Interconnection Oscillation Analysis

Reliability Assessment

November 2018
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Preface

The vision for the Electric Reliability Organization (ERO) Enterprise, which is comprised of the North American Electric Reliability Corporation (NERC) and the seven Regional Entities (REs), is a highly reliable and secure North American bulk power system (BPS). Our mission is to assure the effective and efficient reduction of risks to the reliability and security of the grid.

The North American BPS is divided into seven RE boundaries as shown in the map and corresponding table below. The multicolored area denotes overlap as some load-serving entities participate in one Region while associated Transmission Owners/Operators participate in another.

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRCC</td>
<td>Florida Reliability Coordinating Council</td>
</tr>
<tr>
<td>MRO</td>
<td>Midwest Reliability Organization</td>
</tr>
<tr>
<td>NPCC</td>
<td>Northeast Power Coordinating Council</td>
</tr>
<tr>
<td>RF</td>
<td>ReliabilityFirst</td>
</tr>
<tr>
<td>SERC</td>
<td>SERC Reliability Corporation</td>
</tr>
<tr>
<td>Texas RE</td>
<td>Texas Reliability Entity</td>
</tr>
<tr>
<td>WECC</td>
<td>Western Electricity Coordinating Council</td>
</tr>
</tbody>
</table>
NERC, as the ERO, is tasked with the mission of assuring the reliability of the North American BPS. This is done in a variety of ways, including identifying areas where NERC can play a key role in supporting assessment of interconnection-wide assessments like this Interconnection Oscillation Analysis, a reliability assessment falling under NERC Rules of Procedure. The scope of this report can be found here as approved by the NERC Planning Committee where NERC staff will work alongside SMS members in developing the report. This report provides technical reference material focusing on system (natural) modes of oscillation and an assessment of all oscillations (natural and forced) in each interconnection using time synchronized measurement data for actual system events. The intent of this report is to inform on mode shapes and behaviors and is not to provide mitigation strategies for oscillatory events. This report is primarily dedicated to understanding the processes and methods associated with the analysis of oscillatory events.

This report summarizes the NERC Synchronized Measurement Subcommittee’s efforts to collect interconnection-wide, time synchronized measurement data from phasor measurement units (PMUs) and to analyze the synchrophasor data to determine the system oscillatory characteristics. Analysis of interconnection-wide oscillations supports the electric utility industry in understanding how the BPS responds to grid disturbances and aids in the monitoring and mitigation of poorly damped system modes and significant forced oscillations by identifying the areas of high participation factors. Synchrophasor data collected from Reliability Coordinators (RCs) across each interconnection is assessed to develop trends and characterize the system modes. This analysis is translated into key findings and recommendations for the electric utility industry moving forward.

Conclusions and Findings
For all the chosen events for analysis for all interconnections, only a handful exhibited forced oscillatory behavior and all resonance effects were deemed to be mild, which indicates that the conditions surrounding the event were not as severe as it could have been given the resonance conditions. In the events, a total of six dominant modes were prominent for those events chosen. Each mode was given a name that describes the general shape of the mode where a previous name has not already been given. The frequency range and average damping ratio is provided for these modes in Table E.1. Throughout this report, references to modal damping ratio and frequency are provided, but are not the focus of this report as system conditions will impact the frequency and damping ratio of the natural system mode. Whenever the damping ratio is “well damped” (or greater than 10 percent), the signal oscillation dampens down so quick the numerical percentage is not as relevant. This does not indicate “poor damping” below 10 percent, however. Damping Ratio Performance criteria can be found in individual Reliability Coordinator System Operating Limit Methodologies and discussion of such performance is out of this document’s scope.

<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>
</tbody>
</table>

1 The complete document can be found here.
Recommendations
NERC recommends a few next steps in enhancing the understanding of the oscillatory parameters of the BES. Namely:

- NERC strongly urges each interconnection to take the mode shape plots included in the appendices and to identify which set of generators poses the largest risk in exciting these mode shapes.
- NERC also urges implementing agreed upon modifications to the format for submitting PMU data for this type of analysis as there were consistency issues in this data set. After completing these initial steps, NERC believes that the best approaches for continual study include a pre-emptive approach in identifying changing system mode shapes, as well as a verification test done similar to the structure seen in this report.
- In the Western Interconnection (WI), NERC recommends to better understand the East-West modes, specifically how Montana and Colorado participate in the system modes.
- In the Texas Interconnection (TI), NERC recommends increasing the PMU coverage from the NW to better observe the mode as that region was lacking in the data submitted.
- For the Eastern Interconnection (EI), NERC recommends a better understanding of the two modes near 0.25 Hz.
  - In addition, NERC recommends for the EI to track the 0.78 Hz forced oscillation source observed in many of the events and to monitor the mode shapes of the inter-area modes in the frequency range of 0.67 to 0.8 Hz which were involved in a major forced oscillation event. In particular, it would be useful to understand why these shapes do not extend into the New York/Canada regions in the North and do not extend into the Florida region in the South.
- In general, NERC recommends that all three interconnections continue studies on whether the mode shapes of respective dominant inter-area modes discussed in this report are sensitive to specific path flows, and the source-sink relationships for these modes.
- Since the report discusses the occurrence of two forced oscillation events in EI which led to persistence of wide-area oscillations observed over wide geographical regions each lasting longer than thirty minutes, NERC recommends adequate training and support for system operators and coordination among reliability coordinators on how to handle system conditions during such wide area events.
- For better understanding of such forced oscillation events in planning and operational studies, NERC recommends the system simulation software tools to include the capability for modeling injection of such forced oscillations at different source locations in the grid.

Synchronized Measurement System
For the results to become more useful to the industry at large, NERC recommends interconnections utilize the trend of increasing PMU density in order to gain visibility into previously unmeasured sections of the interconnection. NERC recommends looking at the PMU placement in relationship to the areas of low visibility in the system to confirm or counter the results presented in this report. A continual effort to understand the mode shapes is warranted based off the changing nature of the mode shapes and the multitude of factors that contribute to the mode shape parameters. Future study efforts can utilize the PMU network growth to possibly eliminate uncertainties presented in this report, especially if a majority of generating units were monitored.

Data Formatting Consistency
Throughout the process of collecting and sorting through data, a variety of different approaches for representation of the requested data were observed. The RCs who submitted data in the Eastern Interconnection had vastly different methods for presenting their data. Some of these differences included representing their kV magnitude column in volts rather than kilovolts as their metadata indicated. Others submitted all outgoing signals from the PMU (ex.

<table>
<thead>
<tr>
<th>Western</th>
<th>NS Mode A</th>
<th>0.37-0.42</th>
<th>12.71</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NS Mode B</td>
<td>0.24-0.27</td>
<td>13.525</td>
</tr>
</tbody>
</table>
Latency, breaker status, etc.) that were unused for the oscillations analysis and some did not indicate a region where the signal was located (ex. VoltMag1). NERC recommends that an agreed upon format for sending PMU data for oscillations analysis be implemented and followed by the RCs when a request for information is sent.
Introduction

Oscillations across all interconnections in North America have been observed over the years, with different phenomena causing those oscillations. Some are localized to one or a group of power plants while others are experienced across a wide area. The Western Interconnection, for example, has spent significant effort understanding the oscillatory behavior of that interconnection due the small signal stability risks experienced in the 1996 blackout\(^2\) and continued oscillatory risks during highly stressed operating conditions (although rare). Other interconnections have not collectively analyzed the oscillatory modes of their system using wide-area, time-synchronized data. However, with the proliferation of Phasor Measurement Units (PMUs) and other types of Disturbance Monitoring Equipment (DME), the industry is equipped with the measurements and capability to perform such analysis to better understand inter-area system modes. The purpose and goals of this effort include:

1. Use synchronized measurements across the interconnection during grid disturbances or abnormalities to baseline the oscillatory performance of the interconnection.
2. Provide the industry with a better understanding of inter-area modes and forced oscillations on the BPS.
3. Recommend improvements to monitoring BPS behavior and identifying oscillatory conditions or sources, if and when they occur.
4. Use measured data during BPS disturbances to compare the modal characteristics of the planning models used in transient stability studies (compare model versus actual oscillations) as a component of system-wide model validation.

This analysis involved coordinating with the Regional Entities and all Reliability Coordinators (RCs) to collect wide-area PMU data. Data was also collected from the University of Tennessee – Knoxville (UTK) GridEye/FNET system. Lastly, NERC coordinated with the MOD-032 Designees\(^3\) in order to perform benchmarking of planning cases against the actual oscillation events. These analyses are described in this report as a way to demonstrate oscillatory characteristics of each interconnection. The intent of this report is to inform on mode shapes and behaviors and is not to provide mitigation strategies for oscillatory events.

Historical Oscillation Events

A number of large-scale outages and near miss events have included oscillations as either a cause or effect of the event. This section provides examples of inter-area oscillation events as well as events with interaction between system modes and forced oscillations.


\(^3\) The current list of MOD-032 Designees can be found in this document.
WSCC August 10, 1996 Disturbance
On August 10, 1996, at 15:48 PDT, a sequence of events caused the Western Interconnection to separate into four electrical islands. System conditions included high summer temperatures in much of the interconnection, heavy exports from Canada across the Pacific Northwest into California, and 500 kV line outages in Oregon. The California–Oregon Intertie (COI) flow (about 4,350 MW) was within limits established as an outcome of the July 2-3 outages that had just recently occurred. Flow on the Pacific DC Intertie (PDCI) was 2,848 MW.

At 15:47:36 PDT, system protection removed the faulted Ross – Lexington 230 kV transmission line, also tripping the Swift generating units (207 MW). Reactive output of the McNary hydro units increased to 480 MVAr and then to 494 MVAr. The units held at this level for a short time until system protection began removing them from service. Between 15:47:40 and 15:49 PDT, all 13 units at McNary were removed from service as a result of erroneous operations of a phase unbalance relay in the generator exciters.

As the McNary units tripped due to high reactive power output, a poorly damped inter-area oscillation began across the BPS. Generation in the Upper and Lower Columbia River hydro projects picked up much of the lost generation, further stressing transfers across the system. Eventually the oscillation became negatively damped. Shunt capacitors switched in key locations on the BPA system; however the oscillation continued and the PDCI also began oscillating in response to the poor AC voltage. As the oscillations reached about 1,000 MW and 60 kV peak-to-peak at Malin 500 kV substation, voltage collapsed. This severed the ties between the Pacific Northwest and California and eventually caused the other ties between California and its neighbors to also open due to low voltage and out-of-step protection.

WSCC August 4, 2000 Alberta Separation
On August 4, 2000, Alberta disconnected from the rest of the WSCC system, separating its one 500 kV and two 230 kV ties between Alberta and British Columbia systems. While this separation is studied and is planned for, this particularly event resulted in marginally damped inter-area oscillations occurring following the separation. The oscillation continued for more than 60 seconds. While the separation did not cause any widespread instability or outage, it did identify a poorly damped inter-area mode worth further investigation and study.
WECC November 29, 2005 Oscillation Event
In November of 2005, a failed control valve at Nova Joffre cogeneration facility in Alberta, Canada caused a 20 MW peak-to-peak oscillation to occur at 0.27 Hz. The Western Interconnection has a system mode at about that same frequency. The forced oscillation due to the failure at the plant excited the North-South system mode, resulting in 200 MW peak-to-peak oscillations on the COI (see Figure I.3). For about 5 minutes, the oscillation persisted until the steam supply diminished. This event is useful in illustrating the importance of identifying system modal characteristics to understand how unexpected forced oscillations can interact with the system modes.

WECC September 5, 2015 Oscillation Event
On September 5, 2015, Peak Reliability's online modal analysis software indicated very low damping for the “North-South Mode B.”. At the time, there were no significant changes in transmission topology, generation, or loading to explain the sudden decrease in damping. After investigation, Peak determined that a forced oscillation from a relatively small 30 MVA machine in the Nevada area was the actual problem. Real power flow on a nearby line showed oscillations on the order of 6 MW peak-to-peak. However, the oscillation was experienced across the Western Interconnection since the forced oscillation frequency (0.395 Hz) occurred near a system mode (0.403 Hz). Though the mode’s damping was unchanged, the presence of the forced oscillation confused the modal analysis software. Since this event, algorithms and tools have been developed to prevent similar confusion in the future. Results from a post-event analysis showing both the mode and the forced oscillation are presented in Figure I.4.

Eastern Interconnection June 17, 2016 Oscillation Event
On June 17, 2016, a forced oscillation in the Eastern Interconnection (EI) occurred at 0312 Eastern Daylight Time around 0.27 Hz. The EI has a system mode near that frequency that resulted in an interaction between the forced oscillation and system mode at that frequency. This caused the forced oscillation to show up across the system. The source was determined to be a control valve malfunction at Grand Gulf Nuclear Station (GGNS) in Entergy footprint; however, power oscillations were seen across the entire EI system. Figure I.5 shows the two line flows (green and blue trends) capturing GGNS output. Because of the interaction with the eastern system mode, the 200 MW forced oscillation at Grand Gulf resulted in 40 MW tie line oscillations on one of the New York to New England lines about
1400 miles away (Figure I.6) from the source in Mississippi. This event is explained in more detail in Appendix B. An animation of the event has been prepared by the FNET GridEye monitoring system at University of Tennessee Knoxville. The animation clearly shows inter-area oscillations across the Eastern Interconnection during this event.

Figure I.5: Approximately 200 MW Forced Oscillation at GGNS [Source: Entergy]

Figure I.6: Approximately 40 MW Oscillations Seen in New England Region [Source: ISO-NE]

Characteristics of Each Interconnection
The three major interconnections in the North American power system, namely, the Eastern, Western and ERCOT interconnections, have different oscillatory characteristics because of differences in generation-load patterns and the structure of transmission lines. Western Interconnection (WI) historically has been characterized by long transmission lines that carry power from generation rich regions, hydro plants in Northwest America and Western Canada, coal plants and wind energy farms in Montana and Wyoming, down to load centers in California. WI has experienced major events associated with inter-area mode oscillations where the generators in the North were swinging against

the generators in the South across the long distance transmission lines. Eastern Interconnection (EI) on the other hand has a mesh like transmission line structure where the oscillatory properties are more complex and can change depending on the nature of power exchanges across different regions in EI. This characteristic is true for most sections of the EI; however, the upper Midwest region, which is transmission sparse in comparison to the coastal regions. The Texas Interconnection (TI) like WI also has clear distinct oscillatory modes because of North to South power exchanges. Moreover, the smaller size of the TI compared to EI and WI makes it more sensitive to changes in system inertia and transmission support. The fast growth in wind energy sources in the western portion of Texas has introduced more variability in the transmission line flows in the TI system. In general, the increasing penetration of renewable energy sources in all three interconnections points to a continuously evolving nature of oscillatory modes in the interconnections and emphasizes the need for regular monitoring of the system modes for understanding their significance and implications.

**Measurement Infrastructure**

A phasor measurement unit (PMU) is a device which measures the electrical quantities on the grid using a synchronized time source. Time synchronization is usually provided by the Global Positioning System (GPS), providing a high accuracy, common time reference for measurements taken across the grid. The PMU then converts the sinusoidal time series measurement of voltage and current into a phasor representation. A phasor is a complex number that represents both the magnitude and phase angle of the voltage and current sinusoidal waveforms (60 Hz) at a specific point in time (see Figure 1.7). The resulting measurement is known as a synchrophasor, and these measurements are typically reported at rates of 30-60 samples per second. Compared with conventional measurement technologies such as the supervisory control and data acquisition (SCADA) systems that provide system measurements once every two to four seconds, the higher resolution and time synchronization of PMU technology enables significant improvements in monitoring, control, and performance analysis of the BPS.

![Sinusoidal Waveform and Phasor Representation](image)

*Figure 1.7: Sinusoidal Waveform and Phasor Representation [Source: CERTS]*

Synchrophasor systems consist of PMUs installed throughout the grid, sending measurements over a reporting protocol, IEEE Std. C37.118. The streams of C37.118 measurement frames are aggregated and time aligned at a

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5 For history of the C37.118 standards development, see relevant IEEE standards:
- C37.118-2005 IEEE Standard for Synchrophasors for Power Systems
- C37.118.1a-2014 IEEE Standard for Synchrophasor Measurements for Power Systems – Amendment 1: Modification of Selected Performance Requirements
- C37.118.2-2011 IEEE Standard for Synchrophasor Data Transfer for Power Systems
device called a phasor data concentrator (PDC). Once the synchronized measurements have been collated, checked for data quality, etc., they are provided to historians and advanced applications (either offline or real-time) for further processing and use. The PMUs are generally owned by the equipment owners such as the Transmission Owners (TOs) and Generator Owners (GOs). PMU data is often sent to a central PDC (or sometimes first to a substation PDC) that is either owned by the TO or may be owned by the RC. If not streamed directly, data is passed from the TO to the RC for a wide-area view of the system. In some cases, not all synchrophasor data is sent from the TO to the RC; rather, a reduced set of key measurements are selected for RC observability and use.

With the help of the Recovery Act Smart Grid Investment Grant (SGIG) projects and DOE-sponsored efforts related to synchrophasor technology, the North American power grid has seen a vast deployment of PMUs over the last decade. Thousands of PMUs have been deployed across all interconnections, unlocking visibility into grid dynamics and improved monitoring capability. Figure I.8 shows the map of PMU installations as of 2015, created by the North American Sychrophasor Initiative (NASPI).6

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![Figure I.8: Synchrophasor Deployment Map – 2015](https://www.naspi.org/)

**Data Collection Process**

In June 2016, the NERC SMS scoped out a data collection process in coordination with the Reliability Coordinators (RCs) and Regional Entities (REs) to collect wide-area, time-synchronized PMU data for disturbance events for the purposes of analyzing the oscillatory behavior of those events. The data collection process also served to test the ability to gather interconnection-wide data in large quantities for future event analysis, if needed. Each data request was coordinated with the NERC Synchronized Measurement Subcommittee (SMS) as well as the RCs to ensure a reasonable yet thorough collection of data across a wide range of events. RCs have the wide-area view and stream real-time PMU data from the respective equipment owners. Generally, the RC only receives select measurements determined valuable for the wide-area perspective. These measurement locations are ideal for oscillation analysis studies and provide wide-area coverage of key BPS locations.

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6 [https://www.naspi.org/](https://www.naspi.org/)
The data reporting duration, measurement requirements, formatting requirements, and submission process can be found in the Oscillation Analysis Scope Document.\(^7\)

Chapter 1: Power System Oscillations and Analysis Techniques

This chapter briefly describes some fundamental aspects of BPS oscillations as well as describes various analysis techniques. It also provides information regarding the analysis techniques used in this oscillation assessment.

Fundamentals of Power System Oscillations

Oscillations are always present in the BPS due to the electromechanical nature of the electric grid. Under no significant external influence to the system, the grid still oscillates at its natural frequencies for small disturbances such as constant changes in load. These oscillations are usually well-damped and contained; however, growing or high-energy oscillations can present system instability, potential equipment damage, safety concerns, and power quality issues. In addition to these natural oscillations, forced or “rogue” inputs to the system can also cause oscillations and should be detected and mitigated to the extent possible. To explain these concepts of oscillations on the BPS, it is important to clearly differentiate between the types of electromechanical oscillations that are present. From a practical standpoint, power system oscillations can be categorized as follows:

- **System (Natural):** low-frequency rotor angle oscillations caused by instantaneous power imbalances. These are often differentiated further as follows:
  - **Local:** oscillations where one power plant or generating unit oscillates with the rest of the system, generally caused by heavy loading and generator excitation and turbine-governor controls
  - **Intra-plant:** oscillations where generating units within a power plant oscillate with each other at the same location, generally caused by poor tuning of plant controls, unit control interactions, and unit operating modes
  - **Inter-area:** oscillations characterized by several coherent units or parts of the system oscillating against other groups of machines, often predominant in power systems with relatively weaker inter-area connections
  - **Torsional:** high frequency (below 60 Hz) oscillations caused by resonance conditions between highly compensated transmission lines and the mechanical modes of a steam-turbine generator (typically referred to as subsynchronous resonance).

- **Forced:** sustained oscillations driven by external inputs to the power system, such as unexpected equipment failures, control interactions, or abnormal operating conditions that can occur at any frequency.

Chapter 1 of the *Reliability Guideline: Forced Oscillation Monitoring and Mitigation* provides a useful high-level reference regarding fundamentals of power system oscillations, which is briefly summarized in Table 1.1.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>System</th>
<th>Forced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>Natural property of electro-mechanical system; characterized by frequency, damping ratio, and shape</td>
<td>Due to external forcing function acting on system</td>
</tr>
</tbody>
</table>

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8 Electromagnetic oscillations can also occur in power systems. These types of oscillations are outside the scope of this guideline.

9 These types of oscillations are normally manifested within the plant site and often difficult to observe external to the power plant itself.


<table>
<thead>
<tr>
<th>Characteristic</th>
<th>System</th>
<th>Forced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape</td>
<td>Explains how parts of system interact with one another, related to eigenvectors of the linearized system</td>
<td>Measure of the amplitude and relative phasing of the oscillation at different locations in the system.</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>Appear as sustained oscillations due to the persistence of their source and do not reflect the system’s damping.</td>
</tr>
</tbody>
</table>

**Interactions between System and Forced Oscillations**

The interaction and relationship between natural modes of the system and forced oscillations are documented in the *Reliability Guideline: Forced Oscillation Monitoring and Mitigation*, which can be referred to for more information. This report includes analysis of both types of oscillations captured by PMU data, so it is important for the reader to familiarize themselves with these oscillations. There have been documented instances, described throughout this guideline, where generating plants across North America that experienced a forced oscillation have induced larger system-wide oscillations. This drives the need to understand the system modes in each of the interconnections to be prepared for these types of situations where the oscillations could interact with one another. Understanding the potential interactions is critical when trying to identify the source of oscillations, particularly when they are observed throughout the BPS.

For interactions between system modes and forced oscillations to occur (i.e., “resonance effect”), the following conditions must be met. A strong resonance effect occurs when all three conditions are met, a moderate resonance effect when two conditions are met, and a mild resonance effect when one condition is met.

1. The forced oscillation frequency must be near a system mode frequency
2. The system mode must be relatively poorly damped
3. The forced oscillation must have strong participation in the system mode.

An example of a forced oscillation is in Figure 1.1. The forced oscillation has a frequency of 0.27 Hz (largest peak value of the frequency domain power spectrum density estimate). The forced oscillation also includes second and third harmonics (corresponding to peaks at 0.54 Hz and 0.81 Hz, respectively, in Figure 1.1). The other peak at 0.75 Hz is caused by a different forced oscillation at a different location in the system.

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Types of Oscillation Analysis Techniques

There are numerous algorithms and techniques to analyze power system oscillations either in real-time tools or offline analysis. IEEE Power and Energy Society (PES) developed a comprehensive technical report, Identification of Electromechanical Modes in Power Systems, on power system oscillations and modal identification methods used to study electromechanical modes. It also describes experience and performance of these methods in actual tools. Consider referring to that document for a much more detailed description of some of the techniques described here.

Ringdown Methods

Ringdown methods are used to analyze natural oscillations that result from large disturbances on the BPS (e.g., faults, switching action, loss of generation or load, etc.). These methods include, but are not limited to, the following:

- **Prony Methods**: Prony’s original method proposed in 1795 estimates damped sinusoidal components in a linear system response by expressing the system outputs as linear combinations of fundamental sinusoidal modal components. Prony methods have evolved a lot over the years and the modern versions include Singular Value Decompositions (SVDs) for handling the measurement noise and for reducing the computational burden. This method can estimate the dominant mode frequencies, their damping levels, their mode shapes, and relative energy levels from multiple measurements.

- **Eigensystem Realization Algorithm (ERA)**: The Eigensystem Realization Algorithm (ERA) is a system identification method well suited for the identification of lightly damped oscillations. Its application in a variety of fields is well documented. In this method, the number of significant modal components in a given signal (or signals) is obtained from the singular value decomposition of a matrix whose entries are samples of the system impulse response (Hankel matrix). Typically, this is a relatively small number. Using this information, a reduced linear system realization is computed, i.e., the system state matrices. The significant modal damping ratios and frequencies in the given signals can be readily computed from the reduced system.

- **Matrix Pencil**: Matrix Pencil method formulates the ringdown analysis problem as a generalized eigenvalue problem of an associated matrix pencil. This involves computation of a pseudo-inverse of a matrix that is done using an SVD technique. This also includes a built-in filter for leaving out noise related phenomena in the SVD formulation.

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• **Variable Projection (VARPRO):** The variable projection method is a general nonlinear least-squares optimization technique for fitting a waveform to a basis of fundamental curves. In the context of modal analysis, the waveform is the measured ringdown response which we want to express in terms of a combination of exponentially damped oscillatory waveforms. The basis of curves used in the method include exponentially damped oscillatory waveforms, simple exponentials, and detrending waveforms. The results of the variable projection curve-fitting process are the frequency, damping, amplitude, and phase of each oscillatory component in the response, the amplitude, and decay of each exponential component, and the coefficients of the detrending waveforms. This method is distinguished from other common techniques for modal analysis in that it is a direct curve-fitting technique.15

• **HTLS:** Hankel Total Least Squares first formulates a Hankel matrix from the observed PMU measurements of the event, and then uses a Total Least Squares approach for evaluating the eigenvalues again using a SVD computation. By modeling the noise explicitly in the formulation, the HTLS approach is somewhat better in handling noisy data compared to the other methods.

• **Frequency Domain Methods:** In frequency domain ringdown analysis methods such as MFRA16, the method identifies the system modes by finding the local peaks in the FFT response of the outputs first. Then the damping of the modes is estimated by tracking how the energy of the mode in the frequency domain changes over time. Frequency domain methods for oscillation detection use the fact that the energy in PMU measurements remains relatively constant over time under ambient conditions. When a sustained oscillation begins, it adds significant energy to the collected measurements. Frequency-domain methods for sustained oscillation detection operate by monitoring the signal energy of measurements for significant changes. Detectors operate in the frequency domain because the energy in sustained oscillations is not evenly distributed over the frequency ranges captured by PMU measurements. A significant increase in a frequency range’s energy indicates that a sustained oscillation is present in that frequency range.17

**Ambient Methods**

Ambient methods are used to analyze signals during normal steady-state conditions where the primary excitation to the system is random load changes. These methods include, but are not limited to, the following:

• **Yule-Walker:** The Yule-Walker algorithm is a block-processing method of estimating the frequency and damping ratio of electromechanical modes from ambient synchrophasor measurements. The method operates by first estimating the autocovariance sequence (ACS) of the measured data. It then fits a model that describes the relationship between the ACS at different lag values. The parameters of this model are

associated with a rational polynomial whose poles correspond to the power system’s electromechanical modes.  

- **Least Squares:** The Least-Squares algorithm is a method of estimating the frequency and damping ratio of electromechanical modes from ambient synchrophasor measurements. The method fits a model that describes the current measurement in terms of past measurements and the current random input. This model is parameterized as a rational polynomial whose poles correspond to the power system’s electromechanical modes. An extension allows the parameters of electromechanical modes and forced oscillations to be identified simultaneously. The Least-Squares algorithm can be implemented as a block-processing method, but it can also be implemented recursively to more effectively track changes in the power system.

- **Frequency Domain Decomposition (FDD):** Frequency Domain Decomposition (FDD) is a multi-dimensional ambient modal analysis algorithm for estimating the frequency, damping ratio, energy level, and mode shape of the dominant modes and oscillations from ambient synchrophasor measurements. In this method, power spectrum density (PSD) functions of the ambient measurements are first estimated in the frequency domain. Singular value decomposition (SVD) is then used to combine and extract the principal singular values of the multiple PSD estimates. Local peaks among the singular values can be shown to correspond to frequencies of system modes and oscillations that are observed in the data. Modal properties can then be estimated by analyzing these principal singular values near the peak frequencies. Fast FDD (FFDD) is a recent accelerated version of the algorithm that is effective in simultaneous processing of hundreds of synchrophasor measurements.

- **SSI:** Subspace methods were developed in linear system theory for system identification. Stochastic subspace identification (SSI) formulations in power system oscillation analysis formulate the PMU measurements as outputs of a linear system that is being excited by unknown random load fluctuations which are modeled as independent white noise inputs. The essential features of the linear system model describing the power system can then be estimated and the eigenproperties provide insight on the dominant system modes and oscillations that are observed in the PMU measurements. Being time-domain methods, SSI algorithms involve solving large-dimensional matrix problems and are generally well-known for estimation accuracy though they are computationally intensive. One of these methods has been improved to be called Fast Stochastic Subspace Identification (FSSI), detailed in the reference material.

### Oscillation Detection Methods

Methods have also been developed to detect when sustained oscillations appear. Depending on the algorithm, the targeted oscillations can be forced, poorly damped natural, or either. In the following, descriptions are provided for some of the earliest methods that reflect general detection strategies.

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19 RLS techniques are described in the following references:


Chapter 1: Power System Oscillations and Analysis Techniques

- **RMS-Energy**\(^{21}\): This approach operates by detecting sudden increases in energy associated with sustained oscillations. Input synchrophasor measurements are first filtered to focus on frequency bands associated with different types of oscillations. Next, the root mean squared (RMS) energy of each resulting signal is calculated over a sliding window. Baselining is required to determine the normal range for the signal’s energy. Once this range is established, a corresponding threshold is set to detect when the signal’s energy increases due to a sustained oscillation. Ideally, signals from several locations in the grid are monitored simultaneously. The locations and frequency bands of signals that trigger an alarm can be used to guide the initial response to the alarm.

- **Periodogram**\(^{22}\): The periodogram method is also based on signal energy, but it is specific to forced oscillations and operates in the frequency domain. To begin, the periodogram of the input signal is calculated. The periodogram captures how a signal’s power is distributed over frequency. At the frequency of a forced oscillation, the periodogram tends to become very large. The threshold for detection is based on the signal’s power under ambient conditions, which can be extracted from the signal under analysis. As a result, baselining is not required. The method can detect small oscillations and accurately estimate the frequency of the forced oscillation, characteristics that are useful in some applications.

- **Coherence**\(^{23}\): Coherence methods also operate in the frequency domain, but instead of examining a signal’s energy, they focus on the relationships between signals. Coherence is a measure of how correlated signals are as a function of frequency. When a sustained oscillation is visible throughout a system, the coherence between signals that are normally unrelated tends to increase at the oscillation’s frequency. Alternatively, the coherence between a signal and a delayed version of itself can be examined. A sustained oscillation, present in the signal before and after the delay, increases the coherence and leads to detection. The limited range of the coherence between zero and one simplifies baselining.

- **Oscillation Monitor**: An oscillation monitor operates by detecting any oscillation with near-zero damping. A variety of algorithms can be used to accomplish this task, including ambient methods initially designed to monitor the electromechanical modes that give rise to natural oscillations. Thus, it is important to recognize that an oscillation monitor is primarily concerned with an oscillation’s damping, rather than the damping of system dynamics. Once a sustained oscillation is detected based on its near-zero damping, it can be categorized as natural or forced and addressed properly.

- **Time domain analysis**: Another approach is to detect oscillations in a two stage process\(^{24}\): a) first, detect system events by looking for anomalies in streaming PMU data across multiple signals, and b) analyze the ringdown PMU data to check the modal properties of the ringdown response. This approach has the advantage that it can detect poorly damped, undamped as well as negatively damped oscillations. Also, the

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time window of analysis typically much shorter than the other methods and the method tends to be responsive to sudden changes in system operating conditions.

Source Location Methods
There are different methods used for identifying the source location of an oscillation. These include:

- **Mode Shape of the Oscillation Analysis**: When the forced oscillation does not significantly interact with system modes, the mode shape of the oscillation, i.e., its amplitude and relative phasing, as seen by analyzing the MW or MVAR outputs of power plants can directly point to the source of forced oscillations. When resonance is present between the forced oscillation and a system mode, the mode shape may be misleading\textsuperscript{25}. However, when the resonance effect is weak, the mode shape analysis of available PMU signals can indicate the source of a forced oscillation. For oscillations related to reactive power issues, voltage magnitude signals or MVAR plant outputs can be used. For oscillations related to active power issues such as from speed governor malfunctioning, voltage phase angles or MW plant outputs can be used in mode shape analysis. Recently techniques based on SCADA MW and MVAR plants have been proposed as well.

- **SCADA Based Approaches**: While SCADA measurements are not collected at a high enough sampling rate to fully analyze power system oscillations, they can often help identify the oscillation's source. After an oscillation is detected using synchrophasor measurements, SCADA data from before the oscillation occurred is compared to measurements collected during the oscillation\textsuperscript{26}. Units with significant increases in the level or variation of power output are automatically identified as likely sources of the oscillation.

- **Energy Function Analysis (Dissipating Energy Flow method by ISO-NE)**: This Energy-based method calculates the flow of the Dissipating component of transient Energy (DE) in the network during the oscillatory process. Dissipating energy flows from the source(s) to sink(s) of oscillations. Tracing the DE flow in the network allows identification of the source(s) of oscillations. This methodology is described by Lei Chen in her 2016 paper\textsuperscript{27}. DE can be calculated for any transmission element (line, transformer, and generator) by using frequency, voltage, and current PMU measurements. The Dissipation Energy Flow method is a version of energy-based method for robust, practical implementation with actual PMU data by using PMU data pre-processing. The method allows (a) identification of a specific generator/power plant as the source of oscillations at sufficient observability of the network by PMU; (b) identify a specific area as the source of oscillations by using PMU measurements on tie-line between areas; (c) significant localization of the suspect zone-source of oscillations at limited observability of network by PMU\textsuperscript{28}.

Other Classifications of Analysis Methods
The various types of oscillation analysis methods can also be classified in different ways, which may include:

- **Time Domain vs. Frequency Domain**: Given the linear system formulation of the small-signal analysis assumed in this report, the system dynamics can be analyzed either in time-domain or in the frequency domain. Accordingly, many algorithms for oscillation ringdown modal analysis as well as ambient modal analysis have been developed in both time-domain and in frequency domain. In general, time-domain methods are considered more accurate given ideal conditions, while they tend to be sensitive to measurement noise and assumptions such as the choice of model order and also tend to be computationally


intensive from handling of large-size matrices. Large model orders may be needed for effective handling of
noise, but this introduces spurious modes into the analysis results that require careful filtering to interpret
estimation results. In contrast, frequency domain methods can inherently handle noise issues better by
focusing on the modal frequency content of interest and are also generally computationally faster by
decomposing the analysis into parallel handling of different modes. However, simplifying assumptions made
in the frequency domain formulations tend to make the results more approximate compared to the time-
domain methods.

- **Recursive vs. Block Processing:** In PMU data based oscillation analysis, there are two classes of algorithms,
namely, recursive and block processing methods. In recursive methods, the system model is adjusted
continuously a little at a time by using the latest observed measurements. In this sense, the system is
assumed to evolve continuously over time that the model continuously tries to keep track of. In contrast, the
block processing methods formulate the system model for each estimation instant by using a block of recent
observations, without using recent estimates. Recursive methods are faster in implementation since they
handle smaller data blocks and since the model is adjusted incrementally at each estimation instant. Block
processing methods require larger data analysis windows to estimate the system models and are
computationally more intensive. For sudden changes in system conditions such as in the case of switching
actions, the analysis length of block processing methods can be shortened to improve tracking at the expense
of estimate variance. Recursive methods can be designed to make a similar trade-off using a parameter that
can be adjusted following system events. Data quality is also an important factor in the accuracy of the
recursive methods, since any estimation error introduced tends to linger longer owing to the memory effect
inherent in recursive methods.

**Parameters Utilized for Analysis**
For ringdown analysis Prony, Matrix Pencil (MP), Hankel Total Least Square (HTLS), and Eigenvalue Realization
Algorithm (ERA) are used and for ambient modal analysis, Fast Frequency Domain Decomposition (FFDD) and Fast
Stochastic Subspace Identification (FSSI) are used. The tools were run on a specialized platform to run offline
oscillation analysis. The tools used rank dominant modes on relative energy rather than absolute energy. In the
analysis, whenever a trend was identified in the data, a bandpass filter with corners at 0.1 Hz and 10 Hz could be
applied to the data; however, by default the analysis for these events utilized no filtering of the posted data. Both
direct voltage angle differences and frequency differences were utilized for the majority of events; however, the first
derivative of voltage angle differences was utilized where the study group found the estimates to have a poor fit in
the voltage angle differences or frequency differences. The data was not downsamples; however, signals that had
significant consecutive time or percentage of missing data were discarded from the analysis.
Chapter 2: Oscillation Analysis Results

NERC used a set of oscillation ringdown analysis as described in Chapter 1 in an attempt to identify the modal properties of each interconnection based on the wide-area PMU data collected. The analysis window was chosen using engineering judgment to avoid any nonlinearities or discontinuities in the signals analyzed, and to capture a high signal-to-noise ratio (SNR) in the event data.

To describe the high-level oscillatory behavior across the interconnections, the U.S. Census Regions\(^{29}\) were used (where possible). Where the U.S Census Regions were too general or non-existent (i.e. Canadian Providences), a more detailed geographic region was used. This was simply chosen as an effective way to describe wide-area modes, and is used throughout this report and in the detailed analysis document.\(^{30}\) Multiple sections in this chapter utilize the data found in this companion document and should be read alongside the findings discussed here. Results for each interconnection are summarized in the following subsections, with the major mode shapes and characteristics defined.

![Figure 2.1: U.S. Census Regions used to Describe Oscillation Mode Shapes](Source: U.S. Census Bureau)

**Eastern Interconnection**

A number of system modes were observed in the Eastern Interconnection (EI) in each event analyzed; however, two modes appear to be regularly excited. The EI modes have been observed to be well damped in the events chosen.

\(^{29}\) [https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf](https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf)

\(^{30}\) See Detailed Event Analysis Report [here](https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf)
Coupling these well damped modes with the knowledge that the PMU coverage in the Eastern Interconnection is sparse compared to the number of substations, the ringdown analysis proved challenging to get realistic results. In general, generation tripping near the areas of strong participation excite a North to South mode from the New England to South Atlantic regions; however, some events indicate an interaction with the Midwest region as well. Table 2.1 holds the most common mode frequencies and their damping ratios with respect to each event. For these events in Table 2.1, the mode shapes primarily have two distinct areas swinging against the other, with a few other intermediary areas between these areas. For the 0.16–0.22 Hz mode the two major regions are the North and South portions of the Eastern interconnections, primarily in the South Atlantic regions against the North East regions. The 0.29–0.32 Hz mode is largely defined by the same North to South regions, with some interactions between the Eastern and Western portions of the EI. In comparison, the 0.23-0.24 Hz mode has a clearly defined interaction between three regions between the Midwest, South Atlantic, and New England regions. Further investigation on the 0.23-0.24 Hz mode shape is warranted to understand the interaction with the two identified possible representations of the mode shape. Current data demonstrates a possibility that two modes exist near the same frequency of 0.24 Hz with the South Atlantic being one tail end of the mode, but the interactions between the other regions are still unclear. As Events 3 and 4 were forced oscillation events, a ringdown analysis was not applied and thus are not included in Table 2.1.

<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

The forced oscillations presented in Table 2.2 are representative of the modes found in Events 3 and 4 in the interconnection analysis. While the forced oscillation was present, it excited the indicated natural system mode shapes. The participation factor for the forced oscillation source in the nature system modes was small in Events 3 and 4. As a result, spectral proximity to the natural system model frequency is the primary cause for the small resonance effects. Should the system mode shapes become less damped, the results of Table 2.2 would indicate the higher resonance effects.31

### Table 2.2: Interaction of Forced Oscillation and Inter-Area 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(^{32})</td>
<td>S</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>0.75(^{33})</td>
<td>NO</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>0.7(^{34})</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

The two forced oscillation events in the EI found that the resonance effect between the forced oscillation frequencies and the natural system modes were mild across all of the modal frequencies. Both events had a 0.75 Hz forced oscillation on the system that excited mode shapes near the system mode frequency. Events 3 and 4 forced oscillation resonating with the natural system modes confirmed the natural system mode shapes found in the ringdown analysis performed on the other chosen events. Figure 2.2 shows this interaction and the natural system modes the forced oscillation resonated with follow the ringdown shapes seen in other events. Where the Spectral density (dB/Hz) was high, it demonstrates the signal contained those components. Thus, when there are peaks in the lower regions, the analyzers were able to conclude these system modes resonated during the Forced Oscillation. Event 4 primarily followed this interaction, but since the excitation source of the forced oscillation was different, it was not as prevalent across the system. The unique aspect in Event 3 however was the addition of a 0.28 Hz forced oscillation that excited the complex mode shape in a manner that was slightly larger than the 0.75 Hz forced oscillation, and found the Mississippi location having a strong participation in exciting the system mode. For details on the analysis and the accompanying mode shapes, see the companion document.

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32 The June 17, 2016 event (Event 3) discusses this.
33 Several events discuss this FO; it is mainly persistent in Event 3 and 4.
34 The November 27, 2016 event (Event 4) discusses this.
basis. As the current data allows for two distinct mode shapes for the 0.23-0.24 Hz mode, both are reported in Figure 2.5.

Figure 2.3 Mode Shape Plot for 0.16-0.22 Hz Mode

Figure 2.4 Mode Shape Plot for 0.29-0.32 Hz Mode
It is possible to investigate how the mode shapes change with different operating conditions as the data demonstrates that these might influence oscillatory response. Events 2 and 5 had a very similar excitation location and the mode shapes between Events 2 and 5 demonstrate that they are the same mode; however, the frequency estimate of the mode in Event 2 is 0.17 Hz and Event 5 is 0.22 Hz. Further investigation is recommended.

For the two forced oscillations events studied, the resonance effects were deemed to be mild. The forced oscillation had a similar frequency to a system mode; however, the system mode was well damped and the forced oscillation did not occur in a location with strong participation with the observed system mode. In Event 3 (June 17, 2016), the 0.3 Hz mode shape (Figure 2.6) demonstrates a high participation of the 0.28 Hz forced oscillation source in the 0.3 Hz mode shape; however, that geographic location did not have a high participation factor in the natural system mode. The proximity of the forced oscillation’s frequency to this natural system mode’s frequency is the leading cause of why such a large oscillatory response was seen.
Texas Interconnection

In all the events analyzed, an oscillation mode with frequency of around 0.6–0.7 Hz was observed. Table 2.3 shows how the damping ratio changed in each event analyzed. The mode is considered well damped across all the events.

Unlike the EI and the WI, the Texas Interconnection (TI) has lower damping ratios for the identified major mode with ranges on average below 10 percent. Based on the topology of the interconnection, the regions are separating into generation rich and load rich areas, making this interconnection similar to the Western Interconnection, but on a smaller scale. With this smaller scale, the oscillation risk due to specific contingencies may be higher. Transmission Planners (TPs) should continue to conduct studies that address the damping ratio of inter-area modes. In addition, repeat analysis of these events would be better improved by more PMU coverage and would allow TPs to more accurately benchmark their model to real world events. Figure 2.7 demonstrates the shape of the observed mode.

### Table 2.3: Damping Ratio Mode Comparison

<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>

Key Takeaways:

- The EI contains more complex mode shapes than other Interconnections. Each of the modes have at least three major regions that interact during ringdown events and the forced oscillation events resonated with these complex natural system modes. To complicate the situation, natural system modes in the EI demonstrate high damping ratios, meaning that the Signal to Noise Ratio for the inter-area modes is low.
- The North East, Southern Atlantic, and Midwest regions contain high participation factors in the identified natural system modes.
- All oscillatory behavior had high (> 10 percent on average) damping ratios for non-forced oscillation events. FOs resonated with well-damped (> four percent) natural system modes for the events selected.
Analyzing the TI PMU data proved to be challenging due to the lack of PMU signals provided by the RC. For all events, only a handful of PMU signals were provided, meaning that an error in any one of the signals could have a stronger impact on the overall results of the mode shape and oscillation characteristics. This lack of data was likely a contributing factor to only being able to identify a North Texas to South Texas mode shape (since it was challenging to identify any other cardinal directionality to the modes). More PMU signals are needed to further define the more localized regions that strongly participate in these modes and to rule out any other regional modes that might be at a lower energy than this dominant mode.

**Key Takeaways:**
- More measurement locations are required to fully visualize the inter-area natural system mode
- TI should continue to address damping ratios of inter-area modes in their TP studies
- TI can experience larger oscillatory behavior due to its small size, lower damping ratios (<10%), and topology
- Participation factors are likely in areas between the generation rich and load rich areas.

**Western Interconnection**
System modal behavior has been well understood in the Western Interconnection (WI) for many years from previous studies. The results presented here confirm some of the modes defined in those studies. In particular, the commonly referred to modes of N-S Mode A and N-S Mode B were observed in all events. These modes and their damping ratio for each event are listed in Table 2.4.
Table 2.4: Damping Ratio Mode Comparison

<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>
<th>Event 6 Damping Ratio (%)</th>
<th>Event 7 Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37-0.42</td>
<td>12</td>
<td>9.9</td>
<td>10.2</td>
<td>10.8</td>
<td>13.8</td>
<td>14</td>
<td>18.3</td>
</tr>
<tr>
<td>0.24-0.27</td>
<td>NO</td>
<td>8.6</td>
<td>18.2</td>
<td>9.8</td>
<td>NO</td>
<td>NO</td>
<td>17.5</td>
</tr>
</tbody>
</table>

The mode shapes for the defined modes can be found in Figure 2.8 to Figure 2.9, which confirm the modes defined in the previous oscillations studies by other entities. For Event 4, the analysis proved to be more difficult due to the uniqueness of the event as it contained a very slow drop in frequency that seemed to have no oscillations in its data when viewing the relative bus frequencies. However, once the first derivative of the relative voltage angles was utilized, a realistic and reasonable damping ratio of the natural system mode, verified by ambient methods, was determined.
The presence of a near 1.2 Hz local mode in the Montana region was found that did not fully match the inter-area Montana mode identified in previous WI oscillations studies. This local 1.2 Hz oscillation (see Figure 2.10) mainly involved a few generators close to each other. The strong response of this 1.2 Hz mode however could not be duplicated in model simulations of the event which requires further study to understand the strong response of this local mode during the event.
Key Takeaways:

- The two most commonly distinguished system modes in the Western Interconnection (N-S Mode A and N-S Mode B) were also identified in this analysis.
- WI should continue to address damping ratios of their identified inter-area system modes.
- The Northern and Southern ends of the WI have strong participation factors.
Chapter 3: Benchmarking and Sensitivity Analyses

The analysis of wide-area oscillations using time-synchronized PMU data also afforded NERC the opportunity to do a rough comparison of the interconnection-wide planning cases’ ability to capture the same modal characteristics as the actual system. This helps NERC prioritize its efforts under the Modeling Improvements Initiative, as NERC works with industry to improve these models used for planning and operating the BPS. The importance of such an endeavor lies in the ability to predict any oscillatory behavior for future system studies. NERC performed a series of benchmarking studies to determine if the existing dynamic models can recreate, to some degree, the oscillatory behavior captured using PMU data if the model is subjected to the same disturbance. This chapter details the results and key findings for each interconnection.

Benchmarking Interconnection-wide Models

NERC used PSLF and PSSE simulation software platforms to compare simulated disturbances with actual disturbance data captured from the wide-area PMUs. The cause of each disturbance is known, using information from the NERC Situation Awareness department. The disturbance was simulated in an “off-the-shelf” planning base case provided by the MOD-032 Designee for each interconnection. A case was selected that somewhat matches the conditions in which the disturbance occurred (e.g., “light spring” or “peak summer”). The only modifications to the case were to ensure the units that tripped were operating at the correct pre-disturbance output level. Care was also taken to ensure no severe thermal or voltage violations were present in the powerflow solution of the new dispatch, and that dispatch was utilized to simulate the disturbance for each event. Table 3.1 shows which base case was selected for the analysis.

<table>
<thead>
<tr>
<th>Interconnection</th>
<th>Case Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern</td>
<td>MMWG_2017SUM_2016Series_Final_ds</td>
</tr>
<tr>
<td>Western</td>
<td>17HS2a.sav</td>
</tr>
<tr>
<td>Texas</td>
<td>NT2018_HWLL_Final</td>
</tr>
</tbody>
</table>

By doing so, NERC staff was able to find the general oscillatory characteristics of the interconnection-wide planning models, and to assess their capability to model these oscillations. A value for the oscillation mode frequency within 10% of the physical data was considered to be adequate, and a band of +/- 5 percent for both the damping ratio and relative energy was considered adequate. Many different variables (e.g., transmission line flows, local temperatures, other operating conditions) can impact the results of a simulation versus reality; however, none of these factors were considered to recreate the specific event. The purpose of the benchmarking was to address whether the current state of a base case can reasonably match the observed mode shapes. Results were then analyzed utilizing the ringdown analysis methods discussed in Chapter 2.

Eastern Interconnection

The April 15th, 2016 generation trip event was chosen for model benchmarking. The resource loss totaled 1200 MW from estimations on the FNET report. While the PMU data set contains many signals, most of them are concentrated...
in dense areas, providing an overall sparse view of the Eastern Interconnection. In the simulated case, a total of 206 signals (frequencies, voltage magnitudes, and voltage angles) were recorded across the interconnection. After simulating the disturbance and running the oscillation analysis on the simulation data, the mode shapes and modal characteristics differed between the simulation and the PMU data set. See the results for Event 2 in Appendix C36 for more information on the PMU data. Figure 3.1 shows the simulated generator trip occurring at $t = 5$ seconds, with the analysis window from $t = 9$–$15$ seconds. Results from each oscillation solution engine are shown in Table 3.2. A comparison of modes shapes are presented in Figures 3.2 to 3.4.

The dominant mode is captured quite well in both the PMU data and simulated data. The other dominant modes differ between simulation and actual data. The differences between the oscillation mode between simulated and PMU data are likely due sparsity of PMU coverage compared with the model representation as the more signals available increase the observability of the mode. The different operating conditions between simulated and actual data also likely have an impact. In addition, the simulation demonstrates some non-linearities in the early portion of the second swing, introducing some inherent errors during the time when the oscillation was highly excited.

![Figure 3.1 Analysis Window](image)

<table>
<thead>
<tr>
<th>Table 3.2 Dominant Mode Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant Mode 1</td>
</tr>
<tr>
<td>Simulated</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
</tr>
<tr>
<td>Damping Ratio (%)</td>
</tr>
<tr>
<td>Relative Energy (%)</td>
</tr>
</tbody>
</table>

36 Link to Companion Document Here
Figure 3.2 Simulated (left) versus Physical (right) Dominant Mode Shape 1

Figure 3.3 Simulated (left) versus Physical (right) Dominant Mode Shape 2
Texas Interconnection

The March 10th, 2017 event was chosen for model benchmarking. The resource loss totaled 823 MW from a single generator tripping off-line. Relatively few signals were provided in the PMU data set received, and therefore the simulation results contained more signals. This created a scenario where NERC could determine if the simulated responses could accurately depict a result gained from only a handful of signal samples. After running the analysis, it was determined that the simulated results and the actual results (Event 5 in Appendix C) are consistent with each other.

The simulated disturbance occurred at t = 1 second, with the analysis from t = 2–7 seconds (Figure 3.5). Results from each oscillation solution engine are shown in Table 3.3. The mode shape comparison is also presented in Figure 3.6. Results show a relatively close resemblance between simulated and actual data. As the number of signals in the actual PMU data were low, it is hard to characterize the mode shape truly; however, the simulated results (left portion of Figure 3.6) depicted this much better.
### Table 3.3: Dominant Mode Comparison

<table>
<thead>
<tr>
<th></th>
<th>Dominant Mode 1 Simulated</th>
<th>Dominant Mode 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency (Hz)</strong></td>
<td>0.713</td>
<td>0.67</td>
</tr>
<tr>
<td><strong>Damping Ratio (%)</strong></td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td><strong>Relative Energy (%)</strong></td>
<td>98</td>
<td>95</td>
</tr>
</tbody>
</table>

---

**Western Interconnection**

The January 21st, 2016 event was chosen for model benchmarking. In this case, the number of signals from the simulation were much lower than PMU data set received from Peak RC. While there were a few discrepancies between the simulated and PMU data results (see Appendix D), the results were consistent and the models were accurate in depicting the primary inter-area mode.

The simulated generator trip occurred at $t = 1$ second, and the analysis window was from $t = 10–18$ seconds (Figure 3.7). Results from each oscillation solution engine can be found in Table 3.4. The mode shape comparisons are presented in Figures 3.8 and 3.9. Results demonstrate a reasonably close resemblance for the dominant mode, but the simulation appears to have picked up an inter-area mode while the actual data picked up a local mode. More work should be done to identify secondary modes between the model and actual data and to reflect that work into the interconnection wide models.

---

38 Link to Companion Document here
Chapter 3: Benchmarking and Sensitivity Analyses

Figure 3.7 Analysis Window

Table 3.4: Dominant Mode Comparison

<table>
<thead>
<tr>
<th></th>
<th>Dominant Mode 1 Simulated</th>
<th>Dominant Mode 2 Simulated</th>
<th>Dominant Mode 1 Actual</th>
<th>Dominant Mode 2 Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (Hz)</td>
<td>0.37</td>
<td>0.25</td>
<td>0.42</td>
<td>1.29</td>
</tr>
<tr>
<td>Damping Ratio (%)</td>
<td>8</td>
<td>16</td>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>Relative Energy (%)</td>
<td>72</td>
<td>27</td>
<td>51</td>
<td>31</td>
</tr>
</tbody>
</table>

Figure 3.8 Simulated (left) versus Physical (right) Dominant Mode Shape 1
Chapter 3: Benchmarking and Sensitivity Analyses

Conclusions
Overall, benchmarking results demonstrated that the models were able to recreate the dominant mode in each Interconnection. The value for the oscillation model frequencies were within 10 percent of the PMU data, and damping ratio and relative energy were within +/- 5 percent for the primary dominant mode. Further investigation into the differences for the second dominant modes yielded valuable results for each interconnection’s ability to model their system modes correctly. In short, each inter-area oscillation is observable in the planning cases for each interconnection. The models appear to be relatively sufficient to capture inter-area oscillatory behavior. However, each Interconnection (i.e., the MOD-032 Designees) should continue to monitor grid events and perform benchmarking of oscillatory behavior between simulated response and actual PMU data. This is particularly valuable as PMU density increases across each Interconnection. As the density of PMUs increases, the performance of the planning model should match observed results under the same system conditions. It is demonstrated above that the Eastern Interconnection benchmarking identifies the three major modal shapes in Chapter 2 of this report; however the mode shapes are very sensitive to generation dispatch and flows throughout the system, so the mode shapes may differ from those demonstrated in this and other sections. The WI and TI modes are well captured in the benchmarking section except for the local phenomena found in the events.

Key Takeaways:
• EI and WI should address system models to more accurately reflect the observed data results. The current models are deemed sufficient to capture the dominant mode shapes.
• Each Interconnection should continue to benchmark their planning models with performance events. The rising PMU density helps to observe the natural system mode shape and should assist in this benchmarking.

Using Frequency versus Voltage Angle Data
Ringdown methods are largely dependent on the accuracy of the data used. Different sources of data can results in different answers obtained after performing the oscillation analysis. When analyzing the PMU data, one may use either measured (calculated) PMU frequencies or PMU voltage angles. Efforts were made to compare oscillation analysis results between using PMU frequencies and PMU voltage angles. Entities have stated that using frequencies or voltage angles may result in different results since IEEE Std. C37.118 is prescriptive on calculating the phasor
quantities but less so on calculated frequency. This hypothesis was tested using one of the WI events from January 20, 2017.

Figure 3.10 shows the FFT match for both PMU frequency and voltage angle data (using the angle derivatives option), with similar FFT shapes and reconstructed signals\(^{39}\). However, the spectral density of the FFT for the frequency data contains more low frequency results than the voltage angle data (reflected in the results in presenting higher modal frequencies). A comparison of the three dominant modes is provided in Table 3.5. Notice that the skew towards higher frequency results in the voltage angle versus the frequency data. This provided results that contained much more energy in the higher modes as well as a slight increase in the mode frequency of the low frequency mode. By understanding that the angle data will skew towards higher frequencies, the user can simply adjust the relative energy threshold when utilizing voltage angle data sources to accommodate for this shift. This makes the results similar to using the frequency data. If the user is concerned with a possible low frequency mode (~0.15-0.3 Hz), the frequency data will provide a more conservative damping ratio than the voltage angle data, as the skew impacts the damping ratio of the low frequency modes in the voltage angle data.

![FFT match for both PMU frequency and voltage angle data](image)

**Figure 3.10: Frequency Data (left) and Voltage Angle Data (right) FFT plots**

<table>
<thead>
<tr>
<th></th>
<th>Frequency Data source</th>
<th>Voltage Angle Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency (Hz)</td>
<td>Damping Ratio (%)</td>
</tr>
<tr>
<td>Mode 1</td>
<td>0.441</td>
<td>13.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 2</td>
<td>0.227</td>
<td>12.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode 3</td>
<td>0.826</td>
<td>18.71</td>
</tr>
</tbody>
</table>

### Effects of Changing Inertia on Oscillation Frequencies

In addition to the model benchmarking described above for the TI, the impacts of decreasing inertia on system modal characteristics were also briefly explored. A slightly modified base case with the same disturbance event were used as described above. That case was then compared against a case with the same load level but less on-line generation and lower available headroom (resulting in decreased inertia). These results were then compared to the simulated case to identify any relationship between inertia and the primary components of the system modes (i.e frequency, damping and relative energy).

\(^{39}\) In the first iteration, the raw angle data was found have a poor visualization of the oscillation during the event period, and thus the derivative of the angle measurements (or a pseudo-frequency) was used to obtain the results. These calculations utilize a linear scale between points, so the calculations are affected by how many consecutive data points are missing or the PMU data was not available for a few samples.
damping ratio, and relative energy). Table 3.6 shows the comparison of system inertia and the primary oscillation mode frequency, damping ratio, and energy.

<table>
<thead>
<tr>
<th>Table 3.6: Dominant Mode Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case Simulation (204.8 GVA*s)</td>
</tr>
<tr>
<td>Mode 1</td>
</tr>
<tr>
<td>Mode 1</td>
</tr>
</tbody>
</table>

The damping ratio decreased from the higher to lower inertial cases that correlated with a rise in the frequency of the mode shape. This confirms the expectations of a higher modal frequency usually resulting in a lower damping ratio for a particular mode shape; however, this may be the related by generation dispatch, transmission tie line flows, or aggregate inertial values. Most likely, each of these reasons play a factor in determining the damping ratio. The mode shape comparison for these two inertia levels is demonstrated by comparison in Figure 4.11.

**Figure 3.11 Higher Inertia (Left) versus Lower Inertia (Right) Natural System Mode Shape**

### An Exploratory Analysis on the Western Interconnection

The study group also wanted to determine if the planning models were adequate in capturing the system mode shape and its changes by exciting different portions of the Interconnection. They excited six different regions of the interconnection to see the impacts on the mode frequency, damping ratio, and relative energy for the identified modes in Chapter 2 of this report. For many of the events, the mode shape performed similarly to the measured responses to the interconnection with minor errors due to transmission path flow differences and some generator dispatches, which is to be expected. In addition, the method of excitation for these events included generator tripping, which will amplify the contributions of signals near the generator trip; however, the other aspects of the mode shape we can compare and provide validation between the planning model and the measured events. This analysis show which are the strong controllable regions for the two main inter-area modes of the western interconnection. For instance, Alberta mainly excites the 0.25 Hz NS Mode A, while NW and MT excite the 0.37 Hz NS Mode B. Figure 3.12 demonstrates the differences between the expected and identified results. This evidence suggests there is a possibility that mode shapes can differ depending on the excitation location. Table 3.7 and 3.8 and
also compares the changing damping ratios and relative energies of the two major modes. The relative energy mode comparisons are telling with higher relative energies of the inter-area modes indicating which common inter-area mode has more impact for generation resource loss in that area. These types of studies are encouraged to continue with different seasonal cases and for different operating conditions to fully understand the impact a generation loss has in a regional area with respect to the dominant inter-area mode characteristics.

### Table 3.7: Damping Ratio Mode Comparison

<table>
<thead>
<tr>
<th>Mode Frequency (Hz)</th>
<th>2DC Damping Ratio (%)</th>
<th>2PV Damping Ratio (%)</th>
<th>Alberta Damping Ratio (%)</th>
<th>BC Damping Ratio (%)</th>
<th>Colstrip Damping Ratio (%)</th>
<th>Coulee Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24-0.26</td>
<td>15.1</td>
<td>14.1</td>
<td>18.0</td>
<td>14.3</td>
<td>19.2</td>
<td>12.7</td>
</tr>
<tr>
<td>0.35-0.37</td>
<td>12.0</td>
<td>9.0</td>
<td>NO</td>
<td>8.8</td>
<td>7.3</td>
<td>8.6</td>
</tr>
</tbody>
</table>

Note: NO – Not Observed or Well Damped

### Table 4.08: Relative Energy Mode Comparison

<table>
<thead>
<tr>
<th>Mode Frequency (Hz)</th>
<th>2DC Damping Ratio (%)</th>
<th>2PV Damping Ratio (%)</th>
<th>Alberta Damping Ratio (%)</th>
<th>BC Damping Ratio (%)</th>
<th>Colstrip Damping Ratio (%)</th>
<th>Coulee Damping Ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24-0.26</td>
<td>69.9</td>
<td>69.2</td>
<td>93.2</td>
<td>54.8</td>
<td>68.7</td>
<td>26.6</td>
</tr>
<tr>
<td>0.35-0.37</td>
<td>24.3</td>
<td>23.5</td>
<td>NO</td>
<td>41.8</td>
<td>31.3</td>
<td>73.4</td>
</tr>
</tbody>
</table>

Note: NO – Not Observed or Well Damped

As demonstrated in the differing mode shapes, the excitation location for the event demonstrates how the participation factors between the ends of the region behave with respect to that region. In addition, Figure 3.13
Chapter 3: Benchmarking and Sensitivity Analyses

depicts an identified low relative energy 0.52 Hz mode in the simulations. This mode is described as having ends in the North California to North British Columbia regions and has large participation factors for the Eastern portion of the WI as well, which indicates the presence of a reasonably complex mode shape.

Figure 3.13 0.52 Hz mode shape identified in some of the Exploratory Analysis cases

The 0.52 Hz mode shape in the WI was not well identified in previous studies, and Figure 3.14 demonstrates its relative participation factors defined by the regions. The blue and green regions correlate to the mode shape plot in Figure 3.13. As seen in the figure, the mode shape is complex in nature and has three distinct regions for each half of the mode shape. This mode shape may have been seen in Event 6 in the Western Interconnection Analysis, but is sensitive to the placement of the reference signal in the mode shape analysis.

Figure 3.14 0.52 Hz mode Shape Regionally Defined
Chapter 4: Conclusions and Observations

In this chapter, the overall mode shapes and higher level observations and suggestions are discussed and recommendations for future efforts in identifying the inter-area oscillations is mentioned. As the PMU coverage is expected to increase, new modes and more accurate details of previous modes are expected to be discovered.

Conclusions

For all the chosen events for analysis for all interconnections, only a handful exhibited forced oscillatory behavior and all resonance effects were deemed to be mild, which indicates that the conditions surrounding the event were not as severe as it could have been given the resonance conditions. In the events, a total of six dominant modes were seen. Each mode was given a name that describes the general shape of the mode where a previous name has not already been given. The frequency range, average damping ratio, and average relative energy is provided for these modes in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1: Damping Ratio Mode Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Interconnection</strong></td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Eastern</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Texas</td>
</tr>
<tr>
<td>Western</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Plots of the dominant modes are found in Figures 4.1 to 4.3 and are listed in order of Average Relative Energy in the interconnection. These mode shapes are based on the events chosen and the order presented here may change with future analysis and additional visibility of the respective interconnection. In the figures, each different color represents a leg of the mode shape per interconnection. Colors were chosen based on contrasting coloration from the background color. Inscribed circles identify that two regional possibilities exist for that mode shape, only seen in the EI for the NE-NW-S mode. The different colors coordinate to different phase legs of the mode shape and thus oscillate against each other. For the more complex mode shapes with three distinct phase legs, three colors were chosen. This is to contrast two distinct phase legs with the remaining system “filling in” the remaining mode shape which is identified with only two colors.
Chapter 4: Conclusions and Observations

Figure 4.1 Dominant Mode 1 Geographic Representation

Figure 4.2 Dominant Mode 2 Geographic Representation
Figure 4.3 Dominant Mode 3 Geographic Representation

Key Takeaways:

- Continued analysis of oscillatory behavior is needed to understand newly identified inter-area system modes.
- No forced oscillation event had more than mild resonance effects to natural system modes in the events studied.
- Most Dominant modes have a complex geographic representation but a simple mode shape.
- Most Dominant modes have, on average, high damping ratios; however, system configurations impose a significant variance to this average.

Observations

As demonstrated in Chapter 2 of this report, most of the observed modes were very well damped in the seconds after the studied events. Some things to note across the analysis are that the larger the set of PMU data was, the greater visibility into which geographic regions contribute to that particular system mode. Whenever the system modes were not well damped, the system eventually recovered; however, the recovery time was quite long. For the mode shapes defined on the modes that can go towards the undamped regions, a damping control system that acts to increase the damping ratios for the defined modes can help prevent high energy oscillations and resonance from causing a catastrophic event. Such projects are currently under research and testing in the DOE CERTS\(^\text{40}\) program. It is worth to note that there was no sensitivity done to take out the modeled PSS on generation units. Tuning these systems to dampen system modes will impact the results in this report.

\(^{40}\text{https://certs.lbl.gov/}\)
In addition to cases of lower damping, another high-level observation about these events was that the higher meshed systems seemed to provide better damping ratios in their system. That is, the electrical system parameters between sinks and sources had a denser population of the Ybus matrix than the sparsity seen with loosely connected lines. The interconnections and areas that had these denser matrices provided greater oscillations damping in the inter-area mode shapes. For those interconnections and areas that were not as heavily interconnected, the oscillatory behavior usually had a much lower damping ratio when excited with a high energy oscillation near the system mode.

In general, the size of generation loss in the event played an insignificant role in determining the damping ratio of the most dominant inter-area oscillation excited by that event. That is, an event with twice the MW impact in the interconnection can result in either a higher or lower damping ratio of the dominant inter-area oscillation. This implies that the impact of these generator trips is determined by the transition from the state before the trip and the state after the generator trip. Size will, however, impact which mode shapes dominate the oscillation as the events demonstrate a variance in their relative energy with respect to the excitation location. This important to note for future analysis as the signals close to the generator trip will have greater values of excitation compared to the rest of the system.

**Interaction between Natural and Forced Oscillations**

From the results found in Chapter 2 and in the companion document that contains the detailed results for each Event, the system natural modes that are excited by the forced oscillations demonstrate small resonance. The major consideration for all events then is how strong of a resonance effect each event (in the case of a forced oscillation) has to the natural modes of the system and the damping ratio of the natural system modes. In the chosen events, the primary factor that dictated the resonance effect was the spectral proximity to the natural system modes rather than occurring in an area of high participation to or at a time of low damping ratio for the natural mode. In the chosen events, the primary factor that dictated the resonance effect was the proximity of the forced oscillation’s frequency to the frequency of natural system modes, rather than the location of the forced input or the damping ratio of the modes.

**Recommendations**

NERC recommends a few next steps in enhancing the understanding of the oscillatory parameters of the BES. Namely:

- NERC strongly urges each interconnection to take the mode shape plots included in the appendices and to identify which set of generators poses the largest risk in exciting these mode shapes.
- NERC also urges implementing agreed upon modifications to the format for submitting PMU data for this type of analysis as there were consistency issues in this data set. After completing these initial steps, NERC believes that the best approaches for continual study include a pre-emptive approach in identifying changing system mode shapes, as well as a verification test done similar to the structure seen in this report.
- In the Western Interconnection (WI), NERC recommends to better understand the East-West modes, specifically how Montana and Colorado participate in the system modes.
- In the Texas Interconnection (TI), NERC recommends increasing the PMU coverage from the NW to better observe the mode as that region was lacking in the data submitted.
- For the Eastern Interconnection (EI), NERC recommends a better understanding of the two modes near 0.25 Hz.
  - In addition, NERC recommends for the EI to track the 0.78 Hz forced oscillation source observed in many of the events and to monitor the mode shapes of the inter-area modes in the frequency range of 0.67 to 0.8 Hz which were involved in a major forced oscillation event. In particular, it would be useful to understand why these shapes do not extend into the New York/Canada regions in the North and do not extend into the Florida region in the South.
- In general, NERC recommends that all three interconnections continue studies on whether the mode shapes of respective dominant inter-area modes discussed in this report are sensitive to specific path flows, and the source-sink relationships for these modes.
• Since the report discusses the occurrence of two forced oscillation events in EI which led to persistence of wide-area oscillations observed over wide geographical regions each lasting longer than thirty minutes, NERC recommends adequate training and support for system operators and coordination among reliability coordinators on how to handle system conditions during such wide area events.

• For better understanding of such forced oscillation events in planning and operational studies, NERC recommends the system simulation software tools to include the capability for modeling injection of such forced oscillations at different source locations in the grid.

**Synchronized Measurement System**

For the results to become more useful to the industry at large, NERC recommends interconnections utilize the trend of increasing PMU density in order to gain visibility into previously unmeasured sections of the interconnection. NERC recommends looking at the PMU placement in relationship to the areas of low visibility in the system to confirm or counter the results presented in this report. A continual effort to understand the mode shapes is warranted based off the changing nature of the mode shapes and the multitude of factors that contribute to the mode shape parameters. Future study efforts can utilize the PMU network growth to possibly eliminate uncertainties presented in this report, especially if a majority of generating units were monitored.

**Data Formatting Consistency**

Throughout the process of collecting and sorting through data, a variety of different approaches for representation of the requested data were observed. The RCs who submitted data in the Eastern Interconnection had vastly different methods for presenting their data. Some of these differences included representing their kV magnitude column in volts rather than kilovolts as their metadata indicated. Others submitted all outgoing signals from the PMU (ex. Latency, breaker status, etc.) that were unused for the oscillations analysis and some did not indicate a region where the signal was located (ex. VoltMag1). NERC recommends that an agreed upon format for sending PMU data for oscillations analysis be implemented and followed by the RCs when a request for information is sent.
Appendix A: Past Oscillation Analyses

This section details past studies of inter-area oscillations performed by utilities across North America. These studies are intended to inform.

2005 – ISO-NE Study

ISO-NE, in collaboration with Powertech Labs, performed a small signal stability study for the ISO-NE region exploring the impacts of critical contingencies and power transfers on local and inter-area modes. The study also examined the role and performance of PSSs in mitigating such oscillations. Seven base cases and all N-1 345 kV circuit outages were considered. The study identified some poorly damped local modes, as well as inter-area modes at 0.26 Hz, 0.47 Hz, 0.66 Hz, and 1.0 Hz. For each oscillation considered in detail, the participation factors of each generator in the ISO-NE region were identified and PSS tuning studies were performed.

In particular, the analysis identified two key inter-area oscillation modes that were shown to have low damping:

- Peak load conditions: 0.7 Hz and 0.8 Hz modes close to 4% damping ratio
- Light load conditions: 0.66 Hz mode close to 3% damping ratio

Figure A.1 shows the mode shape for the 0.66 Hz mode under light load conditions.

![Figure A.1: Mode Shape of 0.66 Hz Mode for Light Load Base Case Conditions](Source: ISO-NE)
The observable modes in the ISO-NE system were the primary focus of the study. However, to determine the modes in which generators in the ISO-NE system were participating in, the full set of oscillation modes were explored. Table A.1 shows the oscillation modes with less than 5% damping for one of the light load cases explored. Of those, the 0.66 Hz and 0.73 Hz modes were observable in the ISO-NE system.

### Table A.1: Low Damping Modes for a Light Load Case

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Damping (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80</td>
<td>3.00</td>
</tr>
<tr>
<td>0.66</td>
<td>3.52</td>
</tr>
<tr>
<td>0.96</td>
<td>3.81</td>
</tr>
<tr>
<td>0.73</td>
<td>4.39</td>
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<tr>
<td>0.0</td>
<td>4.69</td>
</tr>
<tr>
<td>0.99</td>
<td>4.84</td>
</tr>
<tr>
<td>0.85</td>
<td>4.91</td>
</tr>
</tbody>
</table>

2010 – MISO and MRO Study

MISO, in collaboration with Powertech Labs, performed a small signal stability study for the MRO region in 2010. This analysis, among other things, analyzed the local and inter-area low frequency oscillation modes observable in the MRO footprint. Figure A.2 shows the system modes for the study cases considered.

![Figure A.2: Inter-Area Oscillation Results from MRO Study in 2010 [Source: MISO]](image-url)
Appendix A: Past Oscillation Analyses

2013 – WECC
In 2013, the WECC in their JSIS subcommittee presented a report whose intent was to characterize the modes of oscillations in an interconnection, so that they can model them appropriately in power system studies, and to develop operating procedures and mitigation measures. Simulations were performed to benchmark oscillation performance.

This paper summarizes the modal properties of the dominant inter-area modes in the wNAPS. The primary focus has been on the most wide-spread and troublesome NS Mode A and the NS Mode B. Initial work on EW Mode A has also been presented. The properties are estimated based upon several years of actual-system data analyses and to a lesser extent, model-based analysis. NS modal properties include:

- NS Mode A is typically near 0.25 Hz. Its damping is typically larger than NS Mode B with typical damping near 10% to 15%.
- NS Mode B is typically in the 0.35 Hz to 0.4 Hz range with a damping of 5% to over 10%.
- The shape for NS Mode A has the northern half of the wNAPS swinging against the southern half. By far, the most dominant observability point is the Alberta Canada area of the system. The node or dividing line is very close to Malin on the COI.
- The shape for NS Mode B has the Alberta area swinging against BC and the northern US which in turn swings against the southern part of the US. The northern node or dividing line is just south of Langdon on the BC/Alberta intertie. The other node is typically south of Tesla and north if Diablo Canyon. The observability is much more widespread than NS Mode A in that no one location is dominant.
- The controllability of NS Mode A is dominated by Alberta while the controllability of NS Mode B is very wide spread. Therefore, contingencies outside Alberta primarily excite NS Mode B.
- The Alberta-BC intertie has the largest impact on the two modes. When Alberta disconnects, the two modes “melt” into one mode typically near 0.32 Hz. This mode typically is more lightly damped. The shape for this mode is very similar to NS Mode B excluding the Alberta area PMUs.

EW Mode A is very near in frequency to NS Mode B. Based upon one day of measurement, the mode seems to have the eastern portion of the system centralized in Colorado oscillating against the system. The mode can also be observed in smaller amplitude in southern California. This paper also demonstrates the need for continued monitoring of these modes and to get a better understanding of lesser visible modes and future modal shapes.

41 See full report at https://www.wecc.biz/Reliability/WECC%20JSIS%20Modes%20of%20Inter-Area%20Oscillations-2013-12-REV1.1.pdf
Figure A.3: Map of the NS Mode B Shape [Source: WECC]
Appendix E: Contributors

NERC would like to thank all members of the NERC Synchronized Measurement Subcommittee for their guidance in developing this report. NERC would also like to thank the Reliability Coordinators for their willingness and support in sharing wide-area, time-synchronized PMU data for this analysis. Each of the Regional Entities also played a key role in ensuring this data was submitted effectively. Lastly, NERC would like to thank Dr. Mani Venkatasubramanian for his expertise in analyzing the grid events. In addition, NERC would also like to thank the DOE CERTS program for funding in this endeavor.

The following list of contributors were involved in the oscillation analysis or development of this report.

<table>
<thead>
<tr>
<th>Name</th>
<th>Entity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aftab Alam (SMS Chair)</td>
<td>California ISO</td>
</tr>
<tr>
<td>Andrew Arana</td>
<td>Florida Reliability Coordinating Council</td>
</tr>
<tr>
<td>Clifton Black</td>
<td>Southern Company</td>
</tr>
<tr>
<td>Kevin Chen</td>
<td>Electric Power Group</td>
</tr>
<tr>
<td>Jeff Dagle</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>Matt Donnelly</td>
<td>Montana Tech</td>
</tr>
<tr>
<td>Jim Follum</td>
<td>Pacific Northwest National Laboratory</td>
</tr>
<tr>
<td>Tim Fritch (SMS Vice Chair)</td>
<td>Tennessee Valley Authority</td>
</tr>
<tr>
<td>Robert Glen</td>
<td>New York ISO</td>
</tr>
<tr>
<td>Patrick Gravois</td>
<td>Electric Reliability Council of Texas</td>
</tr>
<tr>
<td>Pablo Gutierrez</td>
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<tr>
<td>Bryan Hartwell</td>
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<tr>
<td>Neal Hickey</td>
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<tr>
<td>Jim Kleitsch (SMS Past Chair)</td>
<td>American Transmission Company</td>
</tr>
<tr>
<td>Gary Kobet</td>
<td>Tennessee Valley Authority</td>
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<tr>
<td>Dmitry Kosterev</td>
<td>Bonneville Power Administration</td>
</tr>
<tr>
<td>Bernie Lesieurte</td>
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<td>Xiaochuan Luo</td>
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<tr>
<td>David Mahlmann</td>
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<td>Slava Maslennikov</td>
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<td>Keith Mitchell</td>
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<tr>
<td>Alex Ning</td>
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<tr>
<td>Pramila Nirbhavane</td>
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<td>Guru Pai</td>
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<tr>
<td>Jeff Parker</td>
<td>Southwest Power Pool</td>
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<td>John Pierre</td>
<td>University of Wyoming</td>
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<tr>
<td>Deepak Ramasubramanian</td>
<td>Electric Power Research Institute</td>
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<tr>
<td>Don Reichenbach</td>
<td>VACAR South</td>
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<tr>
<td>Alison Silverstein</td>
<td>North American Synchrophasor Initiative</td>
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<tr>
<td>Gagan Deep Singh</td>
<td>SaskPower</td>
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<td>Dan Trudnowski</td>
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<tr>
<td>Mani Venkatasubramanian</td>
<td>Phasor Informatics LLC (NERC Contractor)</td>
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<tr>
<td>Chris Wakefield</td>
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<tr>
<td>Jessica Harris</td>
<td>North American Electric Reliability Corporation</td>
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<tr>
<td>Name</td>
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<tr>
<td>Olushola Lutalo</td>
<td>North American Electric Reliability Corporation</td>
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<tr>
<td>Hongtao Ma</td>
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<tr>
<td>Mohamed Osman</td>
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<tr>
<td>Ryan Quint (Coordinator)</td>
<td>North American Electric Reliability Corporation</td>
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<tr>
<td>John Skeath (Coordinator)</td>
<td>North American Electric Reliability Corporation</td>
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