KPN - ProSmart
Relay Protection in Smart Grid Context

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Today’s Topic - Background

• Frequency domain methods are commonly used to predict the following behaviors:
  – Frequency scan – (small signal phasor-domain model at each frequency)
  – Ferroresonance (old-time methods of Rudenburg)
  – Power line carrier (modal analysis)
  – Voltage collapse (continuous power flow)

• Issues:
  – Nonlinearities: magnetic saturation, in controllers
  – FACTS devices, switching harmonics
  – Frequency dependencies of transmission lines, etc.
  – Small-signal response does not include behavior at rated voltage or overvoltage. We need to obtain the “large-signal” response.
  – Step response of system following faults, switching, etc.
Work done to date


4) Today’s presentation on Voltage Collapse...
Project Work

• **Developing different indices to predict voltage collapse**
  – Fast and accurate recognition of voltage degrading
  – Multi-variable indices
  – Different test systems

• **Wide-area feedback control**
  – Develop a control decision algorithm
  – Considering different wide-area system parameters
  – Feed-back from the system to upgrade the control action

• **Time-domain modeling of the power system**
  – Different load types
  – Shunt compensators; TCR, SVC
  – Phasor Measurement Unit (PMU)

• **Time-domain method to identify voltage collapse**
  – Use actual voltage and current waveforms
  – Plot P-V curve, identify operating point, and available power margin
  – Verify time-domain method accuracy
IEEE 39 Bus System (New-England Power System)

- 39 bus system
- 10 generators
- 29 load buses
- 46 transmission lines
Monitor available power margin using Thevenin equivalent

- Maximum power transfer occurs when the load impedance is equal to Thevenin equivalent impedance.
- The ratio of Thevenin equivalent impedance and the load impedance reveals the operating point and power margin.
- Thevenin equivalent impedance is calculated using two consecutive voltage and current measurements.

\[ V_L = E_{th} - Z_{th}I_L \]
\[ Z_{th} = \frac{V_{L2} - V_{L1}}{I_{L1} - I_{L2}} \]

- Based on the distance to maximum power transfer point, a multi-level alert is generated.

Monitor rate of change of voltage

- The average of three consecutive changes in peak voltage is considered as the rate of change of voltage.
- Different threshold are considered to activate a multi-level alert.

Monitor magnitude of voltage

- Magnitude of voltage is also monitored to track very fast changes.
- Different threshold are considered to activate a multi-level alert.
Case Study

- Load at Bus 24 is increasing
- Index monitor at bus 24 and bus 16
<table>
<thead>
<tr>
<th>Flag-1</th>
<th>Flag-2</th>
<th>Flag-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Normal operation, Z/Zth&lt;0.05</td>
<td>0 Normal operation, Voltage between 0.9 and 1.1 PU</td>
</tr>
<tr>
<td></td>
<td>Caution, voltage drop between 5-10% in 10 second</td>
<td>1 Caution, Voltage between 0.9 and 1.1 PU</td>
</tr>
<tr>
<td></td>
<td>Action, voltage drop more than 10% in 10 second</td>
<td>2 Action, Voltage drop more than 5% in 10 second</td>
</tr>
<tr>
<td>1</td>
<td>Caution, 0.05&lt;Z/Zth&lt;0.2</td>
<td>1 Caution, Voltage between 0.9 and 1.1 PU</td>
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<tr>
<td></td>
<td>Normal, voltage increase or drop less than 2% in 10 second</td>
<td>1 Caution, Voltage between 0.9 and 1.1 PU</td>
</tr>
<tr>
<td></td>
<td>Caution, voltage drop between 2-5% in 10 second</td>
<td>2 Action, Voltage drop more than 5% in 10 second</td>
</tr>
<tr>
<td></td>
<td>Action, Voltage less than 0.9 or greater than 1.1</td>
<td>2 Action, Voltage less than 0.9 or greater than 1.1</td>
</tr>
<tr>
<td>2</td>
<td>Action, Z/Zth&gt;0.2</td>
<td>2 Action, Voltage less than 0.9 or greater than 1.1</td>
</tr>
</tbody>
</table>
Case Study

- Load at Bus 24 is increasing
- Index monitor at bus 24 and bus 16
Bus 24 voltage (normalized) and indices at Bus 24
Bus 24 and 16 voltages (normalized) and indices at Bus 16
### Overall Voltage Stability Index at Each Bus

<table>
<thead>
<tr>
<th>Flag 1</th>
<th>Flag 2</th>
<th>Flag 3</th>
<th>Overall Index</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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<td>0</td>
<td>0</td>
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</tr>
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<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Any combinations in which one of the flags is 2 and another is 1. If all flags are 2.
Voltage at Bus 24

Stability indices at bus 24 and bus 16

(FILE 39-BUS-X_EaCalc_Control4.pl4; x-var t) m:IDX 24 m:IDX 16

(FILE 39-BUS-X_EaCalc_Control4.pl4; x-var t)
Wide-area control actions

- All voltage stability indices transferred to wide-area control center
- Control commands issued based on stability indices and available control actions
- If two control options available, capacitor bank and load shedding, a control table example would be as:

<table>
<thead>
<tr>
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</thead>
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<td>✗</td>
<td>✗</td>
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<td>✔</td>
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<tr>
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<td>1</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
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<tr>
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<td>✗</td>
<td>✗</td>
<td>✔</td>
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<tr>
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<td>1</td>
<td>✗</td>
<td>✔</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
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<td>✔</td>
<td>✗</td>
<td>✗</td>
<td>✔</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✔</td>
</tr>
</tbody>
</table>
Voltage (normalized) and indices at Bus 24

Control command for Capacitor Bank at Bus 24

Control command for Capacitor Bank at Bus 16
Voltage (normalized) and indices at Bus 24

Control command for load shedding at Bus 24 and Bus 16
**Variable Inductive Load**

Time-varying magnetic flux induces a voltage across the inductor.

\[ v_l = \frac{d\phi}{dt} \quad \text{and} \quad L(t) = L_0 + Kt \]

\[ v_l = \frac{\partial L i}{\partial t} \implies \frac{v_{l,k} + v_{l,k-1}}{2} \Delta t = L_k i_k - L_{k-1} i_{k-1} \]

\[ i_k = \left( \frac{L_{k-1}}{L_k} i_{k-1} + \frac{\Delta t}{2 L_k} v_{l,k-1} \right) + v_{l,k} \frac{\Delta t}{2 L_k} \]

We can model the time-varying inductance using a Norton current source and an equivalent conductance.

\[ i_{eq} = \left( \frac{L_{k-1}}{L_k} i_{k-1} + \frac{\Delta t}{2 L_k} v_{l,k-1} \right) \]

\[ g_k = \frac{\Delta t}{2 L_k} \]

**Variable Capacitive Load**

Time-varying electric charge develops a current flow through the capacitor.

\[ i = \frac{\partial C v}{\partial t} \quad \text{and} \quad C(t) = C_0 + kt \]

\[ \frac{i_{c,k} + i_{c,k-1}}{2} \Delta t = C_k v_k - C_{k-1} v_{k-1} \]

\[ i_{c,k} = v_k \frac{2C_k}{\Delta t} - \left( \frac{2C_{k-1}}{\Delta t} v_{k-1} + i_{c,k-1} \right) \]

We can develop an equivalent Norton current source and a resistance to model time-varying capacitor.

\[ I_{inj} = \frac{2C_{k-1}}{\Delta t} v_{k-1} + i_{c,k-1} \]

\[ R_{eq,k} = \frac{\Delta t}{2C_k} \]
Simulated system with time-varying lagging load model

Load power and RMS voltage

P-V curve of loads with different power factors

P-V curves plotted using time-domain method and CPF
Modeling SVC

- Considering compensation limits
- Effects on voltage stability
- Compare PV curves

Developed Model for SVC in ATPDraw

- Phase-Locked Loop (PLL)
- Voltage Regulator
- Pulse Generator
- TCR/FC

General SVC Schematic
Voltage Regulator

- Input: measured voltage
- Output: a signal proportional to the required reactive power compensation to maintain system voltage at the reference value
- Output of the controller would be the desired susceptance value
- Measured voltage > the reference value, then B would be a negative value showing inductive compensation;
- Measured voltage < the reference value, the output of voltage regulator would be a positive value showing capacitive compensation to increase the voltage.
• Bus P-V curve with SVC
• Increase maximum power transfer capability
Modeling PMU

- Extract a single frequency component of the signal
- Using sampled system data

Phasor Estimation at Off-Nominal Frequency

- Sampling rate is constant and it is multiple of the nominal frequency.
  \[ \omega = \omega_0 + \Delta \omega \]
  \[ x(t) = X_m \cos(\omega t + \phi) \]

- Correct phasor representation for this input signal
  \[ \frac{X_m}{\sqrt{2}} e^{j\phi} \]

- Phasor estimation error depends on the difference between the nominal frequency and actual frequency.

- Phasor estimate at off-nominal frequency
  \[ X_r = PXe^{jr(\omega - \omega_0)\Delta t} + QX e^{-jr(\omega + \omega_0)\Delta t} \]

- P and Q coefficients, their values depend upon the nominal frequency and the actual signal frequency and also the sampling rate
• Using a recursive DFT algorithm for phasor estimation with nominal frequency of 60Hz while the signal frequency is 60.5 Hz

Magnitude and angle of phasor - Using 60Hz recursive DFT algorithm to estimate the input signal with f=60.5Hz

**Modeling with Frequency Estimation and FFT Algorithm**

• Use a PLL block to estimate the frequency

• Phasor estimation using an 8-point FFT algorithm

• In each time step new time delays are calculated and the phasor is estimated.
Applications of Time-Domain Analysis

- Nonlinear Component in Power System
  - Nonlinear inductance (Saturable Transformer)
  - Observe saturation effects
  - Effect on voltage stability
  - Compare PV curves.
Applications of Time-Domain Analysis

- Geomagnetic Induced Current (GIC)
  - Voltage Gradients of 3-6 Volts/Km
  - DC Voltage at transformer neutrals
  - Severe offset and continuous saturation on transformers
  - Half-cycle saturated excitation currents
  - Transmission line between Bus 1 and Bus 2: 400 Km
  - 4 Volts/Km voltage gradient

![Diagram of GIC and transformers]
Voltage during normal operation and GIC

P-V during normal operation and GIC
Applications of Time-Domain Analysis

Ferroresonance

- Oscillating phenomena occurring in a power system which contains a nonlinear saturable transformer and series capacitance.
- Ferroresonance especially occurs when the circuit is subjected to a transient disturbance such as switching.
- Voltage and current jump between different stable operating states.
- Ferroresonance characteristics depend on several parameters:
  - Initial conditions of the capacitance and transformer magnetizing inductor
  - Voltage magnitude and initial source phase angle
  - Total loss of the system.
Sub-harmonic mode ferroresonance

Fundamental mode ferroresonance
Thank You