Oscillation Analysis
Informational Webinar
September 13, 2019
# Overview of Webinar

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<td>JP Skeath, NERC</td>
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<td>- <em>Interconnection-wide Data Collection</em></td>
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<td>All</td>
</tr>
</tbody>
</table>
System (Natural) Oscillations: low-frequency rotor angle oscillations caused by instantaneous power imbalances. Often referred to as local, intra-plant, inter-area, and torsional oscillations.

Forced Oscillations: sustained oscillations driven by external inputs to the power system that can occur at any frequency (e.g., unexpected equipment failures, control interactions, or abnormal operating conditions.)
## Characteristics of Oscillations

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>System</th>
<th>Forced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oscillation Mode</td>
<td>Natural property of electro-mechanical system; characterized by frequency, damping ratio, and shape</td>
<td>Not described by oscillation modes due to external forcing function acting on system</td>
</tr>
<tr>
<td>Mode Shape</td>
<td>Explains how parts of system interact with one another</td>
<td>Not described by system mode shapes; they have response based oscillatory characteristics</td>
</tr>
<tr>
<td>Frequency</td>
<td>Frequency at which oscillation is occurring; explains type of phenomena occurring in the BPS depending on range</td>
<td>Can occur at any frequency; often includes harmonic content of the fundamental forced oscillation frequency</td>
</tr>
<tr>
<td>Damping Ratio</td>
<td>Expresses how quickly an oscillation decays; tied to system stability</td>
<td>Typically very near zero since FOs caused by an external persistent input signal; does not necessarily mean the system is unstable</td>
</tr>
</tbody>
</table>
Oscillation Fundamentals

Oscillation Mode Shape

Oscillation Damping Ratio

Normal

Low

Marginal

Unstable

Source: Montana Tech
Characteristics of Oscillations

Source: Montana Tech
Oscillation Analysis Deliverables

- Hydraulics failure of control valve at large power plant in Louisiana area
- Forced oscillation frequency aligned with system mode frequency
- 200 MW oscillations at source; 40 MW oscillations on New England tie lines
- Oscillation persisted for 45 minutes; stopped upon reactor shutdown

*Forced oscillation interactions are not a rare occurrence...*
Interconnection-Wide Oscillation Analysis: Baselining Oscillation Modes in the North American Power System

NERC Synchronized Measurement Subcommittee (SMS) Scope Document

Objective

The objective of the work task to be performed by the NERC Synchronized Measurement Subcommittee (SMS) is to better understand the inter-area modes in each of the interconnections (Eastern, Western, ERCOT, and Quebec). The goal is to identify the modal characteristics (mode shape, mode frequency, mode damping ratio) of the interconnected bulk power system using high resolution, time-synchronized measurement data during major grid disturbances.

Purpose

Some interconnections such as the Western Interconnection have spent significant effort to understand the oscillatory modes of their respective interconnections, particularly due to the small signal stability risks posed to them. However, other interconnections have not cohesively analyzed the oscillatory modes of the system using wide-area synchrophasor data from Phasor Measurement Units (PMUs) or other types of high resolution, time-synchronized Disturbance Monitoring Equipment (DME). With the proliferation of PMUs across all interconnections in North America, in conjunction with the formation of the NERC SMS, the electric utility industry is equipped with the measurements and capability to perform such an analysis to better understand the inter-area modes on the system.

The purpose and goals of this task include:

1. Use synchronized measurements across the interconnection during grid disturbances or abnormalities to baseline the oscillatory performance of the interconnection.
2. Provide the electric utility industry with a better fundamental understanding of inter-area modes and forced oscillations on the bulk power system.
3. Enable better monitoring of system behavior and identify oscillatory conditions or anomalies on the system if and when they occur.
4. Use actual data measured during system events to compare the modal characteristics of the planning models used in transient stability studies (compare model vs. actual) as a component of system-wide model validation.

Oscillation Analysis
Data Request

Related Materials
Oscillation Analysis Scope
Data Request Guide
List of Reliability Coordinator Contacts

The NERC Synchronized Measurement Subcommittee (SMS) is requesting your assistance in collecting synchrophasor data from Phasor Measurement Units (PMUs) or other Dynamic Disturbance Recorders (DDRs) to assess the oscillation behavior of the Eastern Interconnection. Note that this data request applies to the Reliability Coordinators for the Regional Entities in the Eastern Interconnection: MRO, SERC, FRCC, RF, and NPCC. All related materials have been attached to this request and posted on the NERC website (links provided above). The event under consideration is a forced oscillation observed across the Eastern Interconnection during the following time:

Start Time: January 11, 2019 (2019-01-11) 08:35:00 UTC Time (03:35 EST)
End Time: January 11, 2019 (2019-01-11) 09:15:00 UTC Time (04:15 EST)
Interconnection Oscillation Analysis
Reliability Assessment
July 2019

Detailed Event Analysis
July 2019
Eastern Interconnection Oscillation Disturbance

January 11, 2019 Forced Oscillation Event

DRAFT
NERC Oscillation Analysis Technical Report
Coordinated Data Collection

Interconnection-Wide Oscillation Analysis: Baselining Oscillation Modes in the North American Power System

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Oscillation Analysis Data Request

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- Data Request Guide
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# Oscillation Analysis Events

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<thead>
<tr>
<th>Interconnection</th>
<th>Event Number</th>
<th>Chosen Algorithm</th>
<th>Chosen Data Source (All relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>Event 1: 2016-02-01</td>
<td>ERA</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 2: 2016-04-15</td>
<td>Matrix Pencil</td>
<td>First Derivative of Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 3: 2016-06-17</td>
<td>FSSI/FFDD</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 4: 2016-11-27</td>
<td>FSSI/FFDD</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 5: 2017-01-12</td>
<td>HTLS</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 6: 2017-02-14</td>
<td>Matrix Pencil</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 7: 2017-03-16</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td>Texas</td>
<td>Event 1: 2016-01-27</td>
<td>ERA</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 2: 2016-04-18</td>
<td>Prony</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 3: 2016-07-10</td>
<td>HTLS</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 4: 2016-10-23</td>
<td>HTLS</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 5: 2017-03-10</td>
<td>ERA</td>
<td>Bus Voltage Phase Angle</td>
</tr>
<tr>
<td>Western</td>
<td>Event 1: 2016-01-21</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 2: 2016-01-27</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 3: 2016-09-08</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 4: 2016-09-21</td>
<td>Prony</td>
<td>First Derivative of Voltage Phase Angle</td>
</tr>
<tr>
<td></td>
<td>Event 5: 2017-01-20</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 6: 2017-03-09</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
<tr>
<td></td>
<td>Event 7: 2017-05-10</td>
<td>HTLS</td>
<td>Bus Frequencies</td>
</tr>
</tbody>
</table>
• Event Analysis Offline (EAO)
  ▪ Ringdown analysis
  ▪ Prony, Matrix Pencil, HTLS, ERA
  ▪ Aimed at analyzing oscillation events resulting in sudden changes in damping

• Damping Monitor Offline (DMO)
  ▪ Ambient noise based. Continuous. Provides early warning on poorly damped modes.
  ▪ Several algorithms
  ▪ Fast Frequency Domain Decomposition (FFDD), Fast Stochastic Subspace Identification (FSSI).

• FFDD – Fast multi-dimensional analysis
• FSSI – Simultaneous estimation of modes and forced oscillations
Analysis Tool:
Damping Monitor Offline (DMO)

June 17, 2016 Eastern Interconnection Oscillation Event
Analysis Tool: Event Analysis Offline (EAO)
Overview of System Modes

Dominant Mode 1

Dominant Mode 2

Dominant Mode 3

<table>
<thead>
<tr>
<th>Interconnection</th>
<th>Mode Name</th>
<th>Mode Frequency Range (Hz)</th>
<th>Mode Average Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>NE–S</td>
<td>0.16–0.22</td>
<td>9.70</td>
</tr>
<tr>
<td></td>
<td>NW–S</td>
<td>0.29–0.32</td>
<td>16.45</td>
</tr>
<tr>
<td></td>
<td>NE–NW–S</td>
<td>0.23–0.24</td>
<td>12.80</td>
</tr>
<tr>
<td>Texas</td>
<td>N–SE</td>
<td>0.62–0.73</td>
<td>9.26</td>
</tr>
<tr>
<td>Western</td>
<td>NS Mode A</td>
<td>0.37–0.42</td>
<td>12.71</td>
</tr>
<tr>
<td></td>
<td>NS Mode B</td>
<td>0.24–0.27</td>
<td>13.525</td>
</tr>
</tbody>
</table>
EI System Modes

<table>
<thead>
<tr>
<th>Mode Frequency (Hz)</th>
<th>Event 1 Damping Ratio (%)</th>
<th>Event 2 Damping Ratio (%)</th>
<th>Event 5 Damping Ratio (%)</th>
<th>Event 6 Damping Ratio (%)</th>
<th>Event 7 Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16–0.22</td>
<td>NO</td>
<td>13</td>
<td>8.3</td>
<td>7.8</td>
<td>NO</td>
</tr>
<tr>
<td>0.29–0.32</td>
<td>NO</td>
<td>20</td>
<td>NO</td>
<td>12.9</td>
<td>NO</td>
</tr>
<tr>
<td>0.23–0.24</td>
<td>13.4</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
<td>12.2</td>
</tr>
</tbody>
</table>

Note: NO—Not Observed or Well Damped
TI System Mode

0.62-0.73 Hz
N – SE

<table>
<thead>
<tr>
<th>Mode Frequency (Hz)</th>
<th>Event 1 Damping Ratio (%)</th>
<th>Event 2 Damping Ratio (%)</th>
<th>Event 3 Damping Ratio (%)</th>
<th>Event 4 Damping Ratio (%)</th>
<th>Event 5 Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.62–0.73</td>
<td>7</td>
<td>9.9</td>
<td>10.2</td>
<td>8.2</td>
<td>11</td>
</tr>
</tbody>
</table>
WI System Modes

Mode Frequency (Hz) | Event 1 Damping Ratio (%) | Event 2 Damping Ratio (%) | Event 3 Damping Ratio (%) | Event 4 Damping Ratio (%) | Event 5 Damping Ratio (%) | Event 6 Damping Ratio (%) | Event 7 Damping Ratio (%)
---|---|---|---|---|---|---|---
0.37–0.42 | 12 | 9.9 | 10.2 | 10.8 | 13.8 | 14 | 18.3
0.24–0.27 | NO | 8.6 | 18.2 | 9.8 | NO | NO | 17.5
Forced Oscillation Interactions

Table 1.2: Interaction of Forced Oscillation and Interarea Modes

<table>
<thead>
<tr>
<th>FO Frequency (Hz)</th>
<th>0.3 Hz System Mode</th>
<th>0.67 Hz System Mode</th>
<th>0.76 Hz System Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28^1</td>
<td>S</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>0.75^2</td>
<td>NO</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>0.70^3</td>
<td>NO</td>
<td>S</td>
<td>S</td>
</tr>
</tbody>
</table>

Note: S–Mild Resonance Effects; M–Medium Resonance Effects; H–High Resonance Effects; NO–Not Observed
Forced Oscillation Interactions

0.70 Hz Forced Oscillation Resonance Shape

0.69 Hz System Mode Shape
Report Key Findings and Conclusions

Primary:
• Continued detailed oscillation studies (*TP, PC, RC*)
• Standardized data formats (*Industry*)
• System operator training and support (*RC, TOP*)

Secondary:
• Simulation software improvements – oscillation benchmarking (*Vendors*)
• Improved visibility of interarea oscillations (*TO, PC, RC*)

<table>
<thead>
<tr>
<th>Interconnection</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>WI</td>
<td>• Improve understanding of east–west modes (Montana and Colorado participation)</td>
</tr>
<tr>
<td>TI</td>
<td>• Increase PMU coverage from northwestern region</td>
</tr>
</tbody>
</table>
| EI              | • Perform studies to better understand widespread system modes (near 0.25 Hz)  
• Track the 0.78 Hz forced oscillation source; monitor mode shapes around 0.67 to 0.8 Hz  
• Understand why these shapes do not extend to New York/Canada or Florida regions |
January 11, 2019 Forced Oscillation Event Analysis
• Oscillation observed across entire Eastern Interconnection
  ▪ Start Time: 08:44:41 UTC (03:44:41 EDT)
  ▪ End Time: 09:02:23 UTC (04:02:23 EDT)
  ▪ Oscillation frequency = 0.25 Hz (aligns with system mode across EI)
  ▪ Large power swings observed across EI

• RCs identified oscillation using PMU data
  ▪ RC communication challenged; RC Hotline down
  ▪ Early misidentification of oscillation source

• NERC issued PMU data request
Forced Oscillation Source

- Steam turbine at combined cycle plant
- Power-load imbalance (PLI) controls
  - Failed voltage input to feedback
  - Measured $P_{gen}$ reading 2/3 of actual
  - Perceived power-load imbalance
- PLI trigger shuts intercept valves
- 4 second timer to reopen valves
- Imbalance eliminated and valves reopen
  - ... and repeat .... and repeat
- Different voltage measurements for relaying and controls/metering
  - Hence no relay operation
- Plant manually tripped by operator
- Upon inspection, failed wiring in PT cabinet
- Damaged intercept valves
  - Replacement needed
  - Unit off-line for multiple weeks
Initiation of Oscillation Event

FNET Data Display [1/11/2019 Non-obvious Event]
Time: 8:44:6.9 UTC  59.9824 Hz
Persisting Forced Oscillation

Oscillation Mode Shapes (Using Matrix Pencil algorithm)

Mode #1: Frequency: 0.25 Hz, Damping Ratio: 0.16 %, Amplitude: 2.38 °

<table>
<thead>
<tr>
<th>UnitName</th>
<th>Frequency(Hz)</th>
<th>Damping Ratio(%)</th>
<th>Phase (Degree)</th>
<th>Amplitude(Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UsNvFulton0326</td>
<td>0.25</td>
<td>92</td>
<td>0.64</td>
<td>2.16</td>
</tr>
<tr>
<td>UsGaNorcross954</td>
<td>0.25</td>
<td>39</td>
<td>-72.11</td>
<td>3.44</td>
</tr>
<tr>
<td>UsVaNewportnews847</td>
<td>0.25</td>
<td>75</td>
<td>-57.24</td>
<td>1.91</td>
</tr>
<tr>
<td>UsFlMiami742</td>
<td>0.25</td>
<td>33</td>
<td>-64.35</td>
<td>9.26</td>
</tr>
</tbody>
</table>
Line Flows in Florida
500 kV Bus Voltage in Florida
Line Flows in TVA Region

SCADA Data – Flow on 500 kV tie line with Southern Company

200 MW Peak to peak
Line Current on East-West 765kV line

Line Flows in ISO-NE Region

MW flow on 345KV line between NE and NY

*Step changes attributed to unrelated actions locally.
Observed Oscillation

0.25 Hz Mode present in PMU voltage channel
January 11, 2019 Forced Oscillation Oscillation Analysis
Forced Oscillation
Comparison with Oscillation Report

- Confirmed NE-NW-S mode has a composite mode shape
- Resonance between FO and system mode (*low-medium*)
  - Closely matching frequencies
  - Some alignment in participation factors
  - High system mode damping

January 11th Forced Oscillation Analysis
Sustained (Growing) Oscillation

Forced oscillation growing; reason unknown

~ 17.5 Minutes
• RCs should ensure coordination with neighboring RCs regarding how to handle wide-area oscillation events.
  ▪ Industry agrees that more visibility and communication is needed for these type of events
  ▪ Utilities need better understanding of these types of events, and how to identify and respond appropriately

• RCs should incorporate oscillation events and appropriate operating procedures into their operator training

• NERC Reliability Standards should be reviewed for communication during these types of events
Western Interconnection Oscillation Activities
• 2013 WECC JSIS* report described known modes
  - North–South A ~ 0.23 Hz
  - North-South B ~ 0.4 Hz
  - North-South (AB disconnected) ~ 0.32 Hz
  - East-West A ~ 0.45 Hz
  - British Columbia ~ 0.6 Hz
  - Montana ~ 0.8 Hz

• Confirmed in NERC Oscillation Analysis report

*JSIS: Joint Synchronized Information Subcommittee
• Update to WECC modes report
  ▪ Led by WECC JSIS Oscillation Analysis Working Group (OAWG)
  ▪ Scope
    o Using GE PSLF base cases and snapshot cases to perform planning studies
    o Model-based small signal analysis to validate known modes
    o Measurement-based analysis using PMU data

• Dynamic System Tests
  ▪ Probing signal injection with the Pacific DC Intertie (PDCI)
  ▪ Insertion of the Chief Joseph dynamic brake to create ringdown events
• Managing the Peak RC wind-down
  ▪ CAISO now receiving live PMU data from entities for oscillation monitoring
  ▪ Peak RC and Washington State University (WSU) supporting CAISO to set up their tool for forced oscillation source localization

• WECC is beginning study on correlation between system inertia and inter-area oscillations

• Peak RC observed interactions between forced oscillations and the Montana and British Columbia modes – further study planned
Wrap Up:

Key Takeaways and Recommendations
Oscillation Analysis:

- Dominant modes in EI, TI, and WI identified

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- Standardized PMU data formats needed for offline analysis
- Oscillation benchmarking simulation improvements needed

January 11 Forced Oscillation:

- Interactions between forced oscillations and system modes occurred multiple times – recurring theme
- Failure at combined cycle plant involving PLU control
- Interaction with system mode – observed across entire EI
• TPs, PCs, and RCs should continue oscillation studies to understand current and future system modes
  ▪ Current modes: real-time operations
  ▪ Future modes: planning assessments, changing resource mix, dispatch patterns, technologies, etc.
• Improved observability of inter-area oscillations
  ▪ Additional PMUs in certain areas needed (being added)
• Standardized data formats for off-line engineering analysis
• PLU and other cyclic controls should not be set to coincide with reciprocal of system mode frequency \( f = 1/T \)
• Redundancy in turbine control system inputs needed
• Operator training – appropriate actions during oscillation events
• Operating procedures for taking appropriate action to mitigate or eliminate sustained/undamped oscillations
• Interconnection-wide oscillation tools needed
  ▪ Interconnection-wide PMU-quality data set needed
  ▪ Timely/effective source location is crucial for mitigation
• RC coordination with neighboring RCs and GOPs
  ▪ Review NERC Reliability Standards
• Industry education of system modes and forced oscillations
• NERC Reliability and Security Guidelines:

• NERC Reliability Guideline: Forced Oscillation Monitoring and Mitigation:

• NERC Oscillation Analysis Technical Report:

• NERC Oscillation Analysis Detailed Report:

• NERC Synchronized Measurement Subcommittee (SMS) Webpage:

• WECC Oscillations Analysis Work Group (OAWG) Webpage:
  https://www.wecc.org/RAC/Pages/OAWG.aspx

• WECC JSIS 2013 Oscillation Analysis Report:
  https://www.wecc.org/Reliability/WECC%20JSIS%20Modes%20of%20Inter-Area%20Oscillations-2013-12-REV1.1.pdf
Questions and Answers