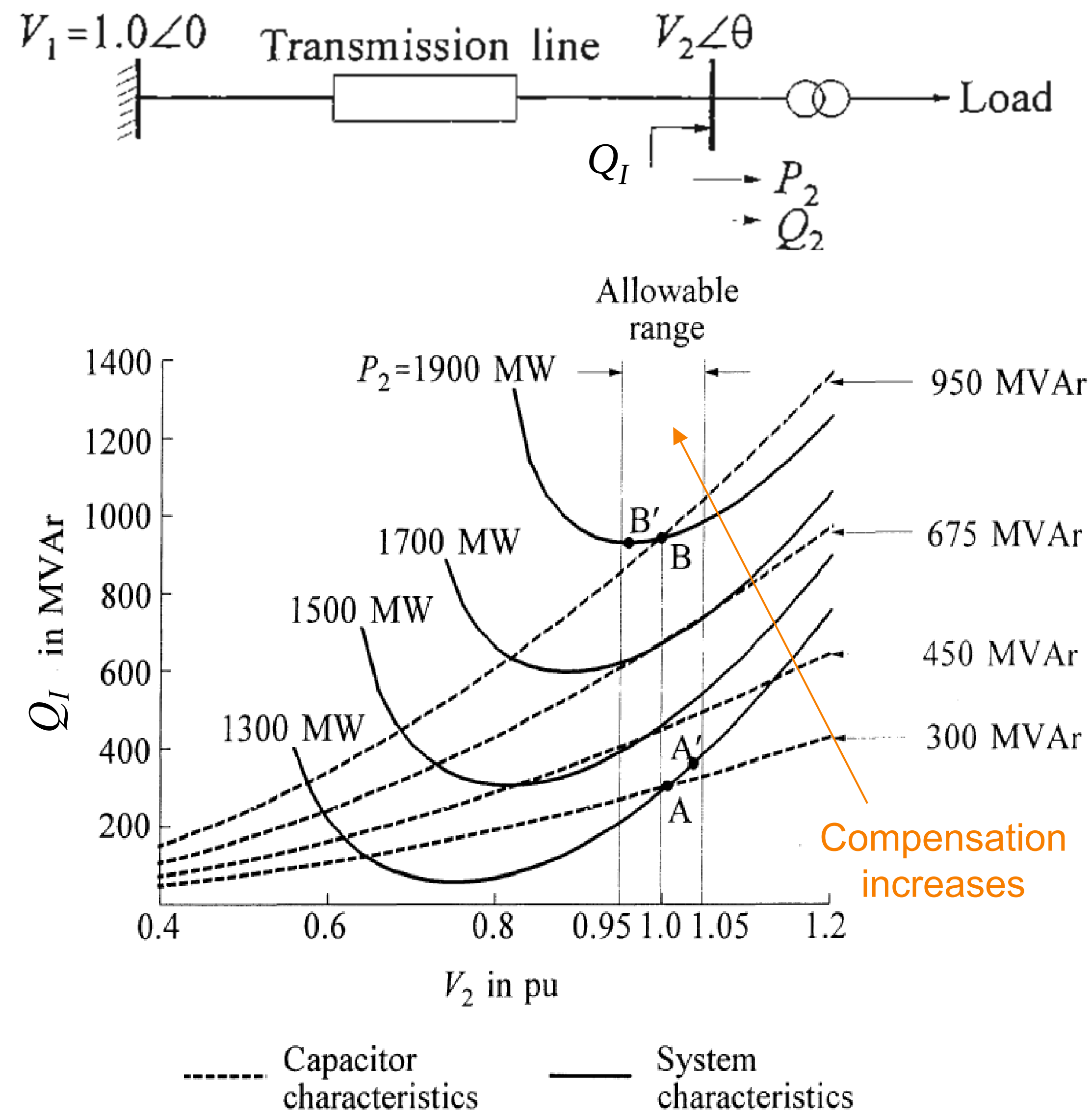


Figure E14.2 System and shunt capacitor steady-state *Q-V* characteristics; capacitor MVAr shown at rated voltage

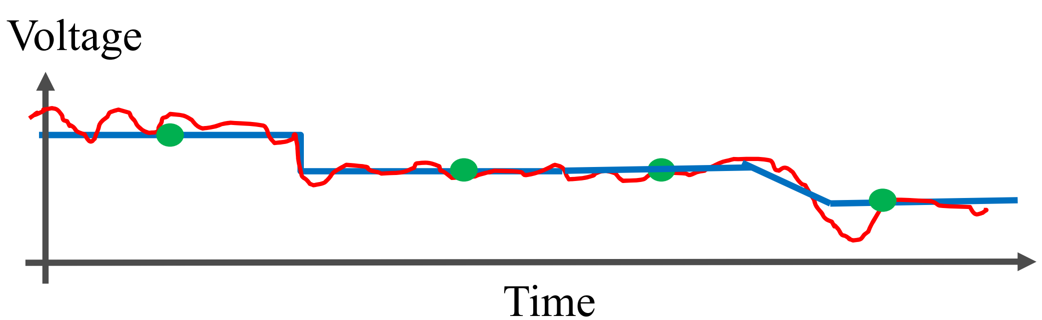
VSA (Voltage Stability/Security Analysis/Assessment)

Objectives:

1. Knowing the distance to voltage instability
   - Operating/planning stability margin may be measured in terms of quantities such as, load level, MW flow through a critical interface, and var reserve.
   - The most appropriate measure for any given situation depends on the specific system and the intended use of the margin
   - Consideration must be given to possible contingencies, e.g. line outages, loss of a generator or a var source, etc.
2. Understanding the mechanism:
   - How and why does instability occur?
   - What key factors contribute to voltage instability?
   - What are the voltage-weak areas?
   - What measures are most effective in improving voltage stability?

Methods:

1. **Dynamic Analysis** considers DEs with time handled implicitly: e.g. enhanced time-domain simulations extended for a longer period (several to tens of minutes)
2. **Quasi-Dynamic Analysis** considers AEs with time handled explicitly, e.g. quasi-dynamic fast time-domain simulations in which fast dynamics are ignored and equations are all algebraic and solved every time when variables associated with slow dynamics are changed
3. **Static (Steady-state) Analysis** considers only AEs (e.g. power flow equations) at selected times



Static Analysis: Sensitivity and Modal Analysis using the Power Flow Model

- **Sensitivity analysis:** Linearize the power flow model for a specific operating condition (i.e. a powerflow solution) and give the sensitivity between power and voltage changes from elements of the Jacobian matrix.

$$P_i = V_i \sum_{j=1}^{n} \left(G_{ij} V_j \cos\theta_{ij} + B_{ij} V_j \sin\theta_{ij} \right)$$

$$Q_i = V_i \sum_{j=1}^{n} \left(G_{ij} V_j \sin\theta_{ij} - B_{ij} V_j \cos\theta_{ij} \right)$$

$$\Rightarrow \begin{bmatrix} \Delta \mathbf{P} \\ \Delta \mathbf{Q} \end{bmatrix} = \begin{bmatrix} \mathbf{J}_{P\theta} & \mathbf{J}_{PV} \\ \mathbf{J}_{Q\theta} & \mathbf{J}_{QV} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta} \\ \Delta \mathbf{V} \end{bmatrix}$$

where $\Delta \mathbf{P}$ = incremental change in bus real power
$\Delta \mathbf{Q}$ = incremental change in bus reactive power injection
$\Delta \boldsymbol{\theta}$ = incremental change in bus voltage angle
$\Delta \mathbf{V}$ = incremental change in bus voltage magnitude

Let $\Delta\mathbf{P}$=0, $\Delta \mathbf{Q} = \mathbf{J}_R \Delta \mathbf{V}$ $\quad \boxed{\mathbf{J}_R = [\mathbf{J}_{QV} - \mathbf{J}_{Q\theta} \mathbf{J}_{P\theta}^{-1} \mathbf{J}_{PV}]} \quad \boxed{\Delta \mathbf{V} = \mathbf{J}_R^{-1} \Delta \mathbf{Q}}$

$\mathbf{J}_R$ is the reduced Jacobian matrix of the system and represents the linearized relationship between incremental changes in bus voltage magnitudes and bus reactive power injections

- **Modal analysis:** Identify voltage stability characteristics of the system by eigenvalues and eigenvectors of $\mathbf{J}_R$

$$\mathbf{J}_R = \boldsymbol{\xi} \boldsymbol{\Lambda} \boldsymbol{\eta}$$

$$\mathbf{J}_R^{-1} = \boldsymbol{\xi} \boldsymbol{\Lambda}^{-1} \boldsymbol{\eta}$$

where $\boldsymbol{\xi}$ = right eigenvector matrix of $\mathbf{J}_R$
$\boldsymbol{\eta}$ = left eigenvector matrix of $\mathbf{J}_R$
$\boldsymbol{\Lambda}$ = diagonal eigenvalue matrix of $\mathbf{J}_R$

Similar to modal analysis on $\mathbf{A}$
$\boldsymbol{\Phi}$ = right eigenvector
$\boldsymbol{\Psi}$ = left eigenvector
$\boldsymbol{\Lambda}$ = diagonal eigenvalue matrix

$$\dot{z}_i = \lambda_i z_i$$

$$\Delta \mathbf{V} = \boldsymbol{\xi} \boldsymbol{\Lambda}^{-1} \boldsymbol{\eta} \Delta \mathbf{Q} = \sum_i \frac{\boldsymbol{\xi}_i \boldsymbol{\eta}_i}{\lambda_i} \Delta \mathbf{Q} \Rightarrow \mathbf{v} = \boldsymbol{\Lambda}^{-1} \mathbf{q} \qquad v_i = \frac{1}{\lambda_i} q_i$$

where $\mathbf{v} = \boldsymbol{\eta} \Delta \mathbf{V}$ is the vector of modal voltage variations (note: $\boldsymbol{\eta} = \boldsymbol{\xi}^{-1}$)
$\mathbf{q} = \boldsymbol{\eta} \Delta \mathbf{Q}$ is the vector of modal reactive power variations

$$\mathbf{v} = \boldsymbol{\eta}\Delta\mathbf{V} = \boldsymbol{\Lambda}^{-1}\boldsymbol{\eta}\Delta\mathbf{Q} = \boldsymbol{\Lambda}^{-1}\mathbf{q}$$

$$v_i = \frac{1}{\lambda_i} q_i$$

- Each λ_i defines a mode of voltage stability and its value determines the proximity to instability
  - If $\lambda_i>0$, the i^{th} modal voltage and the i^{th} modal reactive power variations are along the same direction, indicating that the system is voltage stable
  - If $\lambda_i<0$, the i^{th} modal voltage is unstable
  - If $\lambda_i=0$, the i^{th} modal voltage collapses (i.e. reaching the critical point of the P-V and V-Q curves) since any small change in that modal reactive power causes infinite change in the modal voltage

For a 3-bus system:

$$\begin{bmatrix} 1/\lambda_1 & & \\ & 1/\lambda_2 & \\ & & 1/\lambda_3 \end{bmatrix} \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} \\ \eta_{21} & \eta_{22} & \eta_{23} \\ \eta_{31} & \eta_{32} & \eta_{33} \end{bmatrix} \begin{bmatrix} \Delta Q_1 \\ \Delta Q_2 \\ \Delta Q_3 \end{bmatrix} = \begin{bmatrix} \eta_{11} & \eta_{12} & \eta_{13} \\ \eta_{21} & \eta_{22} & \eta_{23} \\ \eta_{31} & \eta_{32} & \eta_{33} \end{bmatrix} \begin{bmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix}$$

For mode 1:

$$\frac{1}{\lambda_1}(\eta_{11}\Delta Q_1 + \eta_{12}\Delta Q_2 + \eta_{13}\Delta Q_3) = (\eta_{11}\Delta V_1 + \eta_{12}\Delta V_2 + \eta_{13}\Delta V_3)$$

Or

$$\frac{1}{\lambda_1} q_1 = v_1$$

Bus Participation Factors

- The relative bus participation factor (PF) of bus k in mode i is given by $P_{ki} = \xi_{ki}\eta_{ik}$

Similar to PF of the k^{th} state variable x_k in the i^{th} mode in small-signal stability analysis:

$$p_{ki} = \phi_{ki}\psi_{ik}$$

$$\Delta \mathbf{V} = \xi \Lambda^{-1} \eta \Delta \mathbf{Q} = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \Delta \mathbf{Q} \qquad \frac{\partial V_k}{\partial Q_k} = \sum_i \frac{\xi_{ki}\eta_{ik}}{\lambda_i} = \sum_i \frac{P_{ki}}{\lambda_i} = \frac{P_{k1}}{\lambda_1} + \ldots + \frac{P_{km}}{\lambda_m}$$

- P_{ki} determines the participation of bus k into λ_i, or in other words, contribution of λ_i to V-Q sensitivity at bus k.
- $|P_{ki}|$ indicates how effectively a remedial action at bus k can stabilize mode i (i.e. making V-Q sensitivity of λ_i be positive)
- All bus PFs together determine the critical buses and areas associated with each mode.
  - Very few buses with large participations → a local mode of voltage stability
  - Many buses have small but similar degree of participations → a regional mode of voltage stability
- In practice, it is seldom necessary to compute more than 5-10 of the smallest eigenvalues to identify all critical modes.

- Other participation factors (in Kundur's 14.3.3):
  - **Branch PFs** for mode i tell which branches consume more reactive powers in response to an reactive load increase. High branch PFs indicate weak or heavily loaded branches, which are candidates for contingency analysis.

$$P_{ji} = \frac{\Delta Q_{loss} \text{ of branch } j}{\text{maximum } \Delta Q_{loss} \text{ of all branches}}$$

  - **Generator PFs** for mode i tell which generators supply more reactive powers in response to an reactive load increase. High generator PFs suggest locations of reactive power reserves for voltage stability

$$P_{mi} = \frac{\Delta Q_m \text{ of machine } m}{\text{maximum } \Delta Q \text{ of all machines}}$$

Example on a 39-bus system

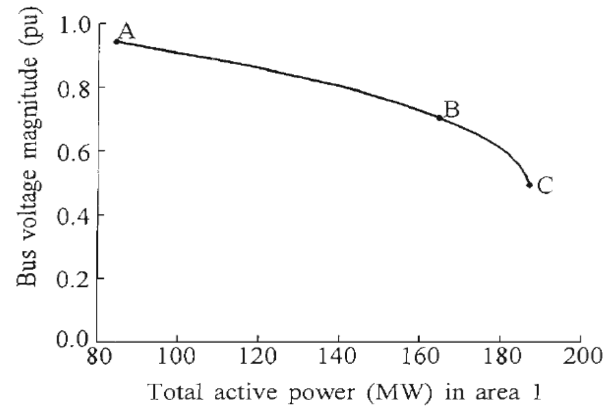


Table 14.1 Five smallest eigenvalues

Operating Point	A	B	C
λ_1	0.3867	0.1446	0.0083
λ_2	1.0271	0.5550	0.3209
λ_3	2.4049	1.5133	0.9334
λ_4	4.1031	2.6280	1.8757
λ_5	4.2699	3.0209	2.3373

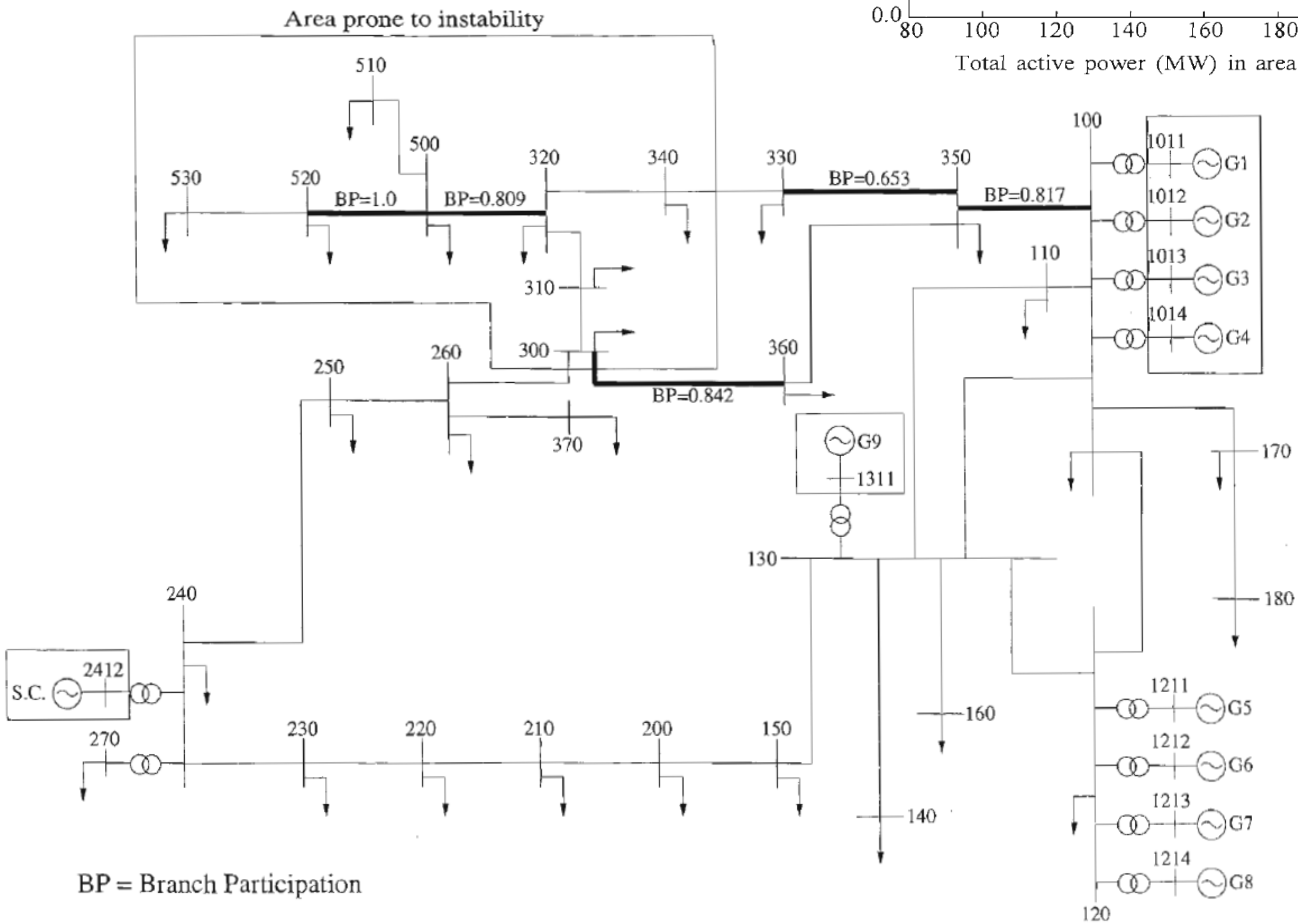


Figure 14.7 Buses and branches with high participation in the least stable mode

Table 14.2 Bus, branch, and generator participations in the least stable mode for operating point C

Bus Participation		Branch Participation		Generator Participation	
Bus	Participation	Branch	Participation	Bus	Participation
530	0.2638	500-520	1.0000	1311	1.0000
520	0.2091	300-360	0.8414	2412	0.2786
510	0.1025	100-350	0.8175	1011	0.2103
500	0.0941	320-500	0.8093	1014	0.2036
320	0.0482	330-350	0.6534	1013	0.2036
310	0.0319			1012	0.2036
300	0.0296				
340	0.0279				

Continuation Powerflow (CPF) Analysis

- Conventional powerflow algorithms are prone to divergence problems at operating conditions near the critical point because the powerflow Jacobian matrix becomes singular there.
- The continuation powerflow (CPF) method [6] can solve power flows for stable as well as unstable equilibrium points.
- Complementary use of conventional and continuation powerflow methods
  - The N-R or Fast Decoupled method (fast) is used to provide solutions up to the critical point.
  - The CPF method (convergent but slow) is necessary only if solutions exactly at and past the critical point are required.
- CPF Algorithm:

1. From an initial solution A, a tangent predictor is used to estimate B for a specified pattern of load increase.
2. A corrector step determines the exact solution C using a conventional powreflow method **with the system load assumed to be fixed**.
3. Voltages for a further load increase are predicted by a new tangent predictor.
4. If the new estimated load D is now beyond the maximum load on the exact solution, a corrector step with loads fixed would not converge; therefore, a corrector step **with a fixed voltage** at the monitored bus is applied to find the exact solution E.
5. As the critical point is reached, to determine the exact maximum load, the size of load increase has to be reduced gradually during the successive predictor step.

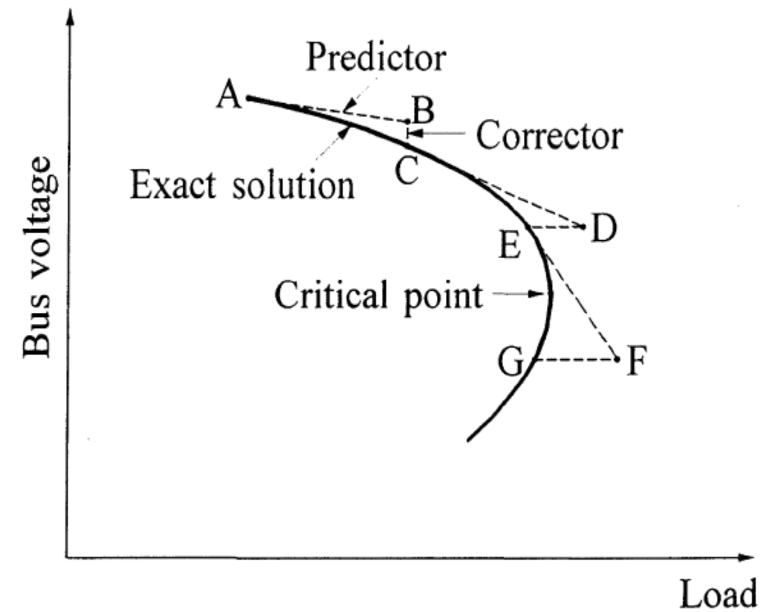


Figure 14.10 A typical sequence of calculations in a continuation power-flow analysis

See a detailed CPF algorithm in Kundur's 14.3.5

Dynamic Analysis (Time-Domain Simulation): Importance of accurate load models

How do residential and industrial loads change when voltage drops?

- **Residential:** Active load will drop with voltage, which will in turn reduce line loading and hence the line reactive losses.
- **Industrial:**
  - Active load will change little because of large components of induction motors.
  - Capacitors in the industrial area will supply less reactive power, thereby causing a net increase in the reactive load
  - At voltages below 85-90% of the nominal value, some induction motors may stall to draw high reactive current, which brings the voltages down further. The voltage drop will cause many motors to drop out. The loss of motor loads will result in voltage recovery. However, after some time, the motors are restored to service, which may cause voltage to drop again if the original cause of the voltage problem still persists. A typical example is the FIDVR issue.
- Accurate load models need to consider:
  - **Large motors and capacitors** in industrial areas
  - **Small motors** in residential areas
  - **Load regulating devices** (e.g. thermostatically controlled loads)
    - When the distribution voltages remain low for a few minutes, they tend to restore load to the normal full voltage value in 10-15 minutes, which makes distribution voltages drop further.
  - **ULTC transformers and distribution voltage regulators** attempt to maintain voltage at points of consumption, which may have destabilizing effects during conditions of voltage collapse. When the ULTCs reach the end of their tap range, distribution voltages drop.

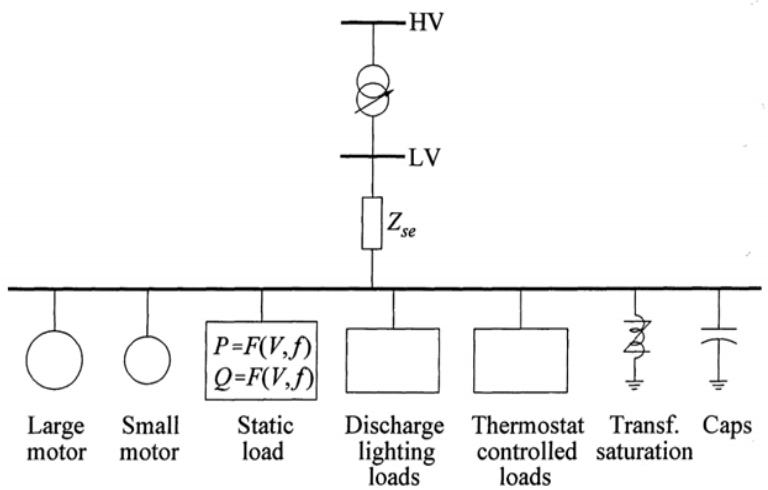


Figure 7.2 Composite static and dynamic load model

Kundur's Example 14.2: Voltage instability under a large disturbance

- **Models:**
  - 6 transformers (1 ULTC)
  - 3 shunt capacitor (buses 7, 8 & 9)
  - Detailed G2 and G3 with thyristor exciters
  - 1 over-excitation limiter (OXL) with G3
  - Load 11: 50% Impedance + 50% Current
  - Load 8: a) constant P&Q;
    b) induction motor;
    c) constant Q + thermostatic P

- **Load levels:**
  1. 6655MW+1986Mvar
  2. 6755MW+2016Mvar
  3. 6805MW+2031Mvar

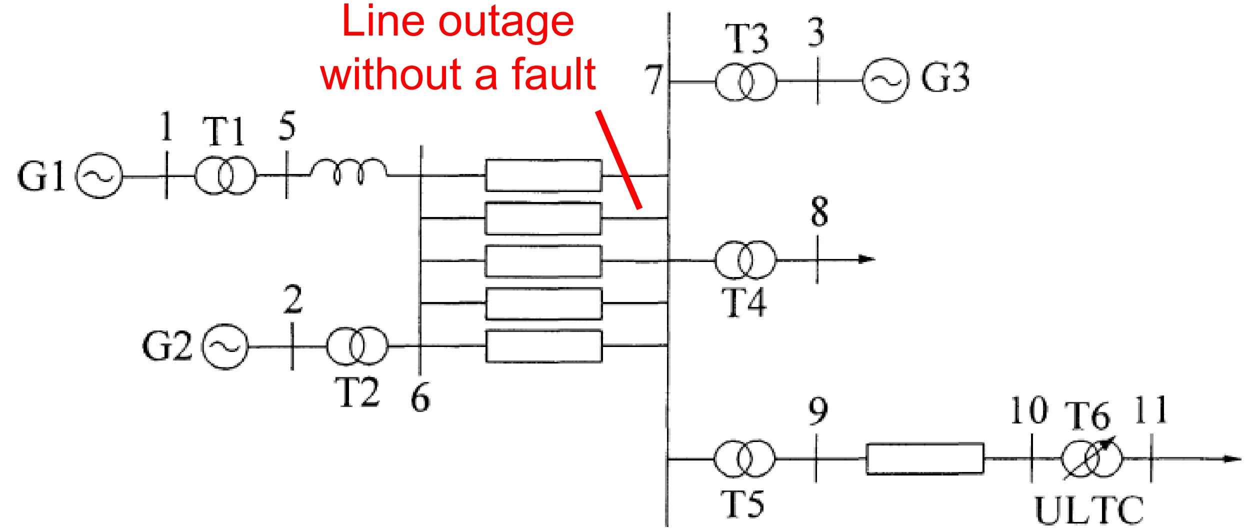


Figure E14.4 Test system

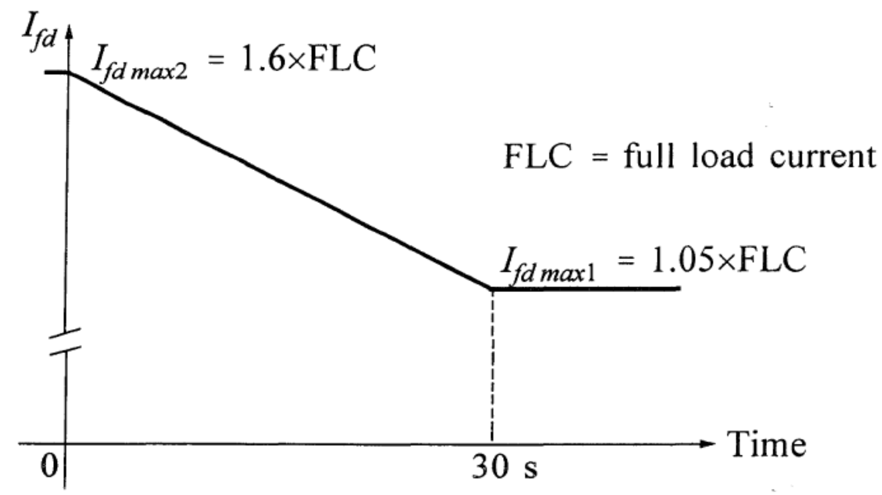
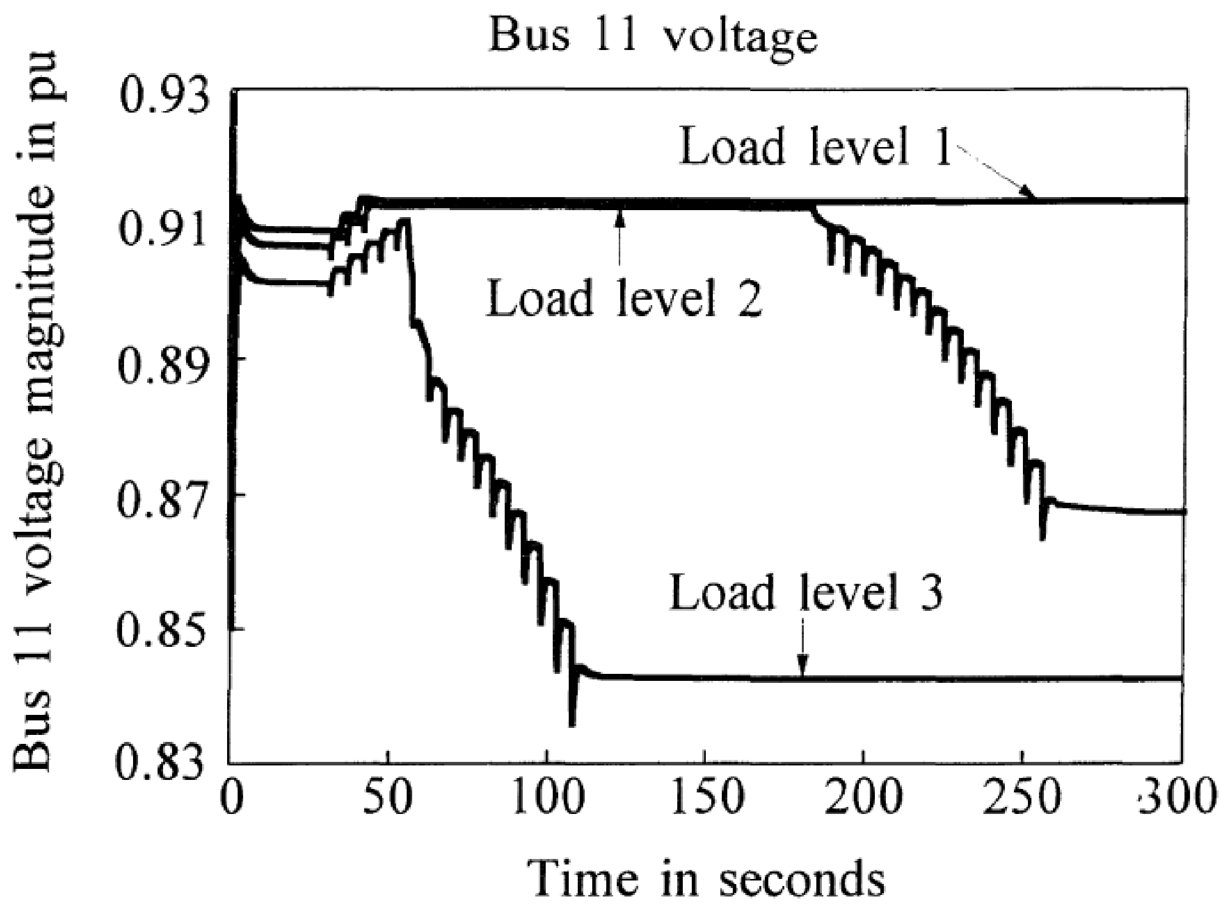


Figure E14.6 OXL characteristic

For example, a field current=1.325FLC allows for 15s, followed by reduction in current level to 1.05FLC over next 15s

Constant P&Q load at bus 8

- Load level 1:
  - The ULTC of T6 restores bus 11 voltage at about 40s.
- Load level 2:
  - While the ULTC of T6 tries to restore bus 11 voltage, the field current limit of G3 is met and the OXL ramps the field current down starting around 180s.
- Load level 3:
  - The field current of G3 reaches its limit at about 50s;
  - Bus 11 voltage drops with each tap movement of the ULTC of T6;
  - The voltage settles when the ULTC reaches its limit and stops.



Induction motor load at bus 8 (load level 2)

- The motor stalls at about 65s, draws rapidly increased reactive power and leads to voltage collapse.

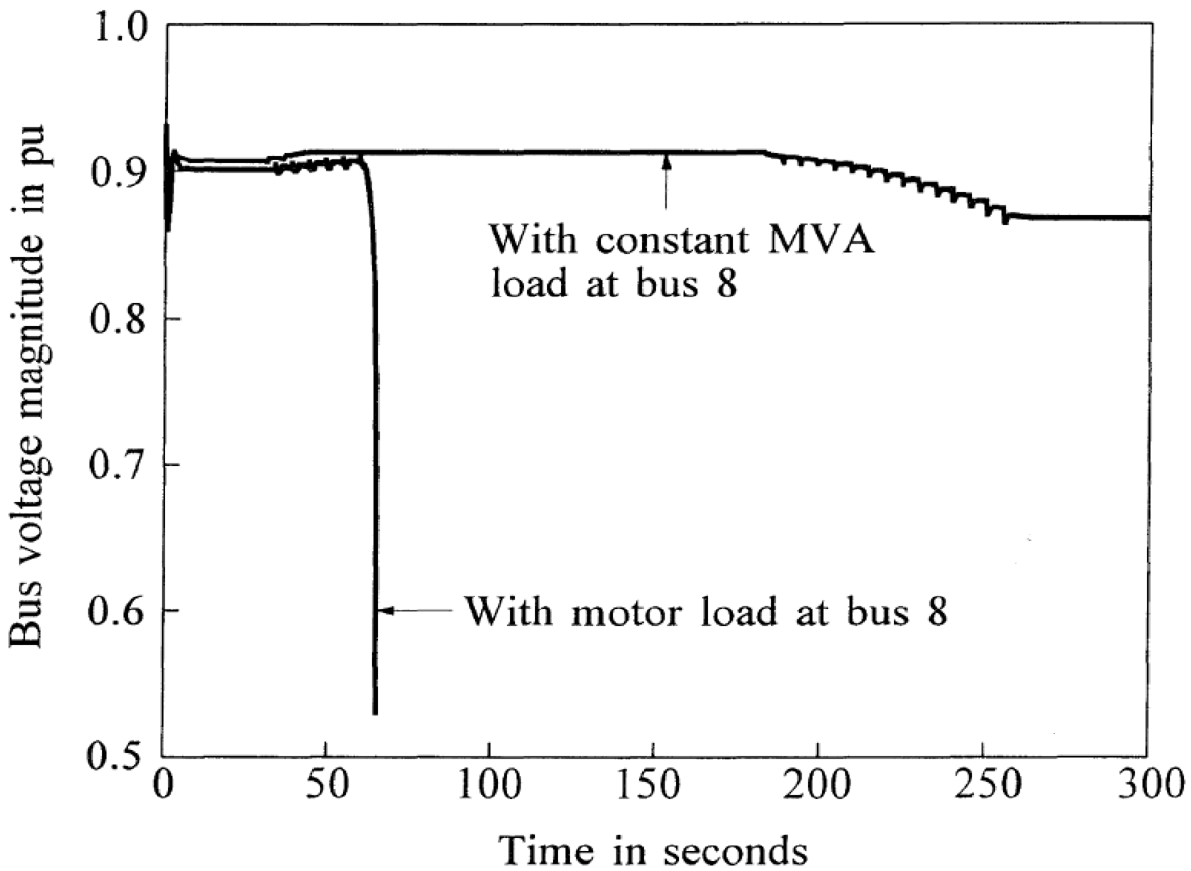
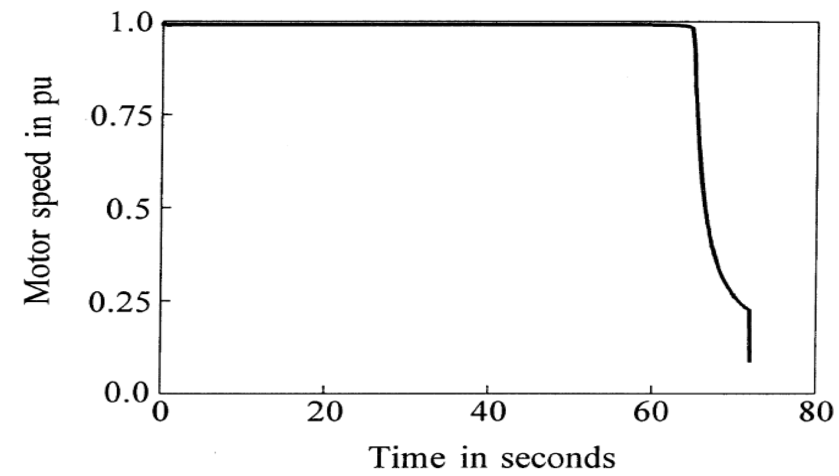
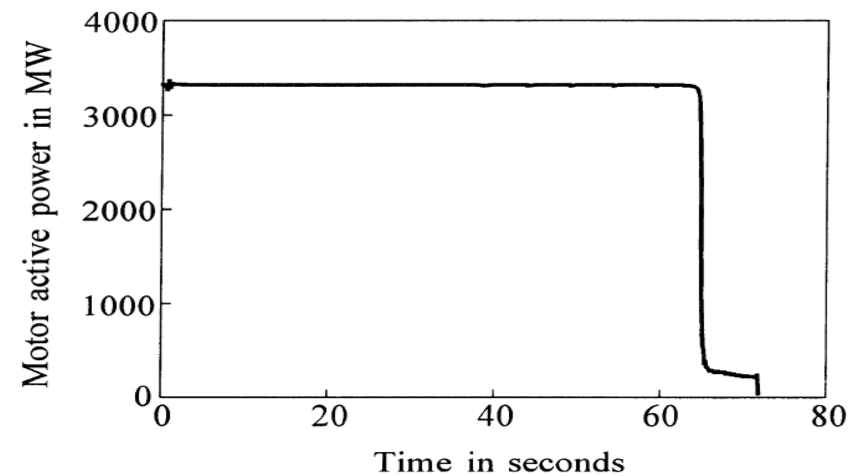
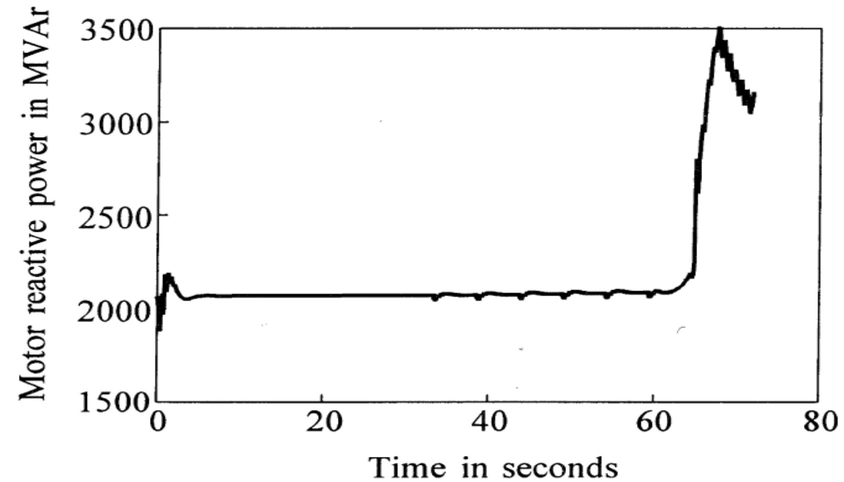


Figure E14.11 Response of voltage magnitude at bus 11 with (a) constant MVA load and (b) induction motor load at bus 8; system load at level 2







Thermostatically controlled load at bus 8 (load level 3)

- The load controller increases the conductance to restore the load and results in a lower bus 11 voltage:

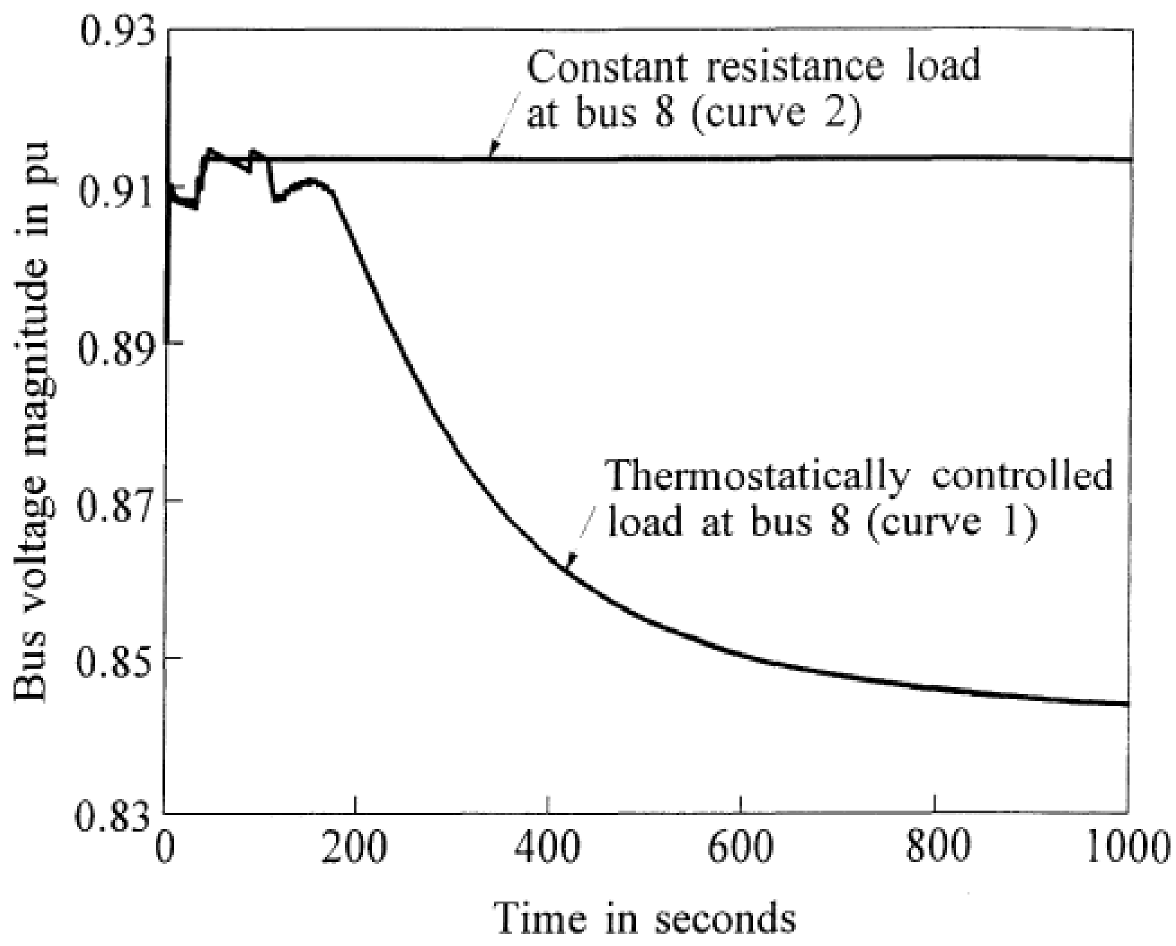
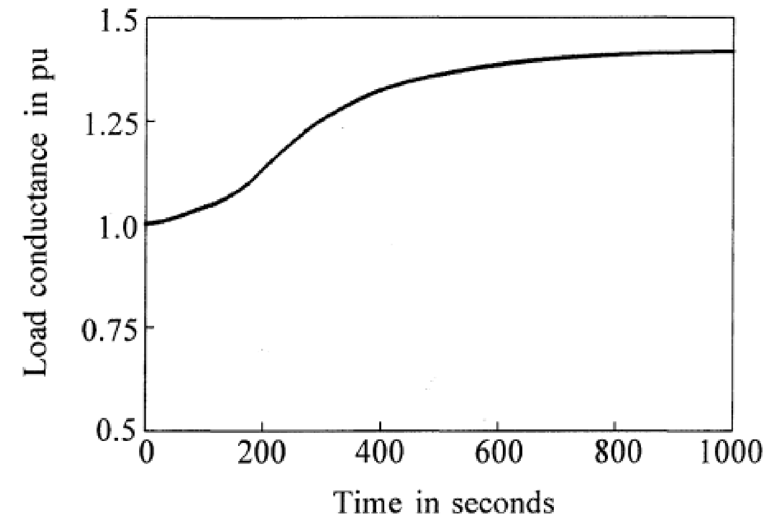
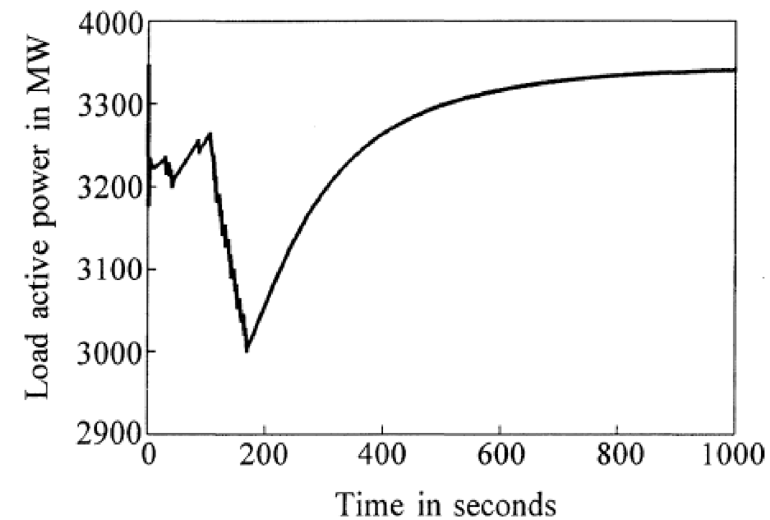


Figure E14.13 Response of voltage magnitude at bus 11 with TC load and constant resistance load at bus 8





Causes of voltage instability

- A typical scenario on the principal driving force for voltage instability:
  - In response to a disturbance, power consumed by loads tends to be restored by motor slip adjustment, distribution voltage regulators and thermostats;
  - Restored loads increase stress on the high-voltage network causing further voltage reduction;
  - Voltage instability occurs when load dynamics attempt to restore power consumption beyond the capability of the transmission network.

- Principal causes
  - The load on transmission lines is too high
  - The voltage sources are too far from load centers
  - The source voltages are too low
  - There is insufficient load reactive compensation
- Contributing factors
  - Generator reactive power and voltage control limitations
  - Load Characteristics
  - Distribution system voltage regulators and transformer tap-changer actions
  - Reactive power compensating device characteristics

Long-Term Voltage Stability and Short-Term Voltage Stability

- The time frame by which voltage instability occurs could be in the range of a few seconds (short-term) to tens of minutes (long-term).
- **Long-term voltage instability (several minutes)**
  - Involves slower acting equipment such as transformer ULTCs, generator field current limiters and thermostatically controlled loads;
  - May be effectively studied using static analysis with complementary use of dynamic analysis;
  - The use of term “static voltage stability” has been discouraged by IEEE PES.
- **Short-term voltage instability (several seconds)**
  - The causes are often faults/short-circuits near loads,
  - Involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC converters,
  - Dynamic models of loads are often essential; analysis requires time-domain simulations,
  - Effective countermeasures include STATCOMs, particularly smaller units connected to distribution network and fast load shedding (UVLS schemes).
- **There is a trend of increasing short-term voltage instabilities due to**
  - Increasing use of low inertia compressor motors for air conditioning, heat pumps and refrigeration;
  - Growth in the use of voltage-insensitive loads with electronic power supplies;
  - Transmission network being pushed harder.

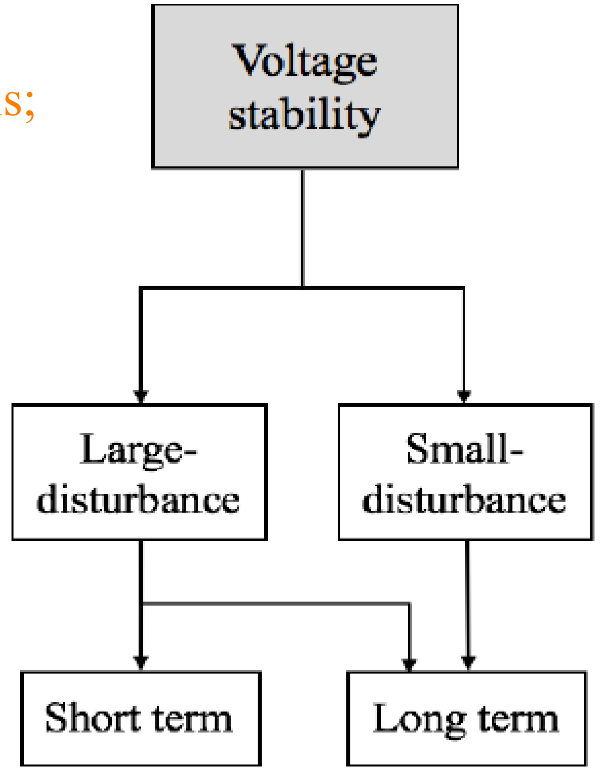
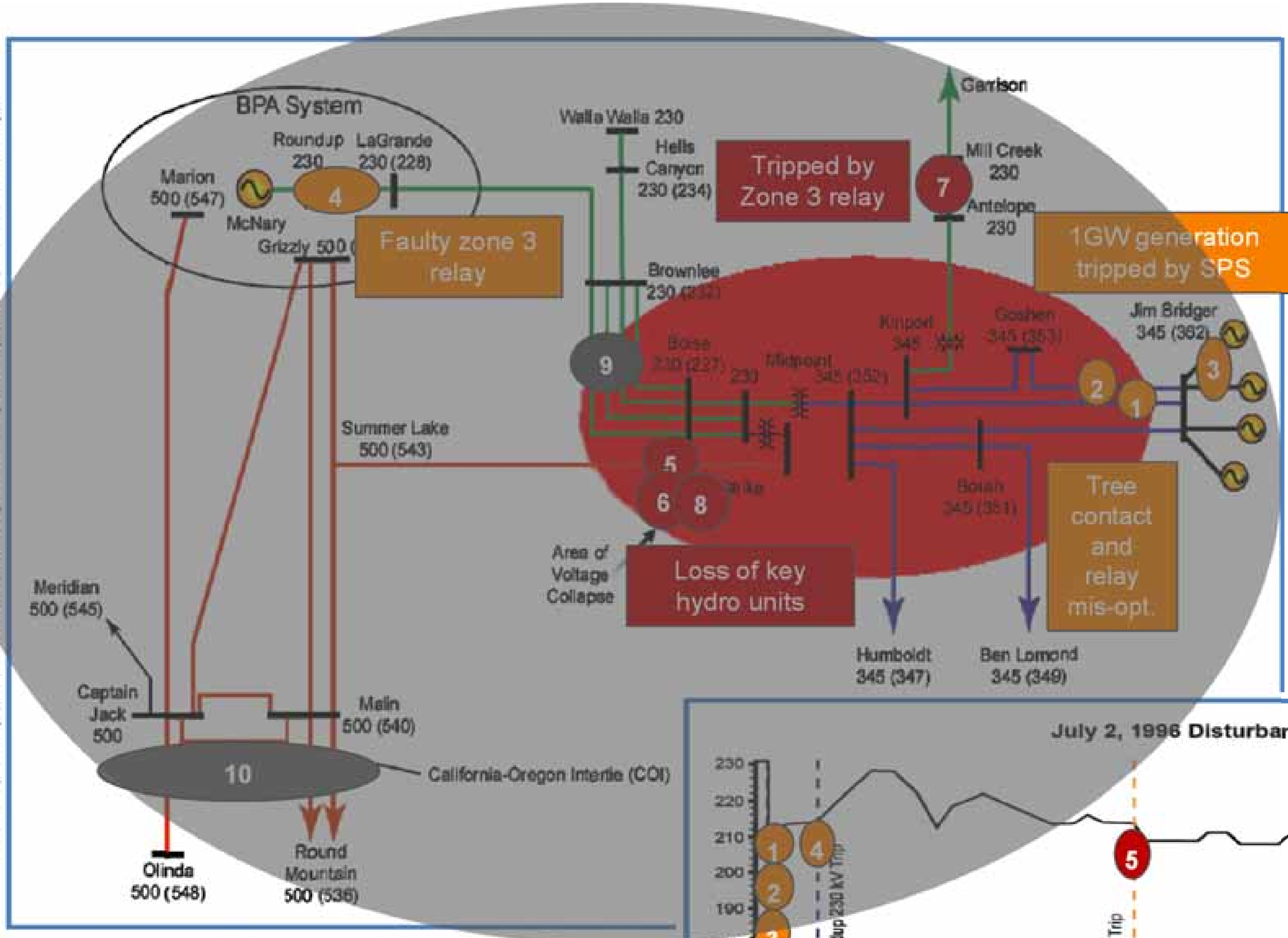


Figure 6-22. One-Line Diagram for July 2, 1996 Disturbance



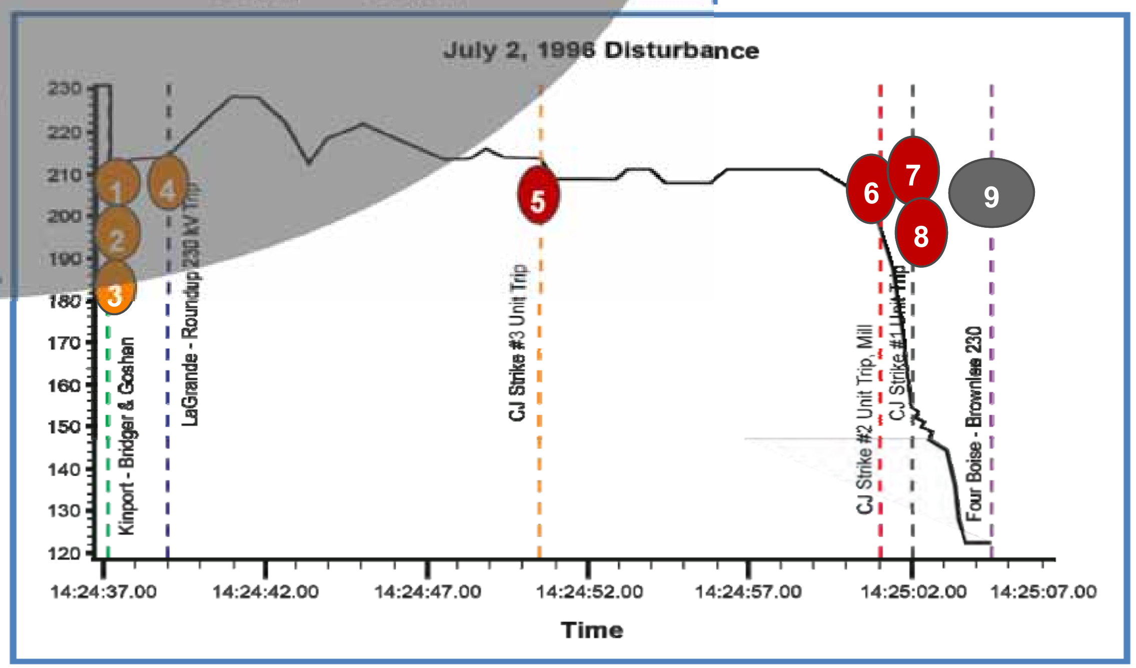


Figure 6-23. Boise 230 kV Voltage Collapse

Example of Voltage Collapse: July 2nd, 1996 Western Cascading Event

- On July 3rd, 1996, i.e. the following day,
  - A similar chain of events happened to cause voltages in Boise area to decline.
  - Different from July 2nd, Idaho Power Co. system operators noted the declining voltages and immediately took the only option available: shedding of Boise area load.
  - Then, the system returned to normal in 1 hour.

- Lessons learned:
  - The July 2nd and 3rd events in Boise, Idaho area emphasize the need for effective and sufficient, rapidly responsive dynamic Mvar reserve.
  - The July 3rd events illustrate the importance of system operators' situational awareness and rapid responses.

Prevention of Voltage Collapse

Read Kundur's Chapter 14.4

- **Application of var compensating devices**
  - Ensure adequate stability margin (MW & Mvar distances to instability) by proper selection of schemes.
  - Selection of sizes, ratings and locations of the devices (especially for dynamic reactive reserves, e.g. synchronous condensers, STATCOM and SVCs) based on a detailed study.
  - Design criteria based on maximum allowable voltage drop following a contingency are often not satisfactory from voltage stability viewpoint.
  - Important to recognize voltage control areas and weak boundaries (buses with high participation factors associated with a voltage instability mode).
- **Control of transformer tap changers**
  - Can be controlled either locally or centrally.
  - Where tap changing is detrimental, a simple method is to block tap changing when the source side sags and unblock when voltage recovers.
  - Use the knowledge of load characteristics to improve the control schemes.
  - Microprocessor-based ULTC controls.
- **Control of network voltage and generator reactive output**
  - Improvement on AVRs, e.g. adding load (or line drop) compensation.
  - Secondary coordinated outer loop voltage control (e.g. the hierarchical, automatic 2-3 layers voltage control).
- **Coordination of protections/controls**
  - Ensure adequate coordination based on dynamic simulation studies.
  - Tripping of equipment to protect from overloaded conditions should be the last resort. The overloaded conditions could be relieved by adequate control measures before isolating the equipment.
- **Under-voltage load shedding (UVLS)**
  - For unplanned or extreme situations, analogous to UFLS.
  - Provide a low-cost means of preventing widespread system collapse.
  - Particularly attractive if conditions leading to voltage instability are of low probability but consequences are high.
  - Characteristics and locations of the loads to be shed are more important for voltage problems than for frequency problems.
  - Should be designed to distinguish between faults, transient voltage dips, and low voltage conditions leading to voltage collapse.