ECE 692
Advanced Topics on
Power System Stability

Measurement-based Voltage Stability Assessment

Spring 2016
Instructor: Kai Sun
Content

• Background on measurement-based voltage stability assessment (VSA)

• Methods:
  – Using a Thevenin (1+1-bus) equivalent
  – Using an N+M-bus equivalent

• Demonstrations
References


Simulation/model based Voltage Stability Assessment

• Strengths
  – Look-ahead capabilities in stability prediction and control for “what-if” scenarios
  – Lots of commercial software tools.

• Limitations in Online Application
  – Model-dependent: the accuracy depends on how accurate the power system models is
  – Contingency-dependent: only applied to selected critical contingencies
  – Requiring a steady-state powerflow solution: the state estimator may fail to converge under stressed operating conditions.
  – Computationally intensive: especially for dynamic simulations

• An alternative approach is Measurement-based VSA
A simple radial system

- How does \( V_R \) change as \( P_R \) increases?

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

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

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

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

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

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

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

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

**Figure 14.1** Characteristics of a simple radial system
Methods on Measurement-based VSA [1]-[6]

For a load pocket area

1. Merge all lines to be one
\[ V = \sum_{i=1}^{N} V_i I_i^* / \sum_{i=1}^{N} I_i^* , \quad S = P + jQ = \sum_{i=1}^{N} V_i I_i^* \]

2. Estimate \( E \) and \( Z_{thv} \) by, e.g., a least square method

3. Transfer limit \( P_{max} \) is met when \( |Z_{load}| = |Z_{thv}| \)

For a wider load area

Measuring synchronized voltages \( V_i \) and currents \( I_i \) at all boundary buses

1. Consider equivalents with details on different transfer paths

2. Estimate all equivalent \( E \) and \( Z \) parameters by optimization methods

3. Analytically solve the limit for each transfer path

\[
\begin{align*}
P_{1max} &= f_1(E, Z_1, Z_2, Z_{L1}, Z_{L2}, Z_T) \\
P_{2max} &= f_2(E, Z_1, Z_2, Z_{L1}, Z_{L2}, Z_T)
\end{align*}
\]
Using a Thevenin equivalent [1]-[3]

Measure **voltage and current waveforms** at the boundary buses (key substations) of the load center using synchro-phasors

Calculate **$V \angle \theta$, $P$ and $Q$** at the fictitious bus using **voltage and current waveforms**

Calculate the external system’s Thevenin Equivalent parameters: $V \angle \theta$, $P$, and $Q \rightarrow E \angle \delta$ and $Z_{\text{Thev}}$

Calculate power transfer limits: $E \angle \delta$ and $Z_{\text{Thev}} \rightarrow P_{\text{max}}$ and $Q_{\text{max}}$

Calculate voltage stability margin: $P_{\text{margin}} = P_{\text{max}} - P$ and $Q_{\text{margin}} = |Q_{\text{max}} - Q|$
Thevenin (1+1-bus) equivalent based method [1]-[3]

\[
\begin{align*}
 P &= |E| EVY \cos(\theta - \delta - \beta) - |V|^2 |Y| \cos \beta \\
 Q &= |E| EVY \sin(\theta - \delta - \beta) + |V|^2 |Y| \sin \beta
\end{align*}
\]

where \(|Y| \angle \beta = 1/ Z_{thev}\)

\[
\begin{align*}
 p &= \frac{P}{|E|^2 |Y|} = v \cos(\theta - \delta - \beta) - v^2 \cos \beta \\
 q &= \frac{Q}{|E|^2 |Y|} = v \sin(\theta - \delta - \beta) + v^2 \sin \beta = p \tan \phi, \text{ where } v = \left| \frac{V}{E} \right|
\end{align*}
\]

Eliminate \((\theta - \delta - \beta)\)

\[
p = p(v^2, \phi, \beta)
\]

\[
\frac{\partial p}{\partial v} = 0
\]

\[
v_{\text{critical}} = \frac{1}{\sqrt{2[1 + \cos(\phi + \beta)]}}
\]

\[
V_{\text{critical}} = \frac{|E|}{\sqrt{2[1 + \cos(\phi + \beta)]}}
\]

\[
P_{\text{max}} = P \bigg|_{V=V_{\text{critical}}} = \frac{|E|^2 |Y| \cos \phi}{2[1 + \cos(\phi + \beta)]}
\]

\[
Q_{\text{max}} = Q \bigg|_{V=V_{\text{critical}}} = \frac{|E|^2 |Y| \sin \phi}{2[1 + \cos(\phi + \beta)]}
\]
Voltage Stability Margin Indices

In terms of active power:
\[ P_{\text{margin}} = P_{\text{max}} - P \]

In terms of reactive power:
\[ Q_{\text{margin}} = |Q_{\text{max}} - Q| \]

In terms of apparent power:
\[ S_{\text{margin}} = S_{\text{max}} - |S| = \sqrt{P_{\text{max}}^2 + Q_{\text{max}}^2} - |S| \]
Example

Abnormal voltage level (< 0.8pu)

- $P_{\text{margin}}$ - Voltage stability limit
- $P_{\text{max}}$ - Voltage stability limit
- $P$ - Real power transferred to the region

Insufficient stability margin
Using an N+1 buses Equivalent \([4]-[6]\)

Offline place PMUs on boundary buses of the load area for voltage stability monitoring

Measure real-time voltage and current phasors

Estimate all parameters of the equivalent using phasor data over a sliding time window

Calculate transfer limits of all tie lines by analytical expressions on \(P_{ij}^{\text{max}}\)

Real-time limit and margin information for operators

Derive the transfer limit of tie line \(i\) with respect to a load change near bus \(j\) as a function of all parameters of the equivalent

\[
\frac{\partial P_i(y_{11}, \ldots, y_{NN})}{\partial y_{jj}} = 0 \quad \Rightarrow \quad P_{i,j}^{\text{Max}}
\]
For a load area fed by multiple tie lines

• Using a Thevenin equivalent
  – Only estimates the total transfer limit of all tie lines

• Using an N+M-bus equivalent
  – Estimates the transfer limit for each line and can better detect and control voltage instability if any line hits its limit earlier than the others
  – Gives the limits of each line with respect to different scenarios of load changes
  – More accurate in estimating the total transfer limit by considering the coupling among boundary buses
Influence from the coupling of boundary buses

Strong

External system

Weak

Load Center
Demonstration on the NPCC 140-bus System

Voltage collapse caused by a generator outage in the load center and load increase.
Comparison of two MB-VSA methods

Zero margin at $t=473s$

Positive margin when voltage collapse happens.
Application in Closed-loop Control

- Automatically switch in a shunt capacitor in the load area if any tie line margin drops below 5%
- Voltage collapse is postponed
Application of the New MB-VSA Method in System Operations

Voltage collapse following a generator trip at bus 21 without control

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Tie lines ranked by MBVSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before generator</td>
<td>30-31, 6-5 (most critical)</td>
</tr>
<tr>
<td></td>
<td>29-30, 8-9, 7-6</td>
</tr>
<tr>
<td></td>
<td>73-35</td>
</tr>
<tr>
<td>After generator</td>
<td>29-30, 8-9, 7-6 (most critical)</td>
</tr>
<tr>
<td>trip at Bus 21</td>
<td>30-31, 6-5</td>
</tr>
<tr>
<td></td>
<td>73-35</td>
</tr>
</tbody>
</table>

Transfer margin on ISO-NE path

Transfer margin on NYISO path

Dispatch more VAR from wind turbines when any line margin<5%

Cut-set 1
Test on a 25k-bus Eastern Interconnection model

From NYISO
Limit for load increase in area 1
Limit for load increase in area 2
Margin > 0

From ISO-NE
Limit for load increase in area 1
Limit for load increase in area 2
Margin < 0
Real-time power
Demonstration on CURENT Hardware Test Bed System [6]
Closed-loop control to prevent voltage collapse

**Without control**
Load increases in the load area leading to voltage collapses.

**With control**
Provide Q via MT-HVDC when any tie line margin is below a threshold.
Project Proposal Presentation

• 4/7 (Thur)
  – Group 2: Weihong Huang and Denis Osipov
  – Group 7: Xiao Kou and Qingxin Shi
  – Group 8: Ishita Ray and Yajun Wang

• 4/12 (Tue)
  – Group 1: Jiecheng Zhao and Yongli Zhu
  – Group 4: Nan Duan and Xiaowen Su
  – Group 9: Jonathan Devadason and Horacio D. Silva Saravia

• 4/14 (Thur)
  – Group 3: Wenyun Ju and Siqi Wang
  – Group 5: Yu Su and Xuemeng Zhang
  – Group 6: Abdulelah Y. Alharbi and Abdullah S. Alsaaffar