ECE 422/522
Power System Operations & Planning/Power Systems Analysis II:

8 - Voltage Stability

Spring 2014
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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. 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 systems.
Voltage Stability vs. Rotor Angle stability

- Voltage stability is basically load stability, and rotor angle stability is basically generator stability.
- For rotor angle stability, we are often concerned with integrating remote power plants 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 collapse at a point in a transmission system remote from loads, it is, in nature, an angle instability problem.

Typical region with voltage stability concerns
A simple radial system

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

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

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

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

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

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

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

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

$I/I_{sc}$, $P_R/P_{RMAX}$, $V_R/E_S$, $I_{sc} = E_S/Z_{LN}$; $\cos \phi = 0.95 \text{ lag}; \tan \theta = 10.0$
• Voltage stability depends on the load characteristics
  
  – Under normal conditions, to increase power $P_R$, a load control strategy usually decreases $Z_{LD}$

  – However, when $Z_{LD} < Z_{LN}$ (heavy load conditions), a decrease in $Z_{LD}$ reduces $P_R$, so a control on power by varying load may be unstable

  – For example, if the load is supplied by transformers with automatic ULTC, the tap-changer action will try to raise the load voltage (absorbing more Mvar from the primary side), which has the effect of reducing the effective $Z_{LD}$ as seen from the system and in turn lowers $V_R$ further to lead to a progressive reduction of voltage
P-V Curve

- Voltage collapse due to passing the critical point (so called “nose” or “knee” point) is referred to as “saddle-point bifurcation”
Normalized P-V curves ($\phi$ varies)

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

A sudden reduction in $\phi$ (increase in $Q_R$)

Note: $P_{RMAX}$ is the maximum power transfer at unity power factor.
V-Q Curve

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

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

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

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

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

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

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

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

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

Eliminate $\delta$ by $\cos^2 \delta + \sin^2 \delta = 1$
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 instability happens when $\frac{dQ_I}{dV_R} < 0$ since
  - All var control devices are designed to operate when an increase in $Q$ is accompanied by an increase in $V$
  - Protective devices may be activated

Note: $P_{R\text{MAX}}$ is the maximum power transfer at unity power factor

Voltage stability limit is reached when $\frac{dQ_I}{dV_R} = 0$
39-bus test system

Uniformly scale up the area load with constant $\phi$
• Probable remedial actions before the limit is reached
  – Inject Q at Bus 530 to increase V
  – Reduce load near Bus 530
Influence of Generation Characteristics

- Generator AVRs provide the primary source of voltage support to maintain constant terminal voltages under normal conditions.

- During conditions of low/high voltages, the Q output of a generator may reach its limit. Consequently, the terminal voltage is no longer maintained constant.

- Then, with constant field current, the point of constant voltage is now $E_q$ behind the synchronous reactance $X_S \approx X_d$. That increases the network reactance significantly to further aggravating the voltage collapse condition.

- It is important to maintain the voltage control capability 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 limit being reached is referred to as “limit-induced bifurcation”
Long-Term 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 tap-changing transformers, thermostatically controlled loads and generator field current limiters
  – May be effectively studied using static analysis techniques with complementary use of dynamic analysis
• **Short-term voltage instability (several seconds)**
  - Faults/short-circuits near loads could be important
  - Involves dynamics of fast acting load components such as induction motors, electronically controlled loads and HVDC converters
  - Dynamic modeling of loads are often essential; analysis requires solution of differential equations using time-domain simulations
  - There is a trend of increasing short-term voltage instability
    - 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
  - Effective countermeasures
    - STATCOMs, particularly smaller units connected to distribution network
    - Fast load shedding.
Example of Voltage Collapse -
July 2\textsuperscript{nd}, 1996 Western Cascading Event
• On July 3\textsuperscript{rd}, 1996, i.e. the following day,
  – A similar chain of events happened to cause voltages in Boise area to decline.
  – Different from the previous day, Idaho Power Company system operators noted the declining voltages and immediately took the only option available: shedding of Boise area load
  – Then, the system returned to normal within 1 hour

• Lessons learned:
  – The July 2\textsuperscript{nd} and 3\textsuperscript{rd} events in Boise, Idaho area emphasize the need for effective and sufficient, rapidly responsive dynamic Mvar reserve.
  – The July 3\textsuperscript{rd} events illustrate the importance of system operators’ situational awareness and rapid responses.
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 differential equations with time handled explicitly and, applies enhanced *time-domain simulations*

• **Quasi-Dynamic Analysis** considers algebraic equations with time handled explicitly, and applies *fast time-domain simulations*
  – Fast dynamics are ignored
  – Equations are algebraic and solved every time the variables associated with slow dynamics are changed

• **Static (Steady-state) Analysis** considers only algebraic equations for a series of snapshots (equilibrium points), and applies *powerflow based techniques*
Continuation Powerflow Analysis

• The powerflow Jacobian matrix becomes singular at the voltage stability limit (nose point)
• Conventional powerflow algorithms are prone to convergence problems at operating conditions near the stability limit
• The continuation powerflow overcomes this problem by reformulating the powerflow equations so that they remain well-conditioned at all possible loading conditions
• Allows the solution of the powerflow problem for stable as well as unstable equilibrium points
• The method described is based on the work of Ajjarapu and Christy published in 1991
  – Locally-parameterized continuation method, which belongs to a general class of methods for solving nonlinear algebraic equations known as path-following methods
1. From an initial solution A, a tangent predictor is used to estimate B for a specified pattern of load increase.

2. Then, a corrector step determines the exact solution C using a conventional powreflow analysis with the system load assumed to be fixed.

3. The voltages for a further increase in load are then predicted based on 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.

As the voltage stability limit is reached, to determine the exact maximum load, the size of load increase has to be reduced gradually during the successive predictor step.

See mathematical formulation in Kundur’s 14.3.5.

Robust and flexible but time-consuming
Prevention of Voltage Instability

• Application of var compensating devices
  – Ensure adequate stability margin (MW and 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 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
  – There is potential for improved control strategies based on a knowledge of load characteristics
  – Microprocessor-based ULTC controls
Prevention of Voltage Instability (cont’d)

• 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 two/three-layer voltage control)

• Coordination of protections/controls
  – Adequate coordination ensured 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)
  – To cater 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
References

- Chapter 14 of Kundur’s book
- EPRI Tutorial’s Chapter 6