Special Reliability Assessment on Oscillatory Modes in North American Interconnections

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Special Reliability Assessment

We thank all the reliability coordinators for providing PMU data.
Objectives

- Analyze **PMU event data** from Eastern, Western, and Texas interconnections
- Inter-Area Modes: what modes, damping levels, mode shapes, energy...
- Seasonal properties
- Interactions with forced oscillations
- PMU data for 8 events in each interconnection collected
- Compare with model based simulations
Report Outline

- Inter-Area Oscillations Fundamentals
- Analysis Techniques
- Event Analysis Results: Eastern, Western and Texas Interconnections
- Findings, Conclusions and Recommendations
- Appendices: Analysis methods
Texas Interconnection Event 5

Generator outage event at 00:11:48
Frequency hits minimum 59.80 Hz at 00:11:51
Recovers to 60 Hz by 00:16:09
Phase Angles Relative to Center

South Texas

North Texas
Analysis using Relative Bus Phase Angles (wrt Center)

Ringdown Analysis window from 00:11:49 to 00:11:56
Ringdown Analysis and Reconstructed Signals

South Texas

North Texas
## Ringdown Analysis using ERA

<table>
<thead>
<tr>
<th>Mode Frequency (Hz)</th>
<th>Damping Ratio (%)</th>
<th>Relative Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.67</td>
<td>11</td>
<td>95</td>
</tr>
</tbody>
</table>

- Modes with relative energy less than 10% are not shown.
- 13 Relative bus voltage phase angle signals used.
- HTLS, ERA, Matrix Pencil and Prony agree for the main 0.67 Hz mode.
- 7 second Analysis window.
Mode Shape of the Dominant Mode

North East TX

South East TX

0.67 Hz at around 11% damping ratio
Simulated Case 1 Frequencies wrt Panda

Northwest Texas

South Texas
## Ringdown Analysis Results for Window 2 to 7 sec

<table>
<thead>
<tr>
<th>Method</th>
<th>Prony</th>
<th>Matrix</th>
<th>HTLS</th>
<th>ERA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1 Freq</td>
<td>0.713</td>
<td>0.713</td>
<td>0.713</td>
<td>0.713</td>
</tr>
<tr>
<td>Mode 1 Damp Ratio</td>
<td>9.16</td>
<td>8.67</td>
<td>8.67</td>
<td>8.67</td>
</tr>
<tr>
<td>Mode 1 Energy (%)</td>
<td>96.71</td>
<td>99.10</td>
<td>99.10</td>
<td>99.10</td>
</tr>
</tbody>
</table>

- 51 Bus Frequencies (Panda 345 bus freq used as reference)
- Analysis window 2 to 7 seconds
- NORTHDC7_345 and EDISON7A_345 dropped from analysis
HTLS Mode Shape of 0.71 Hz Mode

Northwest Texas

South Texas
WECC Case 1 Arizona Bus Frequency

Colorado generator outage event at 00:13:55
Frequency hits minimum 59.83 Hz at 00:14:01
Recovers to 60 Hz by 00:20:39.
Montana Bus Frequency
Phase Angles Relative to COI bus

Alberta

British Columbia

Arizona
Analysis using Relative Bus Frequencies (wrt COI bus)

Ringdown Analysis window from 00:13:56 to 00:14:04
Ringdown Analysis and Reconstructed Signals

Alberta

British Columbia

Arizona
Ringdown Analysis using HTLS

<table>
<thead>
<tr>
<th>Mode Frequency (Hz)</th>
<th>Damping Ratio (%)</th>
<th>Relative Energy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.42</td>
<td>12</td>
<td>51</td>
</tr>
<tr>
<td>1.29</td>
<td>8</td>
<td>31</td>
</tr>
</tbody>
</table>

- Modes with relative energy less than 10% are not shown.
- 128 Relative bus frequency signals used.
- HTLS, ERA, Matrix Pencil and Prony agree for the main 0.42 Hz mode.
- 8 second Analysis window.
Mode Shape of the 0.42 Hz Mode

0.42 Hz mode at around 12% damping ratio
Simulated WECC Case 1 Frequencies wrt Malin

Alberta

BC Hydro

Mexico CFE
Prony Mode Shape of 0.37 Hz Mode

0.37 Hz mode at around 9% damping ratio
November 27 2016 Bus Frequency Time Plots

Alabama

Out of phase

New Jersey
0.7 Hz Oscillation Mode Shape

New Jersey

Alabama

TN

AR

Alabama (source)
FFDD Power Spectrum@12:10AM (Before)

Main modes
0.25 Hz
0.4 Hz
0.5 Hz
0.75 Hz

Forced Oscillation Interacting with System Mode
System Modes
FSSI Estimates Before GA Osc Event

- **0.78 Hz Mode** (Damping Ratio around 7%)
- **0.67 Hz Mode** (Damping Ratio around 6%)
- **0.75 Hz Osc**
0.67 Hz System Mode Shape from FSSI
0.78 Hz System Mode Shape from FSSI
Power Spectrum @ 3:15 AM (During)

Forced Oscillation Interacting with System Modes

Main mode 0.75 Hz
FSSI Estimates During GA Osc Event

Frequency vs Damping Ratio - 11/27/2016 12:39:30 AM to 12:46:00 AM

- 0.75 Hz Osc
- 0.78 Hz System Mode
- 0.67 Hz System Mode
- 0.7 Hz Osc

Damping Ratio / %
0.69 Hz System Mode Shape from FSSI
0.7 Hz Oscillation Mode Shape from FSSI
Resonance Conditions for 0.7 Hz

Georgia Oscillation

- 0.7 Hz Oscillation versus 0.67 Hz System Mode
- 0.67 Hz Well-damped (6% Damping Ratio)
- Forced Osc location near the two distant ends (strong participation) of the System Mode (not true)
- GA Location 22% Relative Energy for the Mode
- Interaction with 0.78 Hz mode?

Only 1+ conditions valid: Resonance effect small.
Special Reliability Assessment Summary

- Many inter-area modes in North American interconnections
- Mode shapes appear to be consistent in general across different events
- Damping levels have been from 6% to 10+% 
- Many forced oscillations are present that are exciting inter-area modes
- Mode shapes comparison between model based simulation and system PMU capture very useful.
- Report full draft by end May 2018