ECE 522
Power Systems Analysis II

5 - Voltage Stability

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Instructor: Kai Sun
Content

• Basic concepts
  – Voltage collapse and Saddle-node bifurcation
  – P-V curve and V-Q curve

• Voltage Stability Analysis (VSA)
  – Modal analysis
  – Continuation powerflow

• Causes and prevention of voltage instability
References

1. Chapter 14 of Kundur’s book
3. EPRI Tutorial’s Chapter 6
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 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.
Factors Influencing Q Transfer

- Q flows from the high voltage side to the low voltage side.
- But Q cannot be transmitted over long distances because
  - It would require a large voltage gradient to do so.
  - An increase in Q transfer causes an increase in $Q_{loss}$ as well as $P_{loss}$
**Voltage Stability vs. Rotor Angle stability**

- Rotor angle stability is basically 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.
  - 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.
- **Transient voltage stability** is usually closely associated with transient rotor angle stability. If voltage collapses at a point (e.g. the center of oscillation) in a transmission system remote from loads, it is, in nature, angle instability.
A simple radial system

- How does $V_R$ change as $P_R$ increases?

\[
V_R = Z_{LD}I \quad \quad P_R = V_RI \cos \phi
\]

\[
\bar{I} = \frac{\bar{E}_S}{Z_{LN} + \bar{Z}_{LD}}
\]

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

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

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

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

\[
P_R = V_RI \cos \phi = \frac{Z_{LD}}{F} \left(\frac{E_S}{Z_{LN}}\right)^2 \cos \phi
\]

(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 instability happen?

- Voltage stability depends on the dynamics or controls with loads
- Under normal conditions, $Z_{LD} \gg Z_{LN}$ and an increase in active load $P_R$ usually comes with a decrease in $Z_{LD}$
- However, when $Z_{LD} < Z_{LN}$ (heavily loaded), a decrease in $Z_{LD}$ reduces $P_R$, so a control to maintain the load by decreasing $Z_{LD}$ becomes unstable
- For instance, consider a load supplied through an ULTC transformer. When the tap-changer tries to raise the load voltage (absorbing more Mvar from the primary side), which has the effect of reducing the effective $Z_{LD}$ and in turn further lowers $V_R$ seen from the primary side and may lead to a progressive reduction of voltage if the primary side is weak in terms of reactive power.

![Schematic diagram](image)

**Figure 14.1** Characteristics of a simple radial system
Concerns of Using Tap Changing Transformers

• Normally, when the turns ratio is adjusted, the Mvar flow across the transformer is also adjusted.

• However, since a transformer absorbs Mvar to build its internal magnetic field, when its secondary voltage is raised via a tap change, its Mvar usage increases and its primary voltage often drops. *The greater the tap change and the weaker the primary side, the greater the primary voltage drop.*

• If the primary side is weak, the tap change may not necessarily increase the secondary voltage. Therefore, spare Mvar must be available for a tap change to be successful.

**An example:**

±10% / 33-position ULTC

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(a) Flat Taps

(Neutral point: 0% ~ 138kV)

(b) Raise Five Positions

(5/16x10% = +3.125% ~ 142.3kV)

(c) Raise 16 Positions

(+10% ~ 151.8kV)
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

\[ E_S = 1.0 \text{pu}, \quad Z_{LN} \angle \theta = j0.5 \text{pu}, \quad \cos \phi = 0.97. \]

- Sketch the \( P_R - V_R \) curve at bus R and find values of \( P_R \) and \( V_R \) at the critical point.
- If the real power load is represented by a ZIP load mode \( P_R = P_0(V_R^2 + 0.9V_R + 4.0) \), where \( P_0 \) varies depending on the load level. Estimate the minimum \( |V_R| \) before voltage collapse.

\[
F = 1 + \left( \frac{Z_{LD}}{Z_{LN}} \right)^2 + 2 \left( \frac{Z_{LD}}{Z_{LN}} \right) \cos(\theta - \phi)
= 2 + 2 \cos(\theta - \phi) = 2.486
\]

\[
V_R = \frac{1}{\sqrt{F}} \frac{Z_{LD}}{Z_{LN}} E_S = 0.634 \text{ pu}
\]

\[
P_R = \frac{Z_{LD}}{F} \left( \frac{E_S}{Z_{LN}} \right)^2 \cos \phi = 0.780 \text{ pu}
\]
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.
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

- If $Q_I$ is injected by a var source at the load bus:

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

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

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

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

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

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

V-Q curve for specific $P_R$ and $\phi$ (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 IEEE 39-bus system

- 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 are maintained constant
- During conditions of low/high voltages, the var output of a generator may reach its limit. Consequently, the terminal voltage is not longer maintained constant
- Then, with constant field current, the point of constant voltage is now $E_g$ 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 Q/current limit being reached is referred to as “limit-induced bifurcation”
Influence of Reactive Compensator Characteristics
Kundur’s Example 14.1

• The compensator is designed to increase compensation ($\Delta Q$) in order to increase voltage ($\Delta V$)

• At Point A (low compensation)
  – The slope $\Delta Q/\Delta V$ of the system is greater than that of the shunt capacitor
  – With the compensation increase, A→A’; V is increased at A’, so compensation stops increasing
  – **Voltage is stable**

• At Point B (high compensation)
  – The slope $\Delta Q/\Delta V$ of the system is smaller than that of the shunt capacitor
  – With the compensation increase, B→B’; V is decreased at B’, so compensation will continue to increase (nonstop)
  – **Voltage is unstable**

*Figure E14.2*  System and shunt capacitor steady-state $Q-V$ characteristics; capacitor MVar shown at rated voltage
Objectives of Voltage Stability Analysis (VSA)

- **Proximity**: how close is the system to voltage instability?
  - Operating/planning stability margin (distance to instability) may be measured in terms of physical quantities, e.g., 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 (line outages, loss of a generating unit or a var source, etc.)

- **Mechanism**:
  - How and why does instability occur?
  - What are the key factors contributing to instability?
  - What are the voltage-weak areas?
  - What measures are most effective in improving voltage stability?
Methods of VSA

- **Dynamic Analysis** considers DEs with time handled implicitly
  - Enhanced time-domain simulations (more accurate and longer)
- **Static (Steady-state) Analysis** considers only AEs and time is handled implicitly
  - Powerflow based techniques
- **Quasi-Dynamic Analysis** considers AEs with time handled explicitly
  - Quasi-dynamic fast time-domain simulations
    - Fast dynamics are ignored
    - Equations are algebraic and solved every time the variables associated with slow dynamics are changed
Dynamic Analysis

• Advantages:
  – Captures the events and chronology leading to voltage instability
  – Accurately replicates the actual dynamics of voltage instability if accurate simulation models are used.
  – Performance of system and individual devices is provided

• Disadvantages:
  – Substantial data requirements: credibly modeling voltage-related devices; beyond those for transient stability simulations (accurate for 10 sec.)
  – Needs to simulate for long times (up to tens of minutes)
  – Simulations do not readily provide sensitivity or stability margin information

• Applications:
  – Essential for studies involving the coordination of controls and protections
  – Short-term voltage stability analysis
  – Postmortem studies
  – Benchmarking of simplified studies (steady-state analysis)
Influence of Load Characteristics

When voltage drops

- **Residential loads**
  - Active load will drop with voltage, which will in turn reduce line loading and hence the line reactive losses

- **Industrial loads**
  - Active load will change little because of large components of induction motors.
  - However the 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.
Importance of accurate load models for voltage stability analysis

- 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
  - 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

• 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

![Diagram of Kundur's Example 14.2](image)

**Figure E14.4** Test system

**Figure E14.6** OXL characteristic