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NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Oscillation Analysis

Informational Webinar

September 13, 2019

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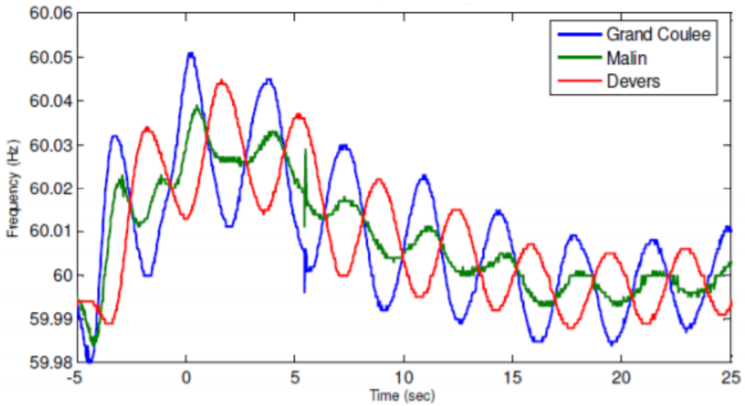
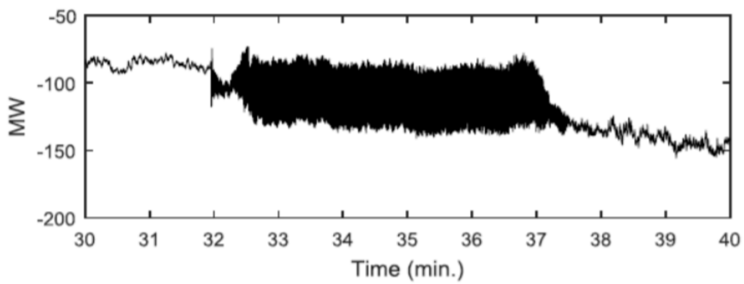
Overview of Webinar

Topic	Presenters
Introduction - *Oscillation Analysis Fundamentals* - *Interconnection-wide Data Collection*	Ryan Quint, NERC
NERC Oscillation Analysis Technical Report - *Interconnection-wide Data Collection* - *Oscillation Analysis Techniques* - *Results and Findings*	JP Skeath, NERC Mani Venkatasubramanian, Phasor Informatics
January 11, 2019 Forced Oscillation Event Analysis - *Plant Failure Events Analysis* - *Interconnection-wide Oscillation Analysis*	Tim Fritch, TVA JP Skeath, NERC
Western Interconnection Oscillation Activities - *Historical Oscillation Analyses* - *Current Focus Areas*	Jim Follum, PNNL
Wrap Up - *Key Takeaways & Recommendations*	Ryan Quint, NERC
Q&A	All

System Oscillations and Forced Oscillations



- **System (Natural) Oscillations:** low-frequency rotor angle oscillations caused by instantaneous power imbalances. Often referred to as local, intra-plant, inter-area, and torsional oscillations.

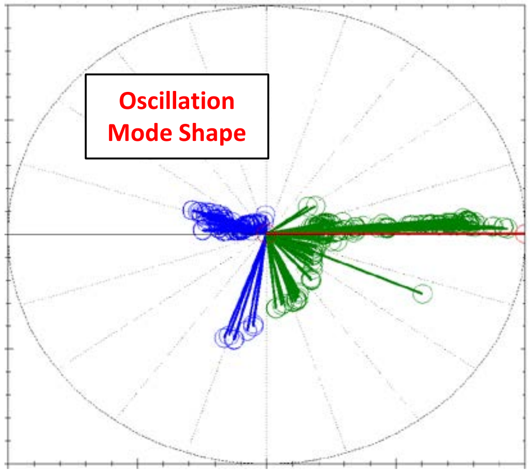


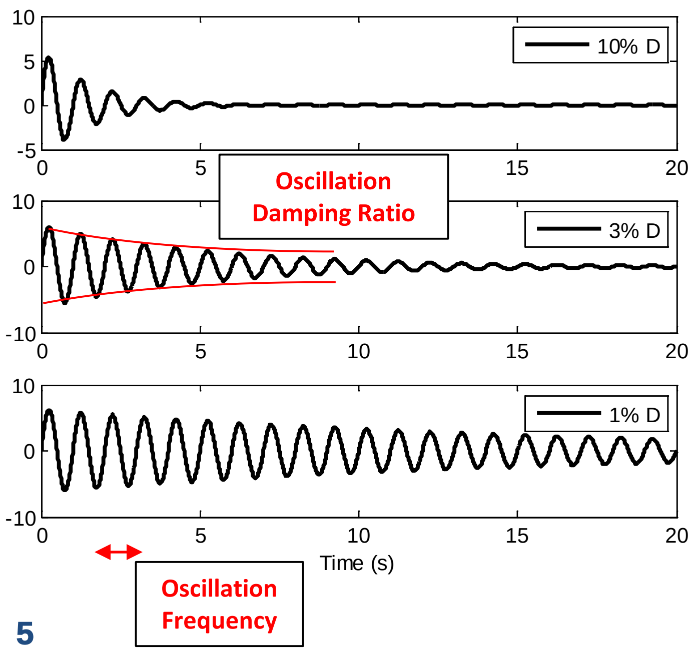
- **Forced Oscillations:** sustained oscillations driven by external inputs to the power system that can occur at any frequency (e.g., unexpected equipment failures, control interactions, or abnormal operating conditions

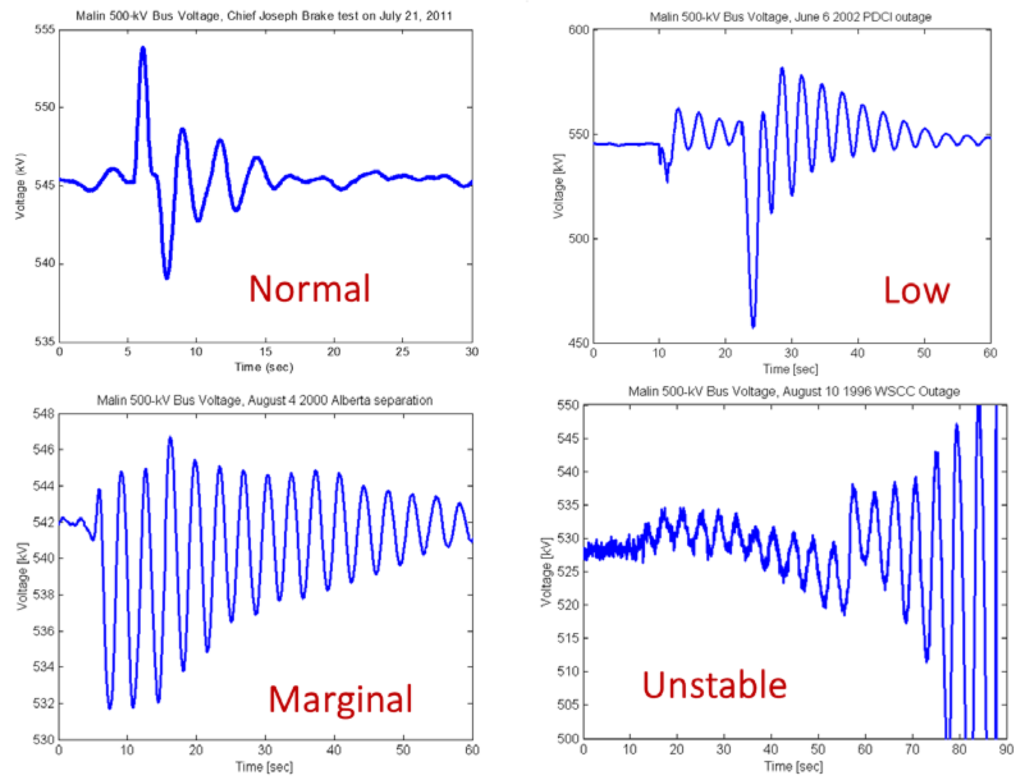
Characteristics of Oscillations

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

Oscillation Fundamentals

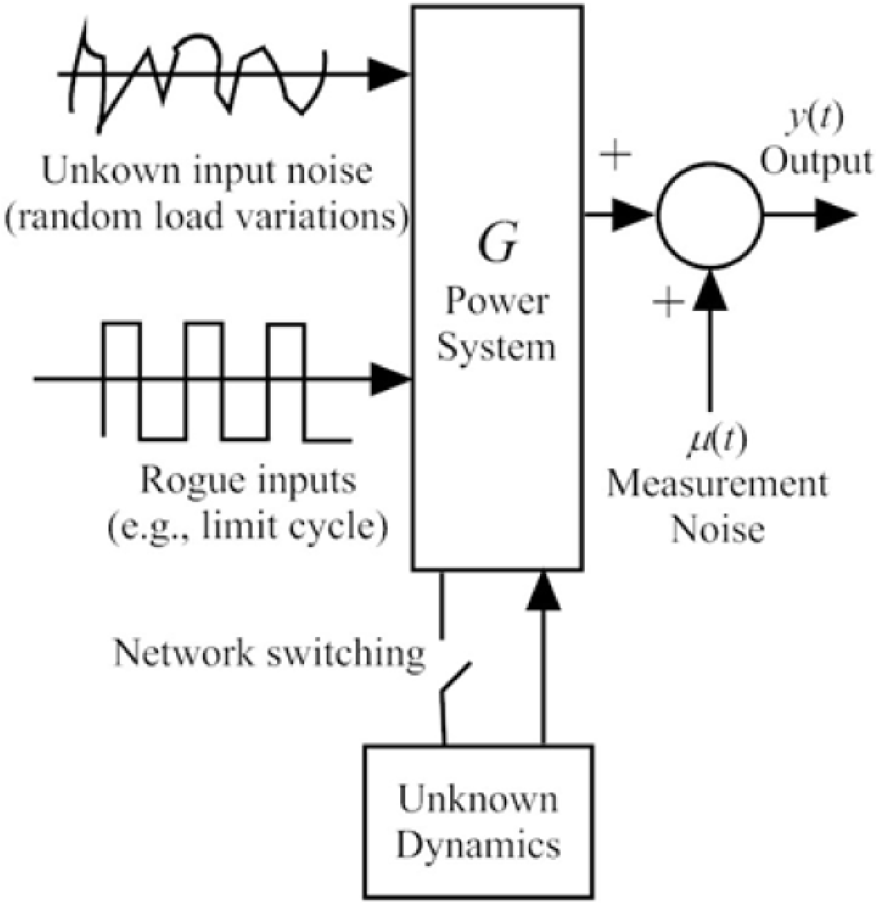


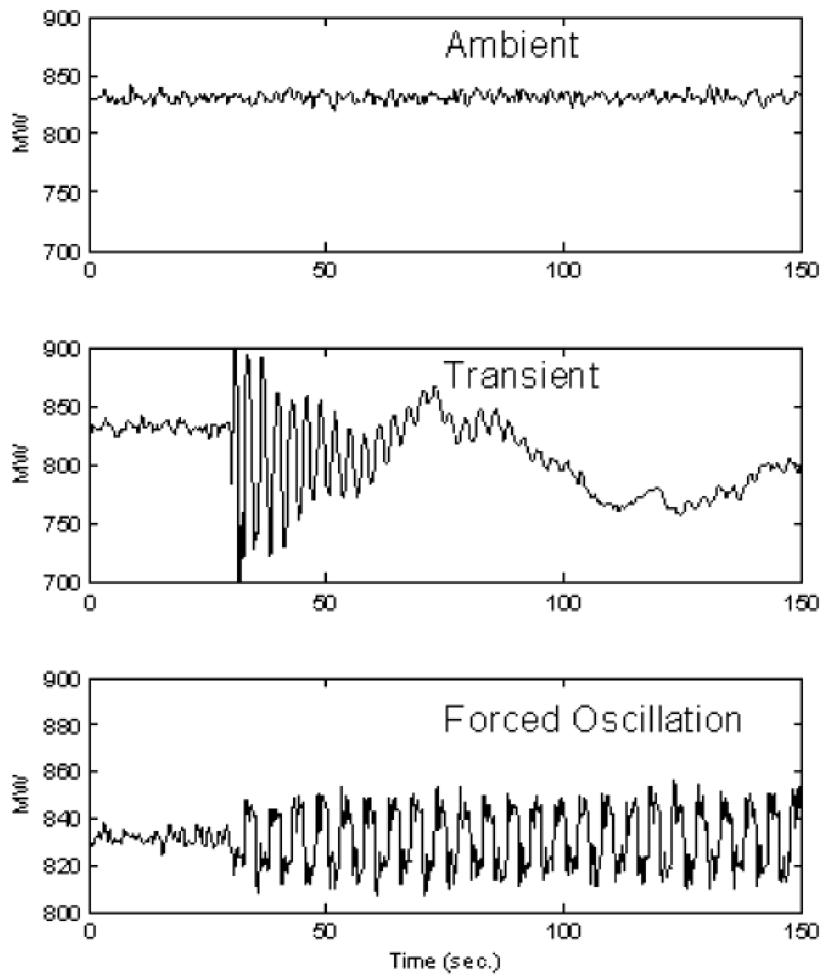




Source: Montana Tech

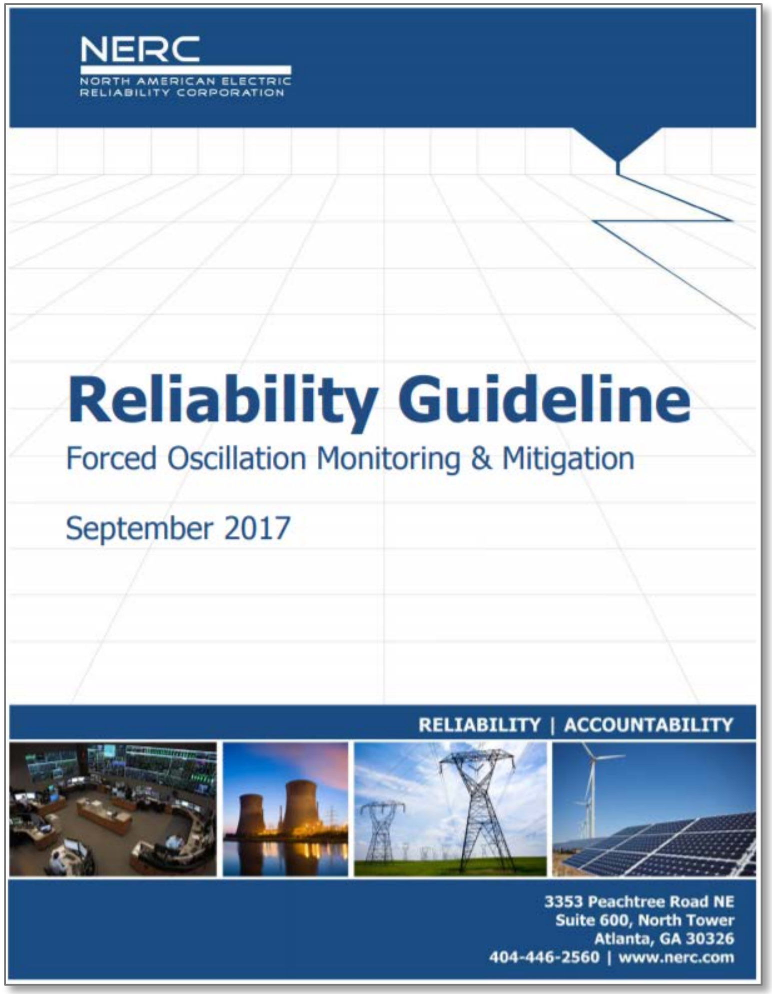
Characteristics of Oscillations

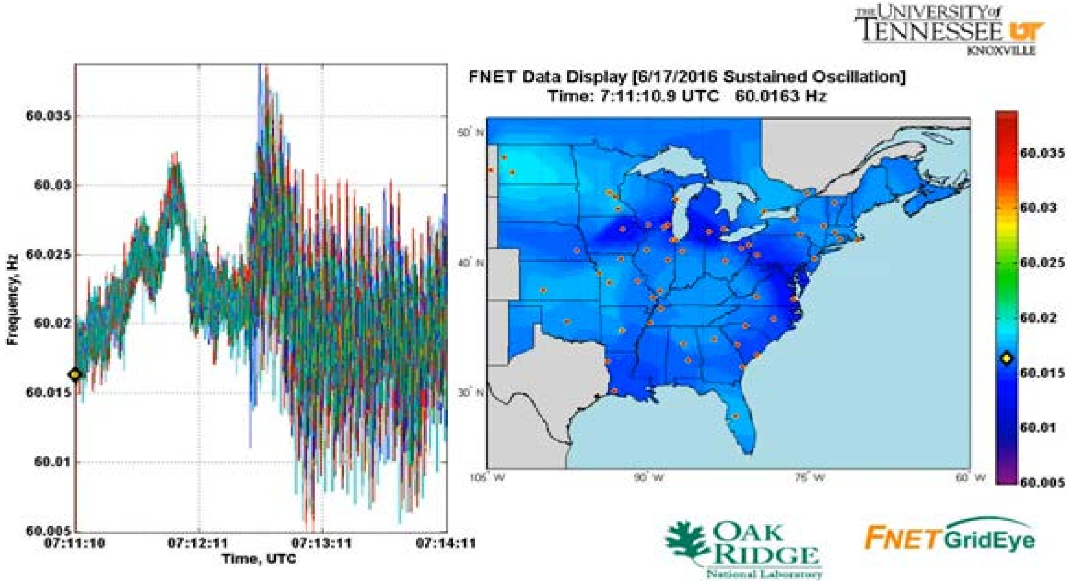




Source: Montana Tech

Oscillation Analysis Deliverables





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

Forced oscillation interactions are not a rare occurrence…

Oscillation Analysis Deliverables

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

NERC Synchronized Measurement Subcommittee (SMS)
Scope Document

Objective

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

Purpose

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

The purpose and goals of this task include:

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

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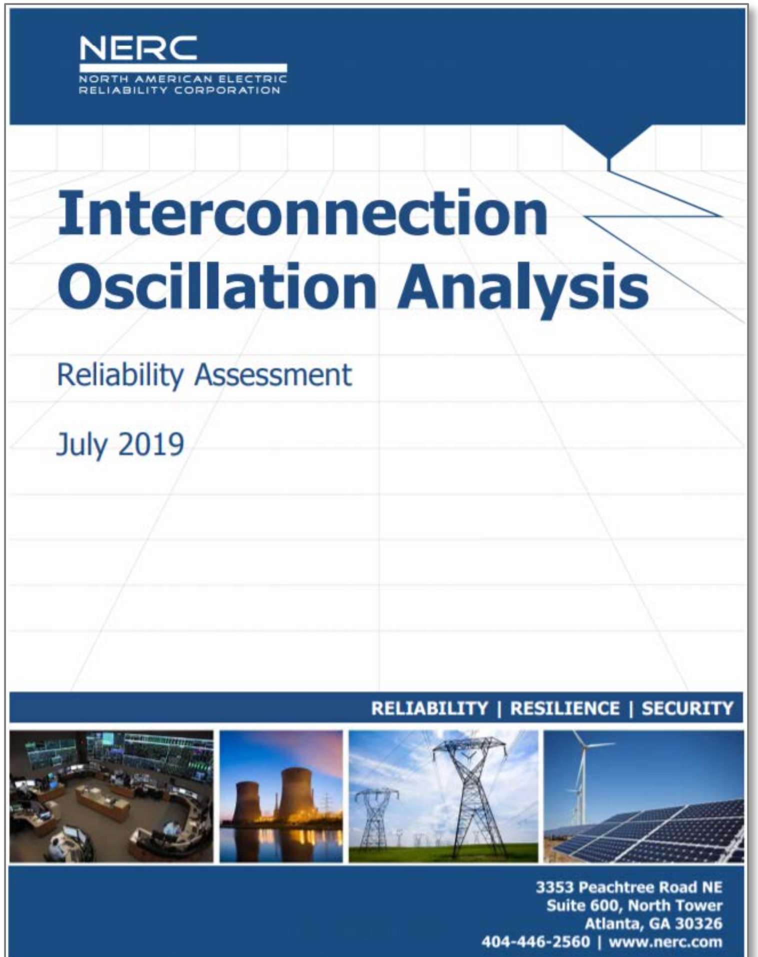
Oscillation Analysis
Data Request

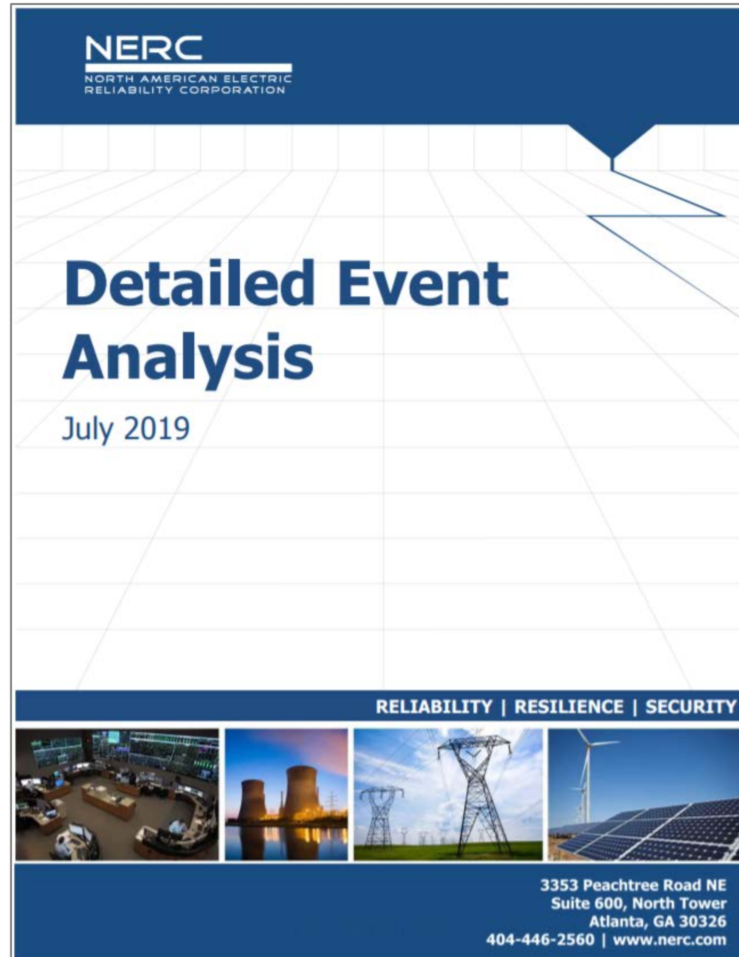
Related Materials
Oscillation Analysis Scope
Data Request Guide
List of Reliability Coordinator Contacts

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

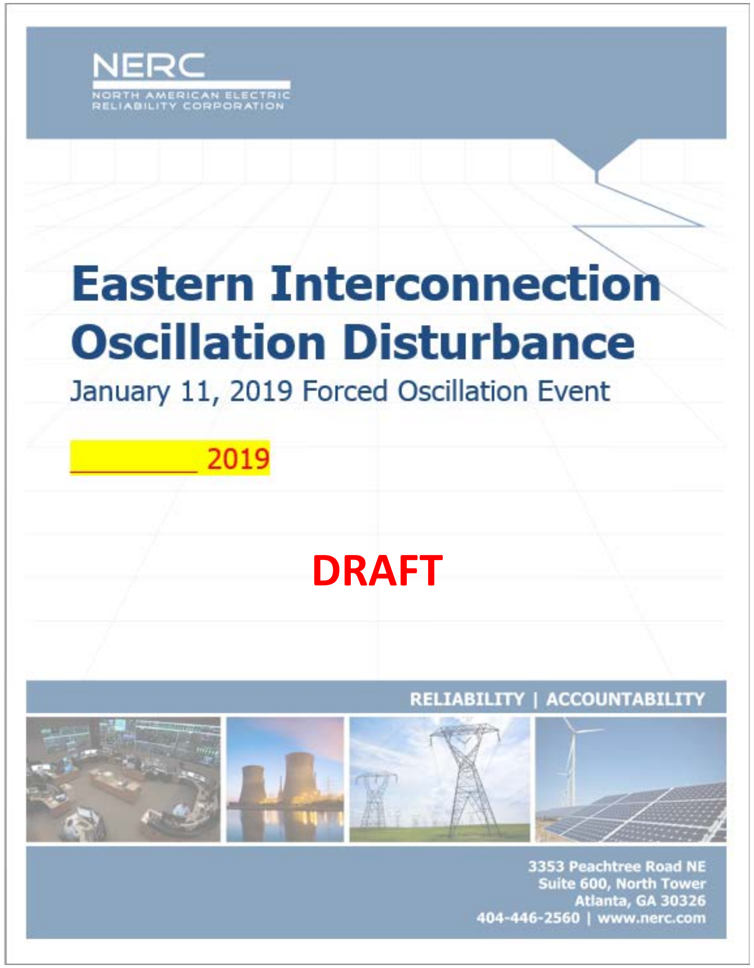
Start Time: January 11, 2019 (2019-01-11) 08:35:00 UTC Time (03:35 EST)
End Time: January 11, 2019 (2019-01-11) 09:15:00 UTC Time (04:15 EST)

Oscillation Analysis Deliverables





January 11, 2019 Oscillation Event



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Eastern Interconnection Oscillation Disturbance

January 11, 2019 Forced Oscillation Event

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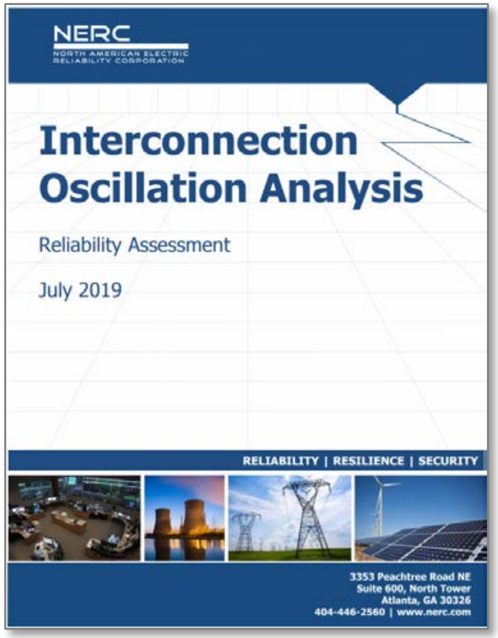
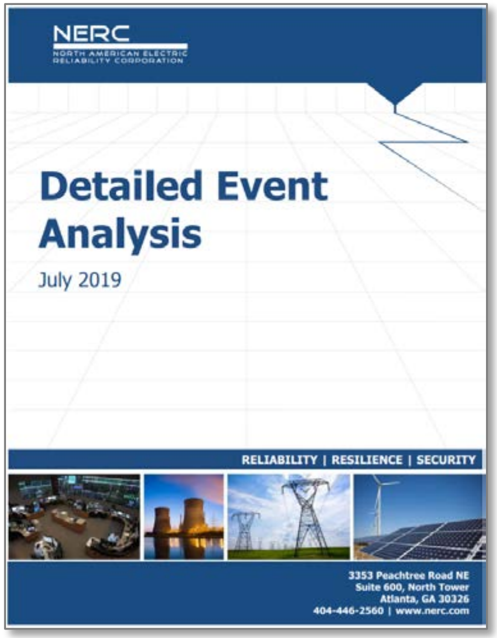
NERC Oscillation Analysis Technical Report





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Coordinated Data Collection

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Oscillation Analysis

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Oscillation Analysis Events

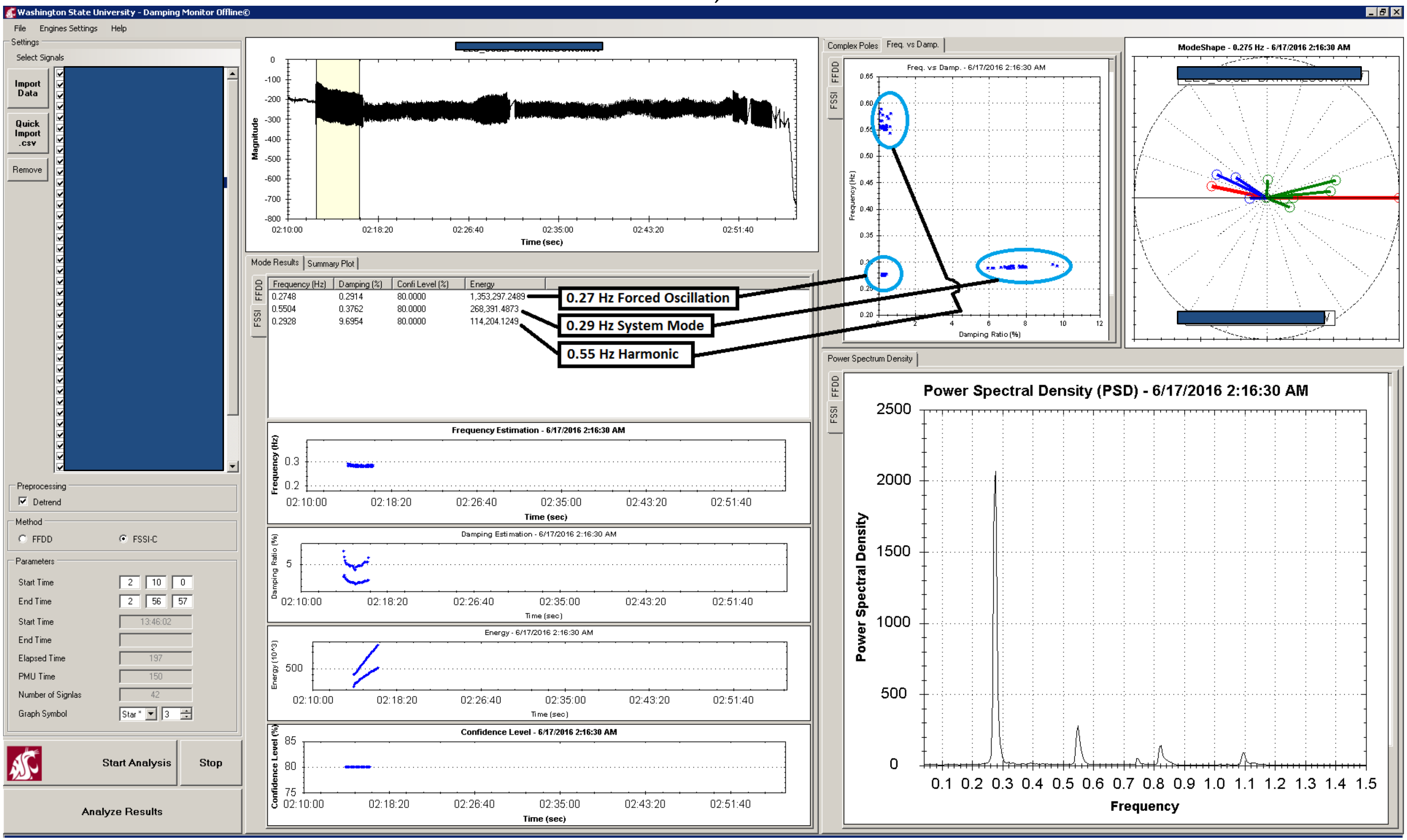
Table I.1: Analysis Reporting Algorithm and Data Source per Event			
Interconnection	**Event Number**	**Chosen Algorithm**	**Chosen Data Source (All relative)**
Eastern	Event 1: 2016-02-01	ERA	Bus Frequencies
	Event 2: 2016-04-15	Matrix Pencil	First Derivative of Voltage Phase Angle
	Event 3: 2016-06-17	FSSI/FFDD	Bus Frequencies
	Event 4: 2016-11-27	FSSI/FFDD	Bus Frequencies
	Event 5: 2017-01-12	HTLS	Bus Voltage Phase Angle
	Event 6: 2017-02-14	Matrix Pencil	Bus Voltage Phase Angle
	Event 7: 2017-03-16	HTLS	Bus Frequencies
Texas	Event 1: 2016-01-27	ERA	Bus Voltage Phase Angle
	Event 2: 2016-04-18	Prony	Bus Voltage Phase Angle
	Event 3: 2016-07-10	HTLS	Bus Voltage Phase Angle
	Event 4: 2016-10-23	HTLS	Bus Voltage Phase Angle
	Event 5: 2017-03-10	ERA	Bus Voltage Phase Angle
Western	Event 1: 2016-01-21	HTLS	Bus Frequencies
	Event 2: 2016-01-27	HTLS	Bus Frequencies
	Event 3: 2016-09-08	HTLS	Bus Frequencies
	Event 4: 2016-09-21	Prony	First Derivative of Voltage Phase Angle
	Event 5: 2017-01-20	HTLS	Bus Frequencies
	Event 6: 2017-03-09	HTLS	Bus Frequencies
	Event 7: 2017-05-10	HTLS	Bus Frequencies

Analysis Techniques

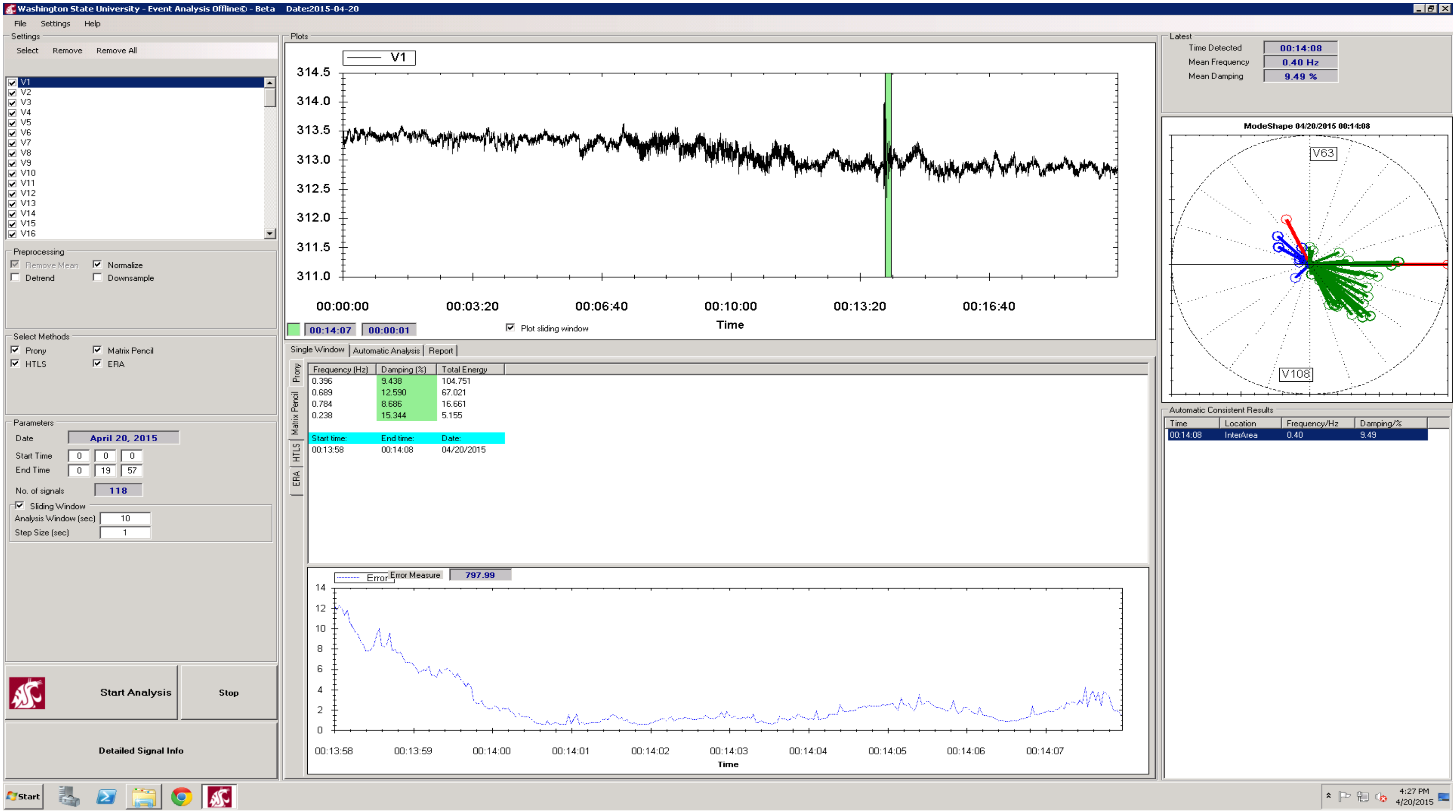
- Event Analysis Offline (EAO)
  - Ringdown analysis
  - Prony, Matrix Pencil, HTLS, ERA
  - Aimed at analyzing oscillation events resulting in sudden changes in damping
- Damping Monitor Offline (DMO)
  - Ambient noise based. Continuous. Provides early warning on poorly damped modes.
  - Several algorithms
  - Fast Frequency Domain Decomposition (FFDD), Fast Stochastic Subspace Identification (FSSI).
- FFDD – Fast multi-dimensional analysis
- FSSI – Simultaneous estimation of modes and forced oscillations

Analysis Tool: Damping Monitor Offline (DMO)

June 17, 2016 Eastern Interconnection Oscillation Event



Analysis Tool: Event Analysis Offline (EAO)



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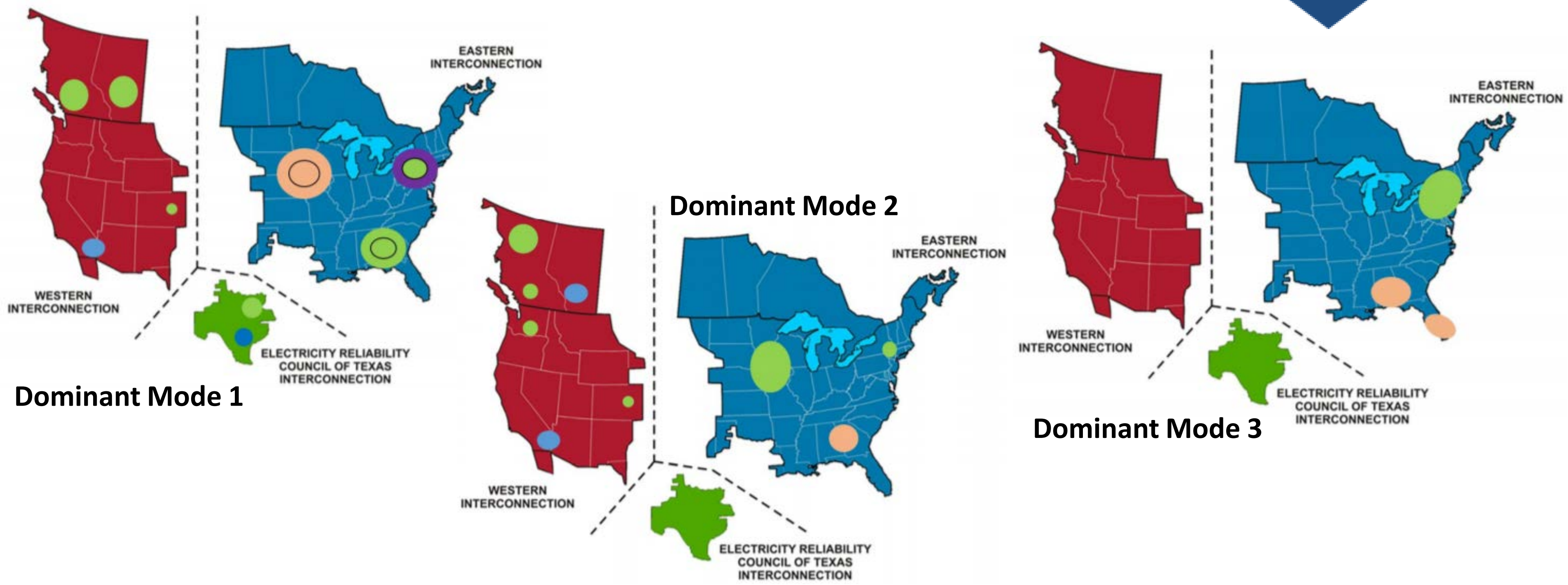
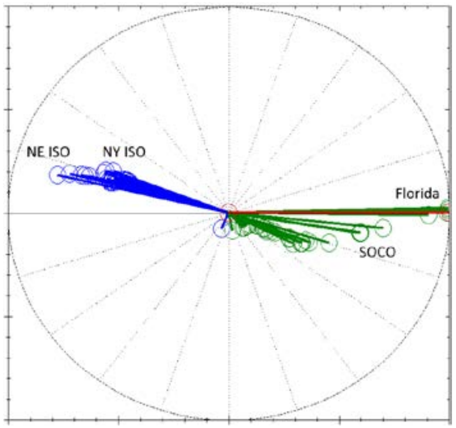
Overview of System Modes

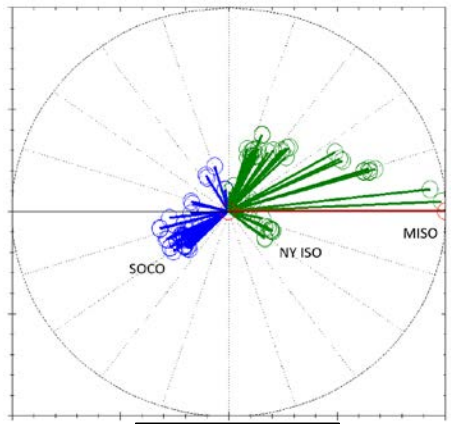


Interconnection	Mode Name	Mode Frequency Range (Hz)	Mode Average Damping Ratio (%)
Eastern	NE–S	0.16–0.22	9.70
	NW–S	0.29–0.32	16.45
	NE–NW–S	0.23–0.24	12.80
Texas	N–SE	0.62–0.73	9.26
Western	NS Mode A	0.37–0.42	12.71
	NS Mode B	0.24–0.27	13.525

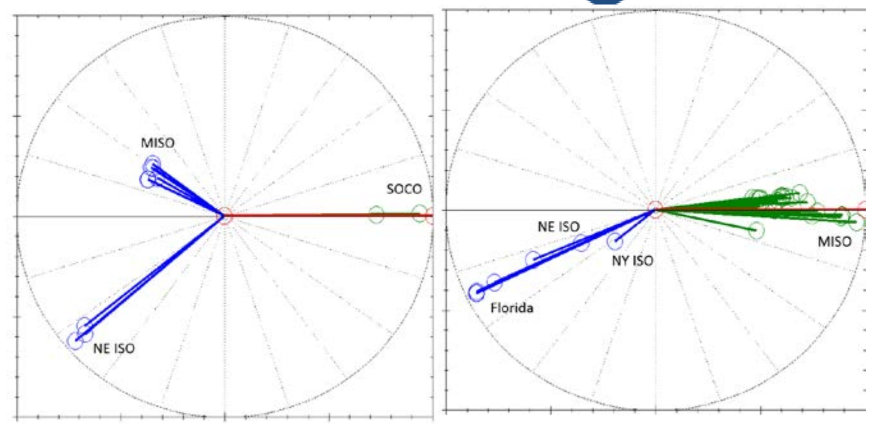
EI System Modes



0.16 – 0.22 Hz
NE - S



0.29 – 0.32 Hz
NW - S

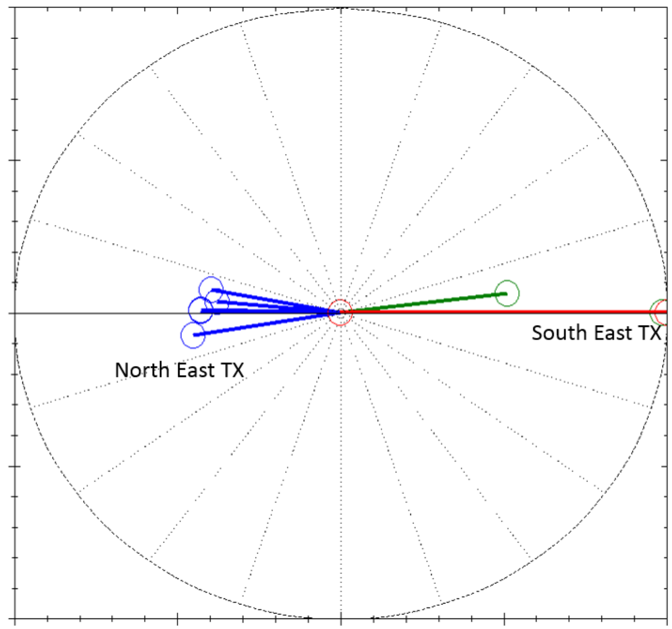


0.23 – 0.24 Hz
NE – NW – S
***Two Distinct Mode Shapes**

Mode Frequency (Hz)	Event 1 Damping Ratio (%)	Event 2 Damping Ratio (%)	Event 5 Damping Ratio (%)	Event 6 Damping Ratio (%)	Event 7 Damping Ratio (%)
0.16–0.22	NO	13	8.3	7.8	NO
0.29–0.32	NO	20	NO	12.9	NO
0.23–0.24	13.4	NO	NO	NO	12.2

Note: NO–Not Observed or Well Damped

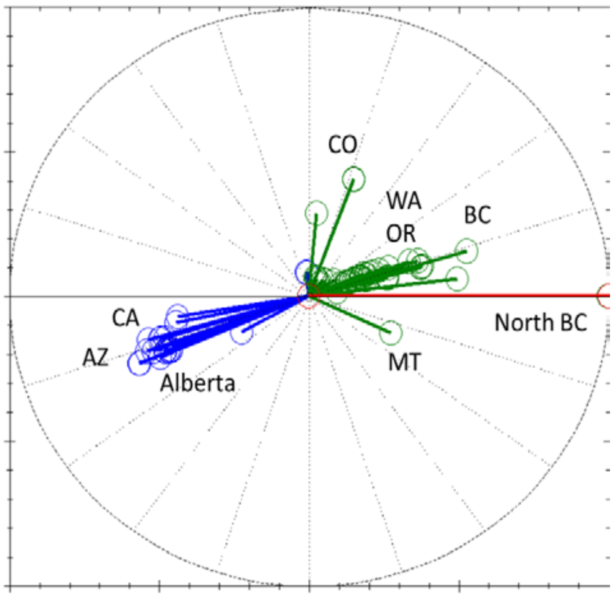
TI System Mode



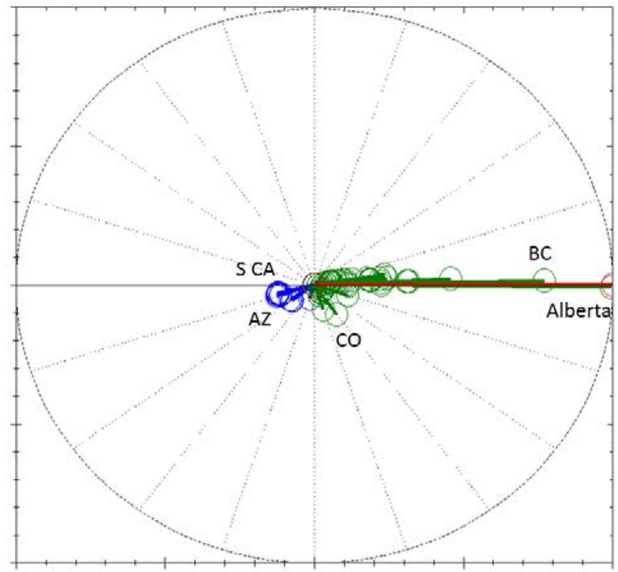
0.62-0.73 Hz
N – SE

Mode Frequency (Hz)	Event 1 Damping Ratio (%)	Event 2 Damping Ratio (%)	Event 3 Damping Ratio (%)	Event 4 Damping Ratio (%)	Event 5 Damping Ratio (%)
0.62–0.73	7	9.9	10.2	8.2	11

WI System Modes



0.37 – 0.42 Hz
NS Mode A



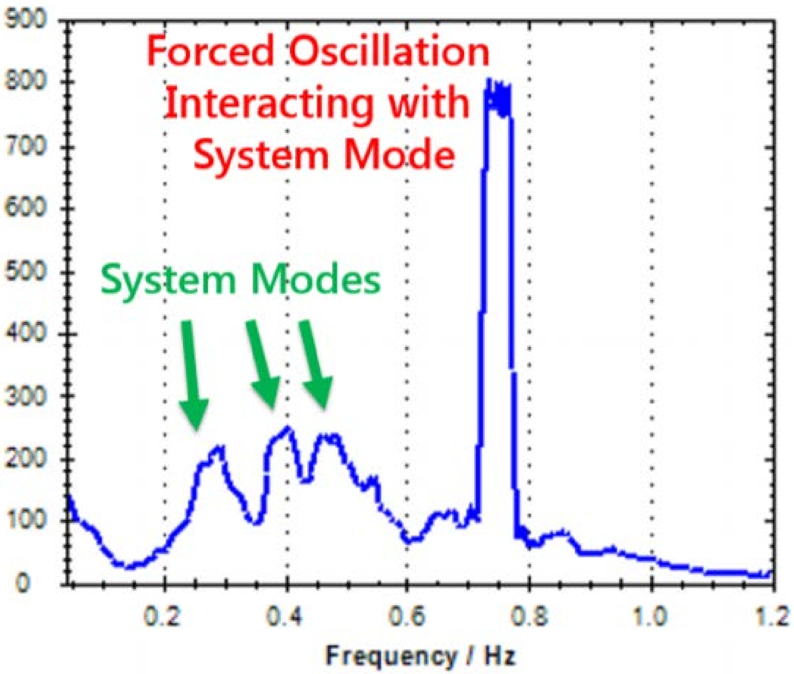
0.24 - 0.27 Hz
NS Mode B

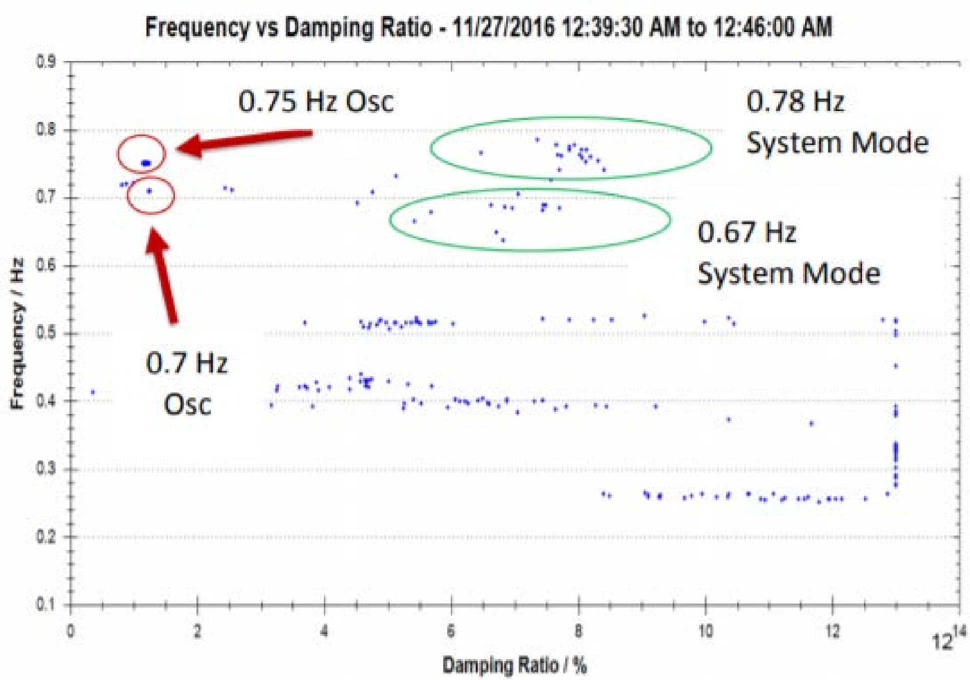
Mode Frequency (Hz)	Event 1 Damping Ratio (%)	Event 2 Damping Ratio (%)	Event 3 Damping Ratio (%)	Event 4 Damping Ratio (%)	Event 5 Damping Ratio (%)	Event 6 Damping Ratio (%)	Event 7 Damping Ratio (%)
0.37–0.42	12	9.9	10.2	10.8	13.8	14	18.3
0.24–0.27	NO	8.6	18.2	9.8	NO	NO	17.5

Forced Oscillation Interactions

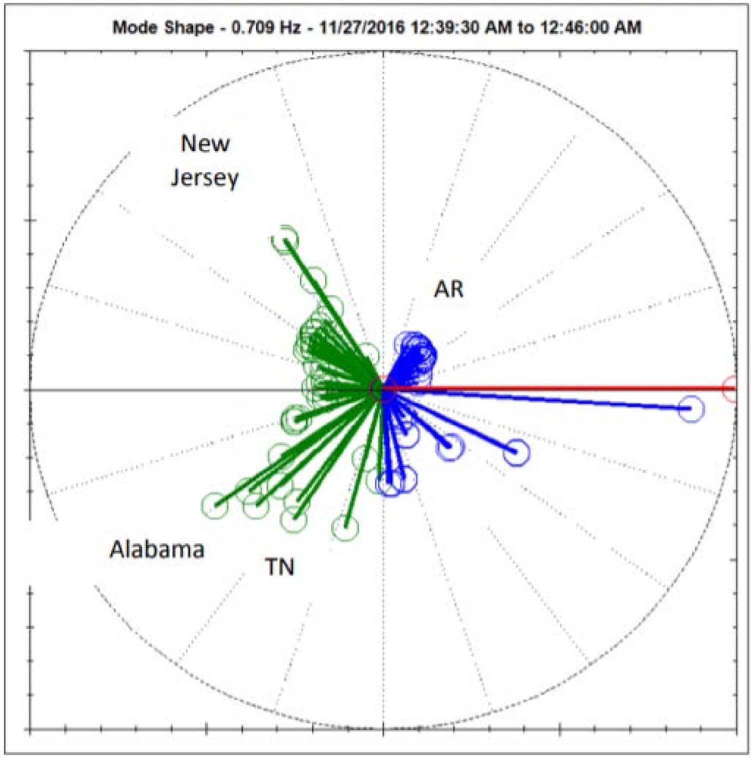
Table 1.2: Interaction of Forced Oscillation and Interarea Modes			
FO Frequency (Hz)	0.3 Hz System Mode	0.67 Hz System Mode	0.76 Hz System Mode
0.28[11]	S	NO	NO
0.75[12]	NO	S	S
0.70[13]	NO	S	S

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

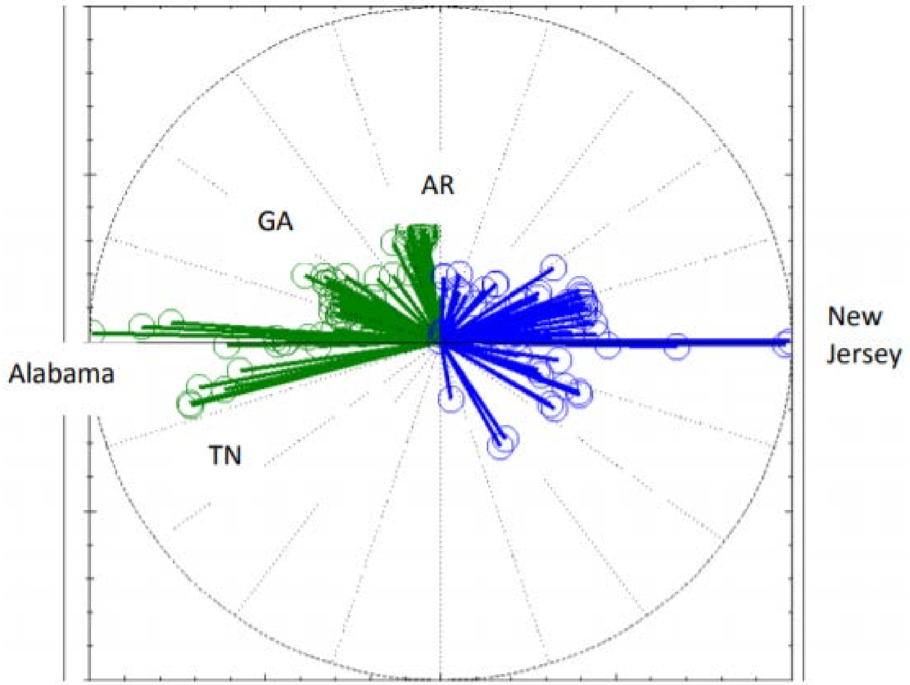




Forced Oscillation Interactions



0.70 Hz Forced Oscillation Resonance Shape



0.69 Hz System Mode Shape

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Report Key Findings and Conclusions

Primary:

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

Secondary:

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

Interconnection	Recommendation
WI	• Improve understanding of east–west modes (Montana and Colorado participation)
TI	• Increase PMU coverage from northwestern region
EI	• Perform studies to better understand widespread system modes (near 0.25 Hz) • Track the 0.78 Hz forced oscillation source; monitor mode shapes around 0.67 to 0.8 Hz • Understand why these shapes do not extend to New York/Canada or Florida regions

January 11, 2019 Forced Oscillation Event Analysis

Background

- Oscillation observed across entire Eastern Interconnection
  - Start Time: 08:44:41 UTC (03:44:41 EDT)
  - End Time: 09:02:23 UTC (04:02:23 EDT)
  - Oscillation frequency = 0.25 Hz (aligns with system mode across EI)
  - Large power swings observed across EI
- RCs identified oscillation using PMU data
  - RC communication challenged; RC Hotline down
  - Early misidentification of oscillation source
- NERC issued PMU data request

attached to this request and posted on the NERC website (links provided above). The event under consideration is a ***forced oscillation observed across the Eastern Interconnection*** during the following time:

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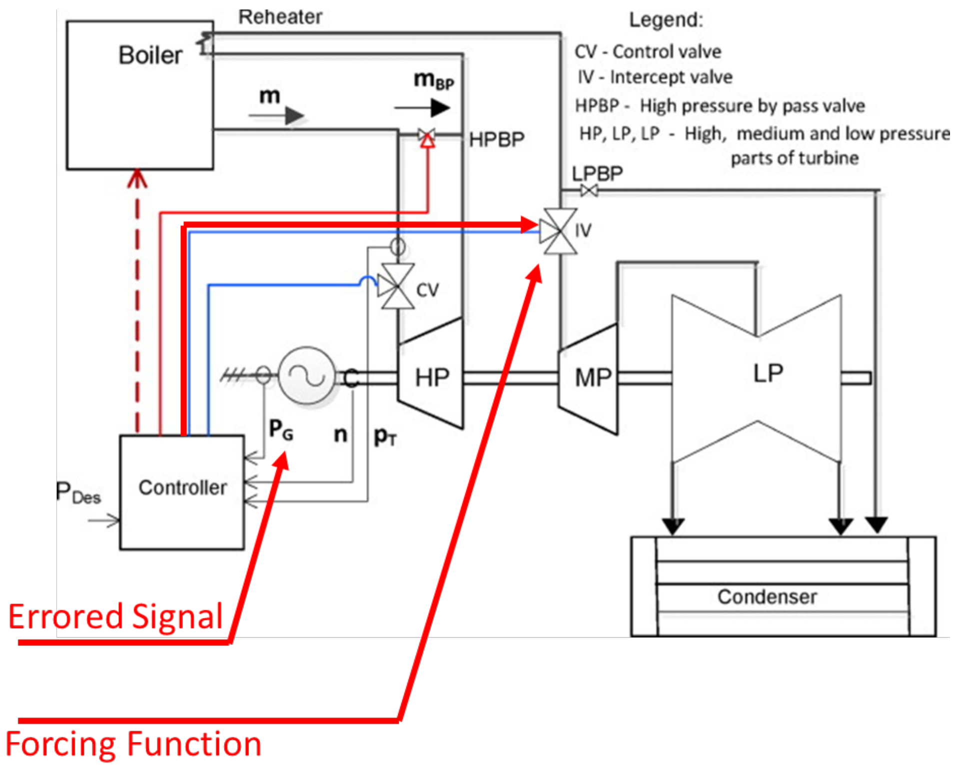
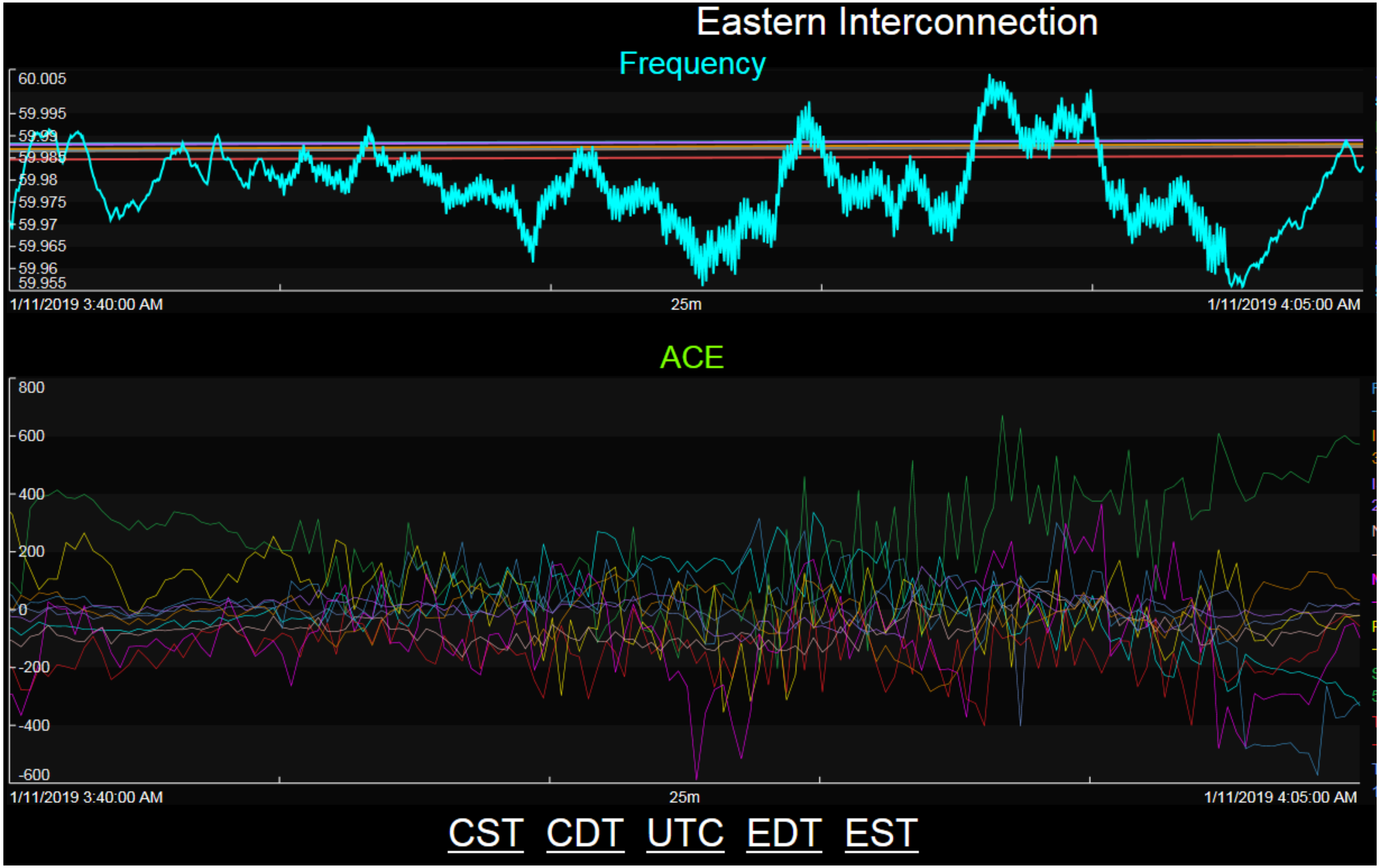
Each Reliability Coordinator should submit the requested data electronically in the required data

Forced Oscillation Source

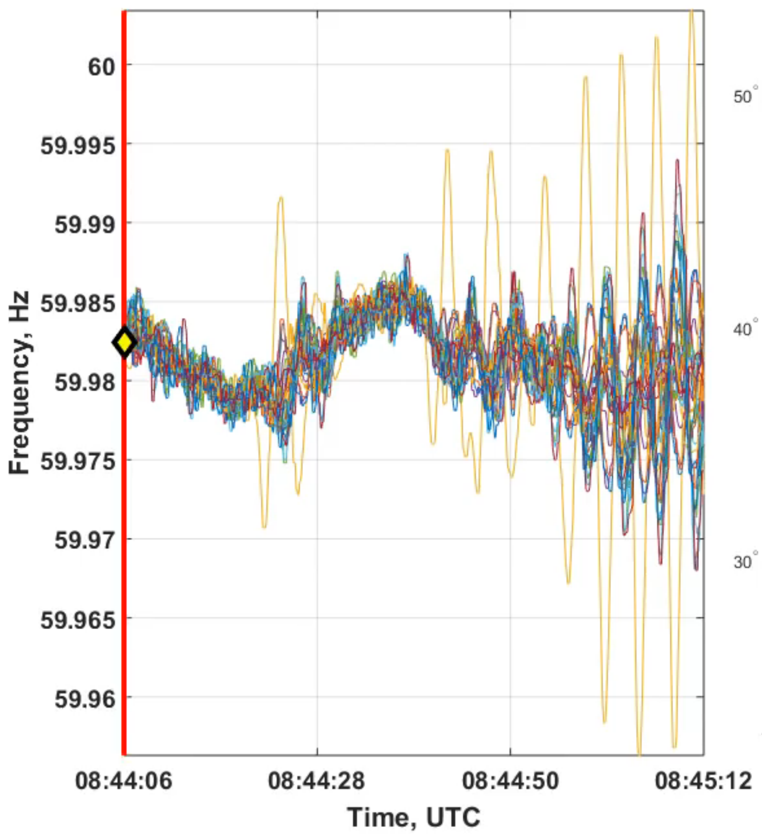


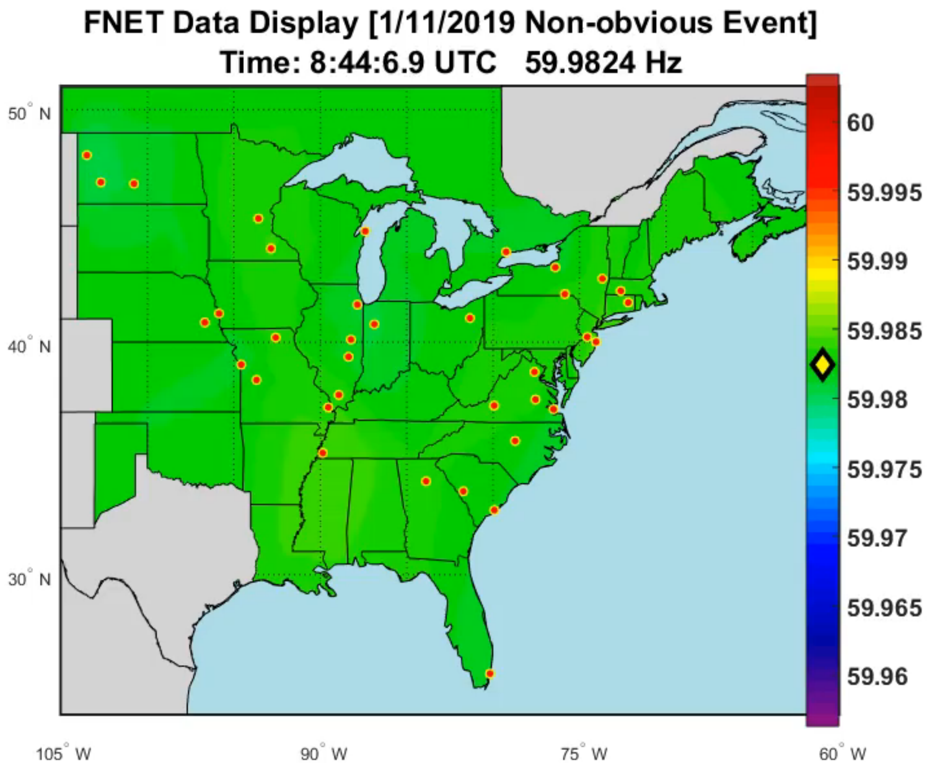
- Steam turbine at combined cycle plant
- Power-load imbalance (PLI) controls
  - Failed voltage input to feedback
  - Measured P_{gen} reading 2/3 of actual
  - Perceived power-load imbalance
- PLI trigger shuts intercept valves
- 4 second timer to reopen valves
- Imbalance eliminated and valves reopen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

NERC Data Historian Information



Initiation of Oscillation Event

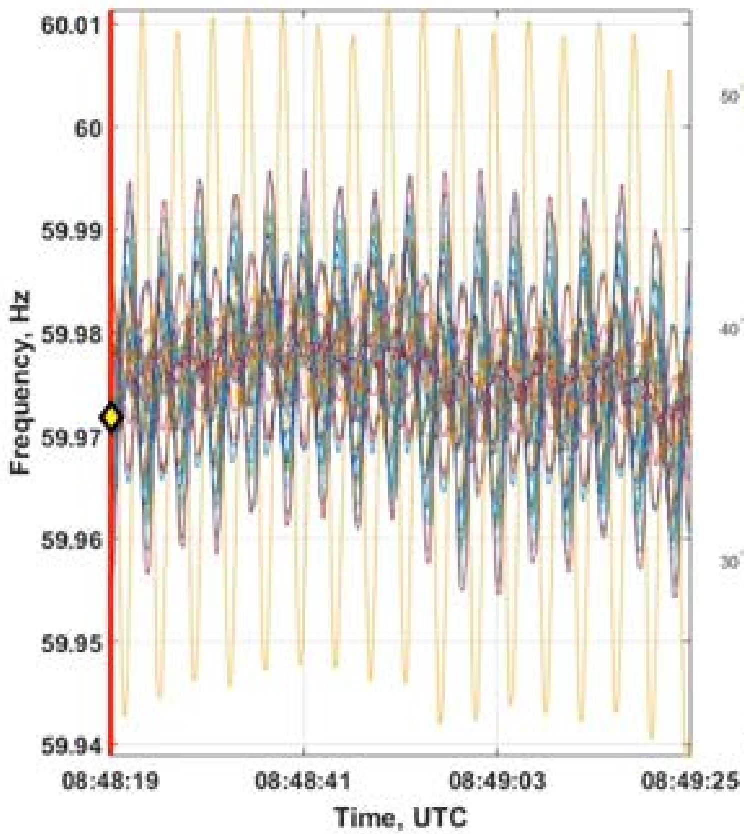


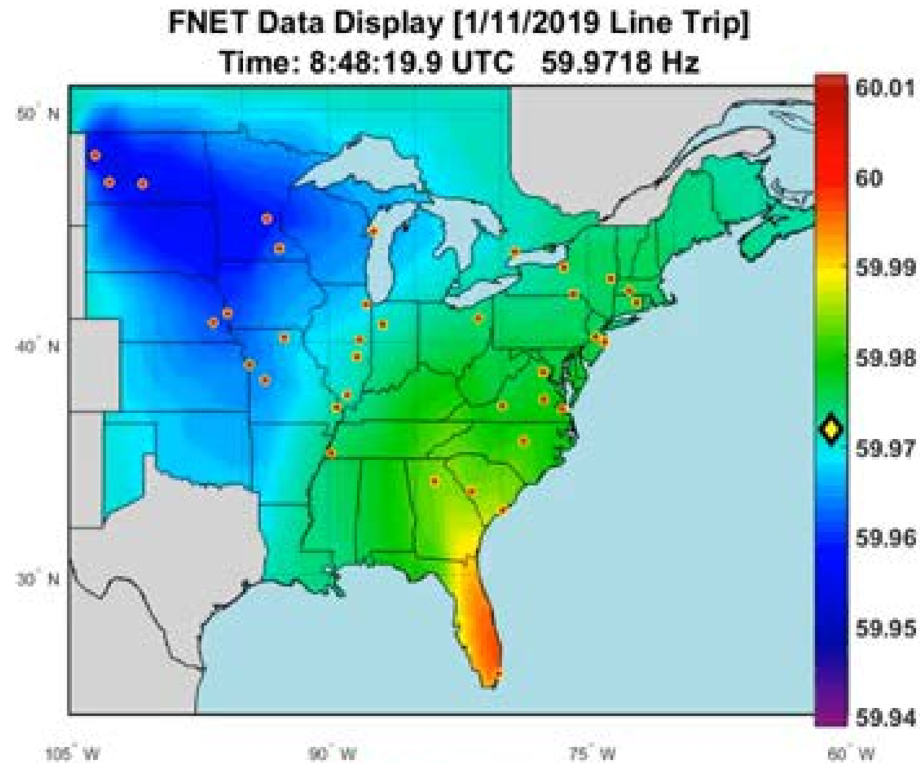


Oak Ridge National Laboratory

The University of Tennessee Knoxville

Persisting Forced Oscillation





Oscillation Mode Shapes (Using Matrix Pencil algorithm)

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

UnitName	Frequency(Hz)	Damping Ratio(%)	Phase (Degree)	Amplitude(Degree)
UsNyFulton826	0.25	.92	0.64	2.18
UsGaNorcross984	0.25	.39	-72.11	3.44
UsVaNewportnews847	0.25	.75	-57.24	1.81
UsFlMiami742	0.25	.33	-64.35	9.26

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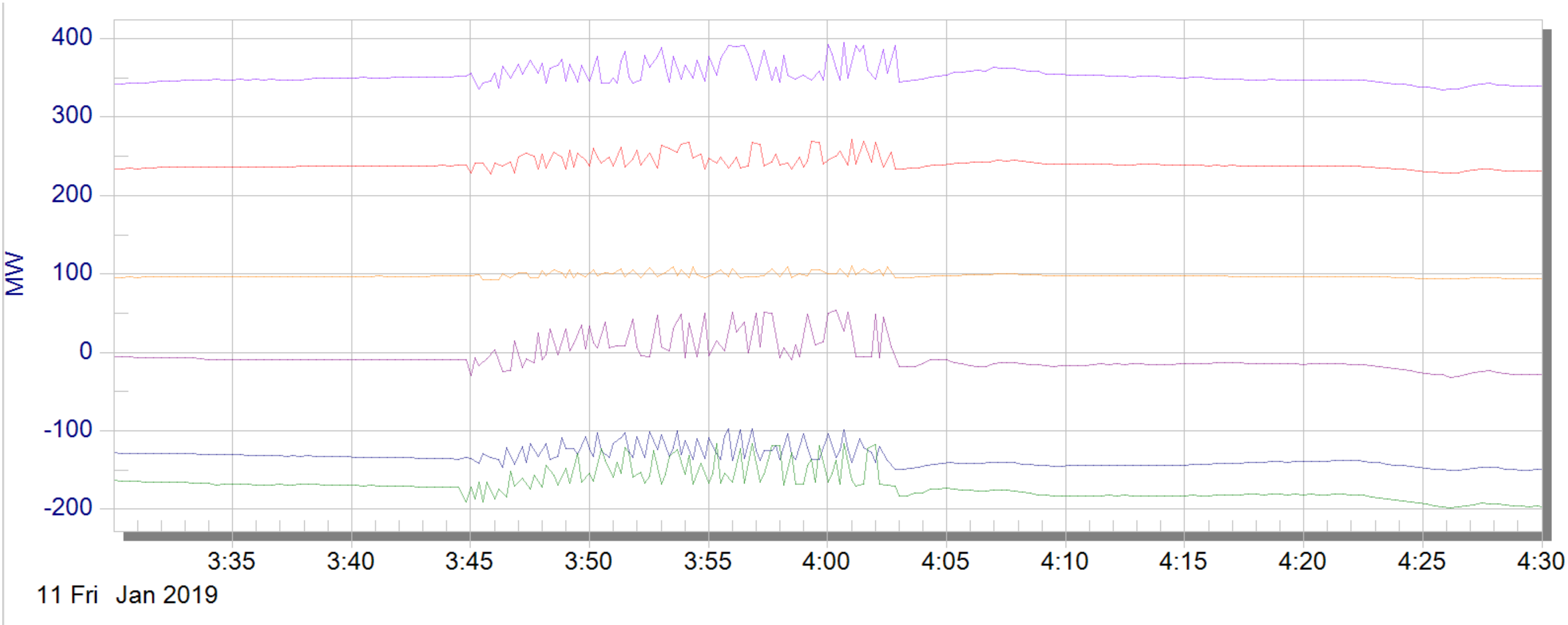
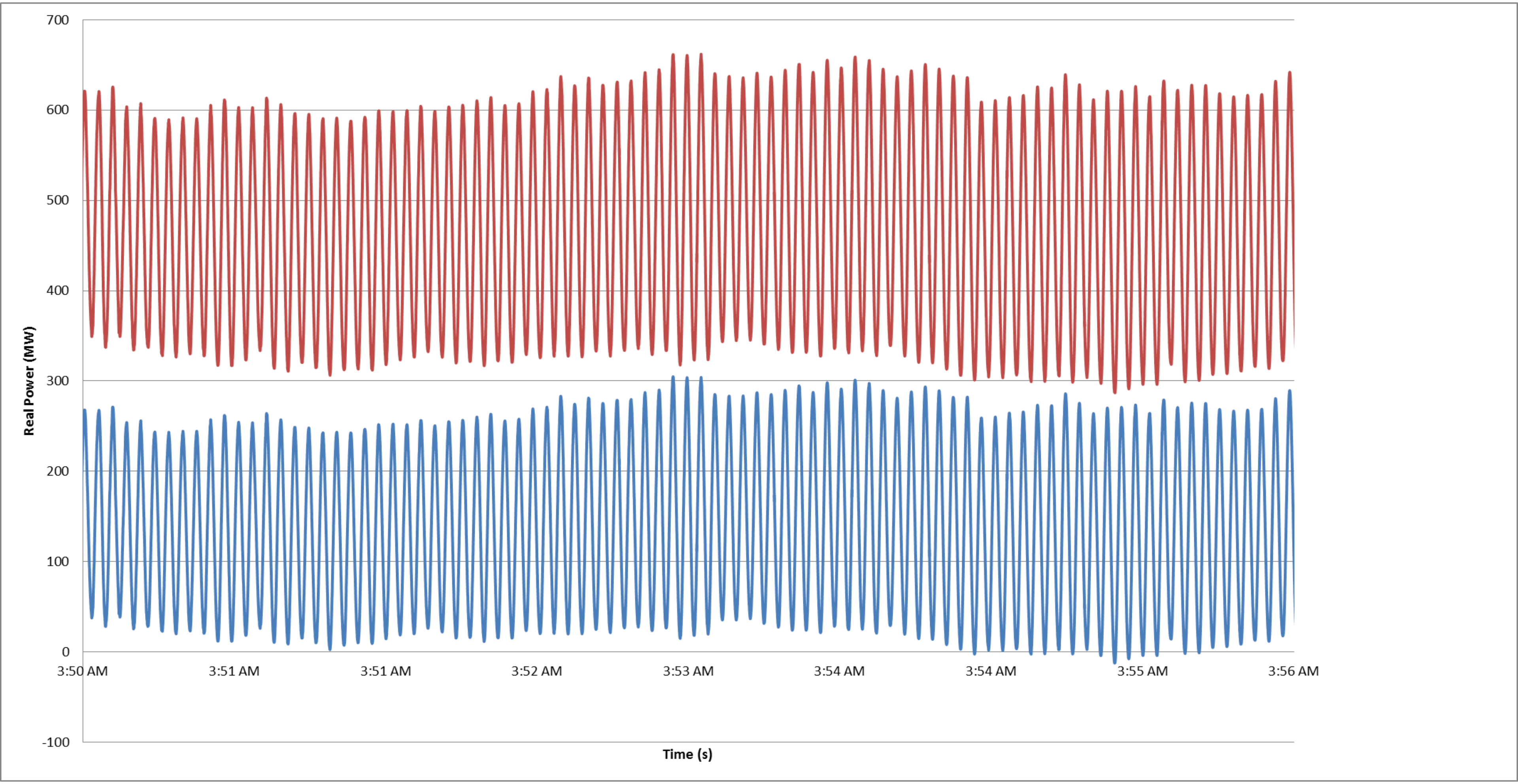
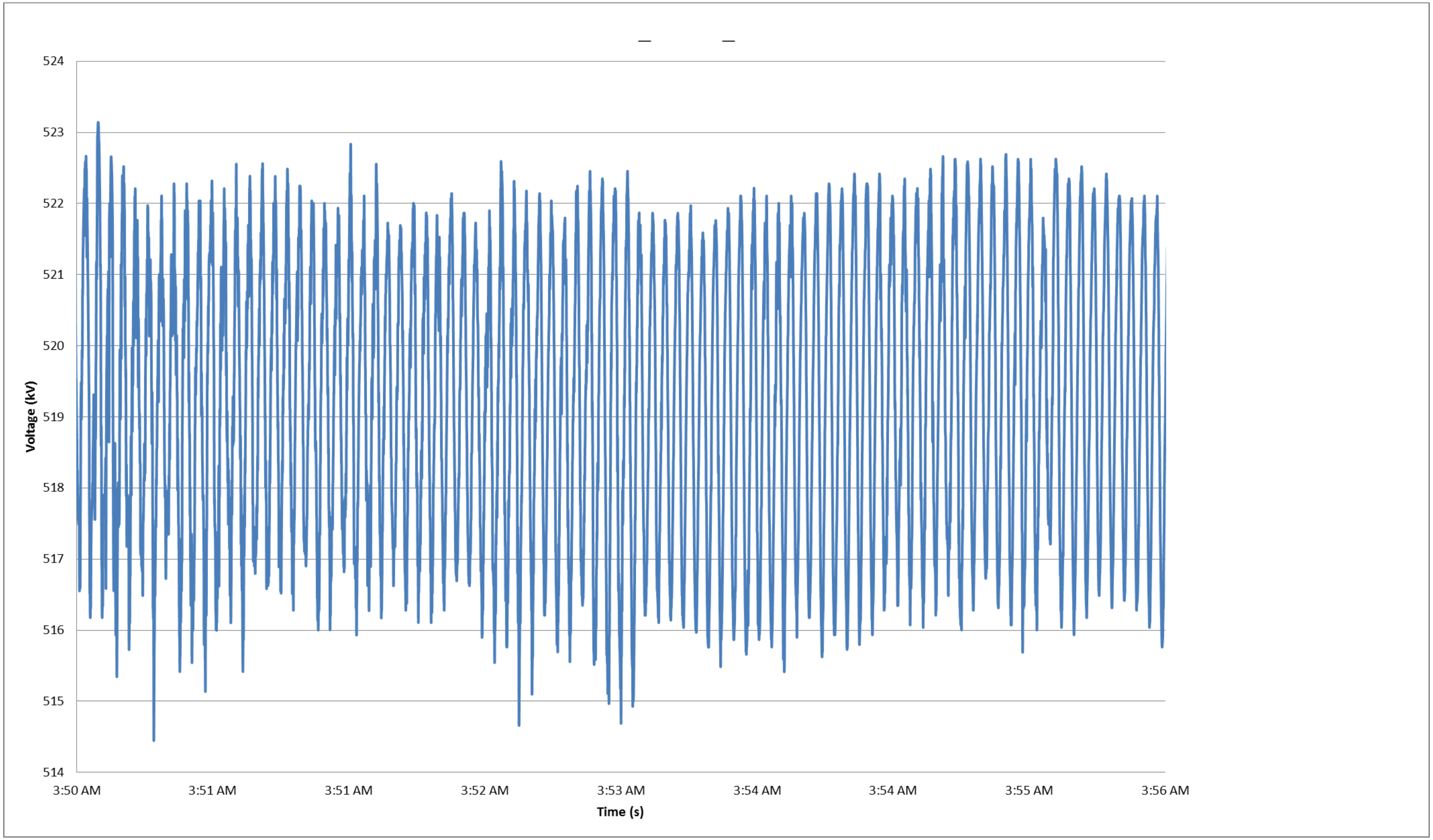
Generator Analysis



Line Flows in Florida



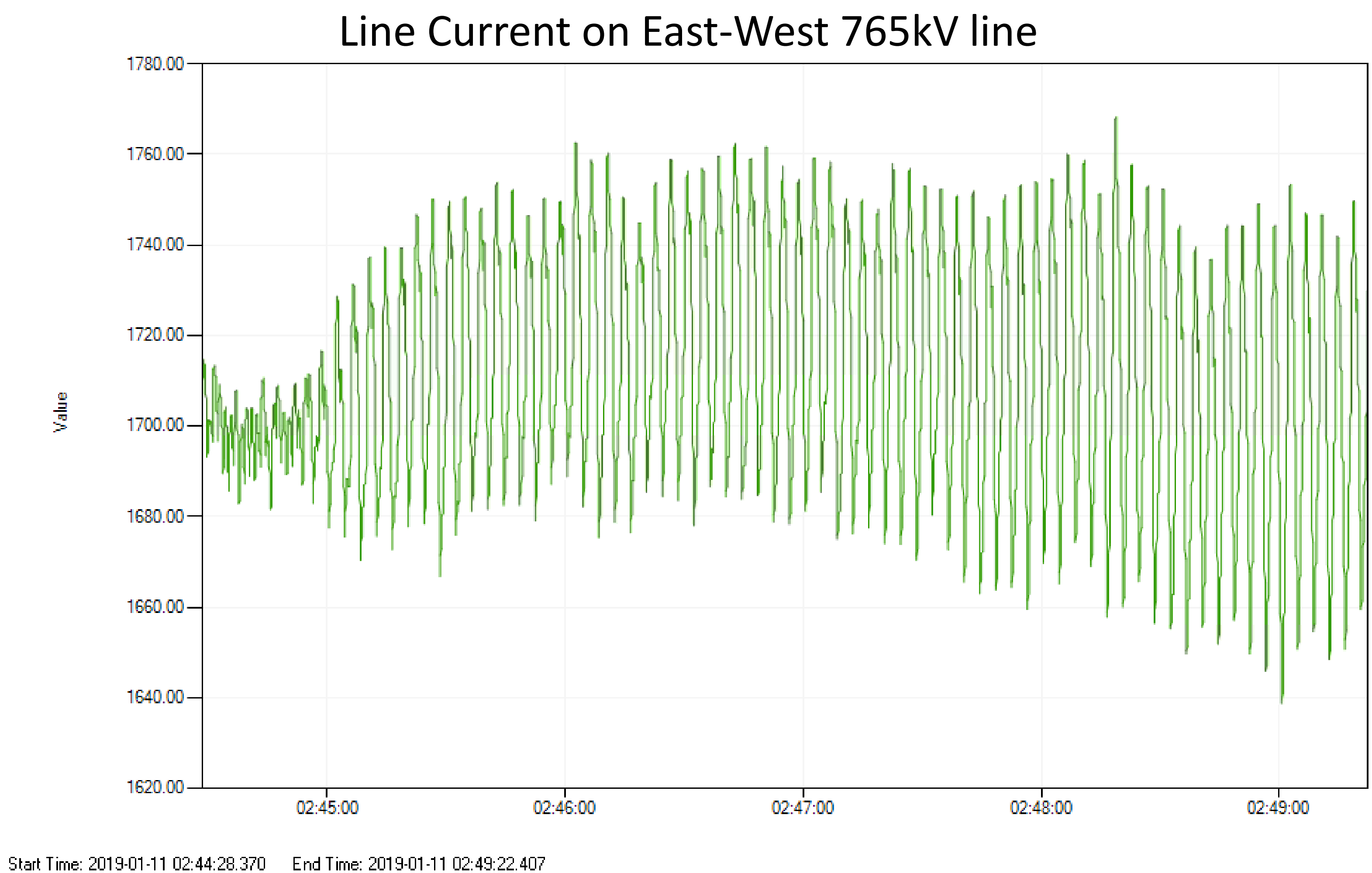
500 kV Bus Voltage in Florida



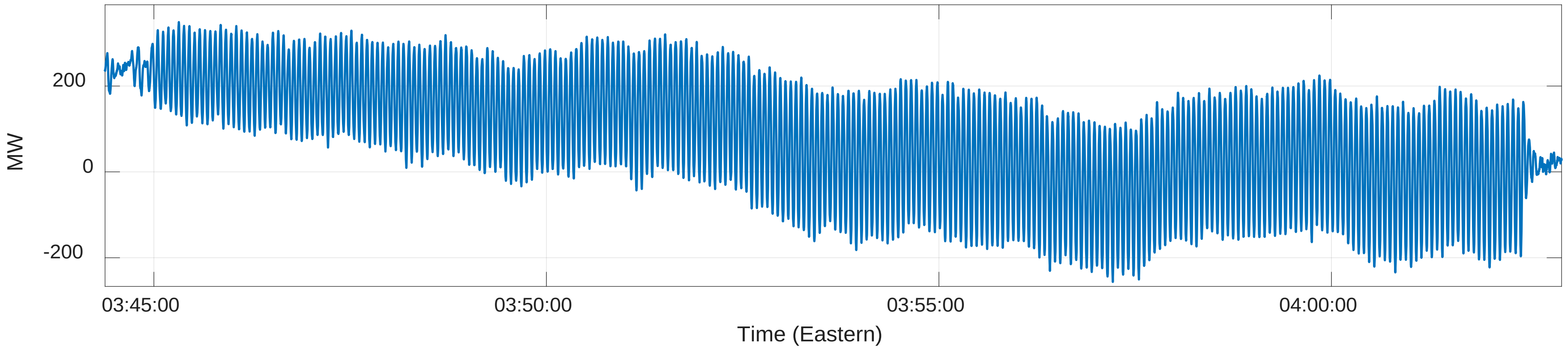
Line Flows in TVA Region

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

Line Current in ComEd Region

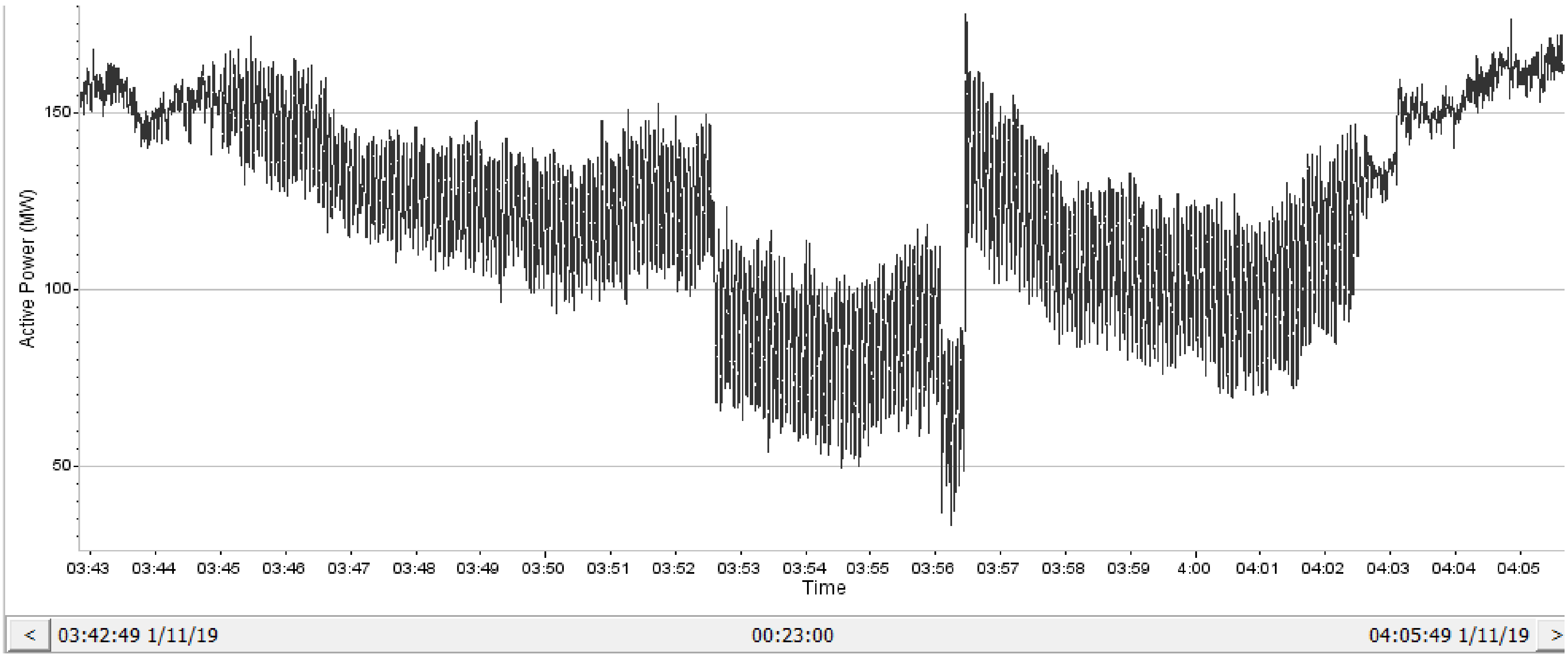


Line Flows in AEP Region



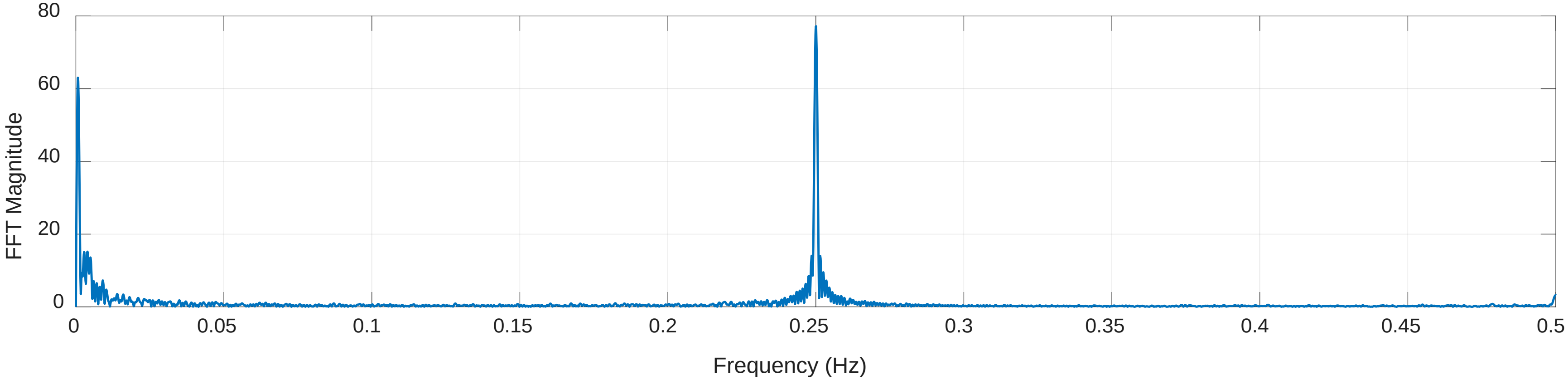
Line Flows in ISO-NE Region

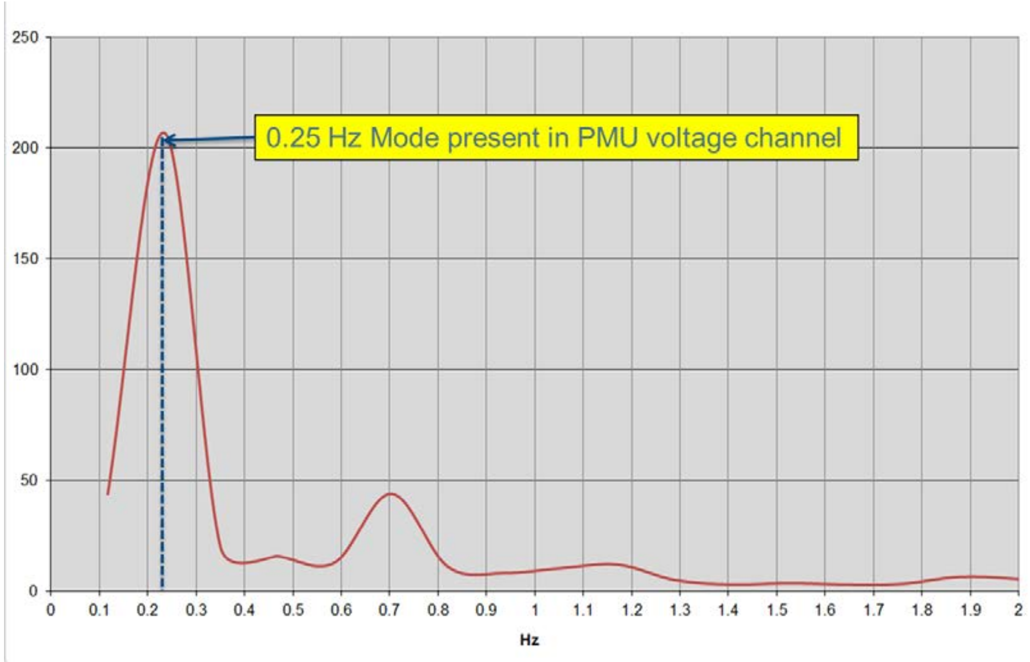
MW flow on 345KV line between NE and NY



*Step changes attributed to unrelated actions locally.

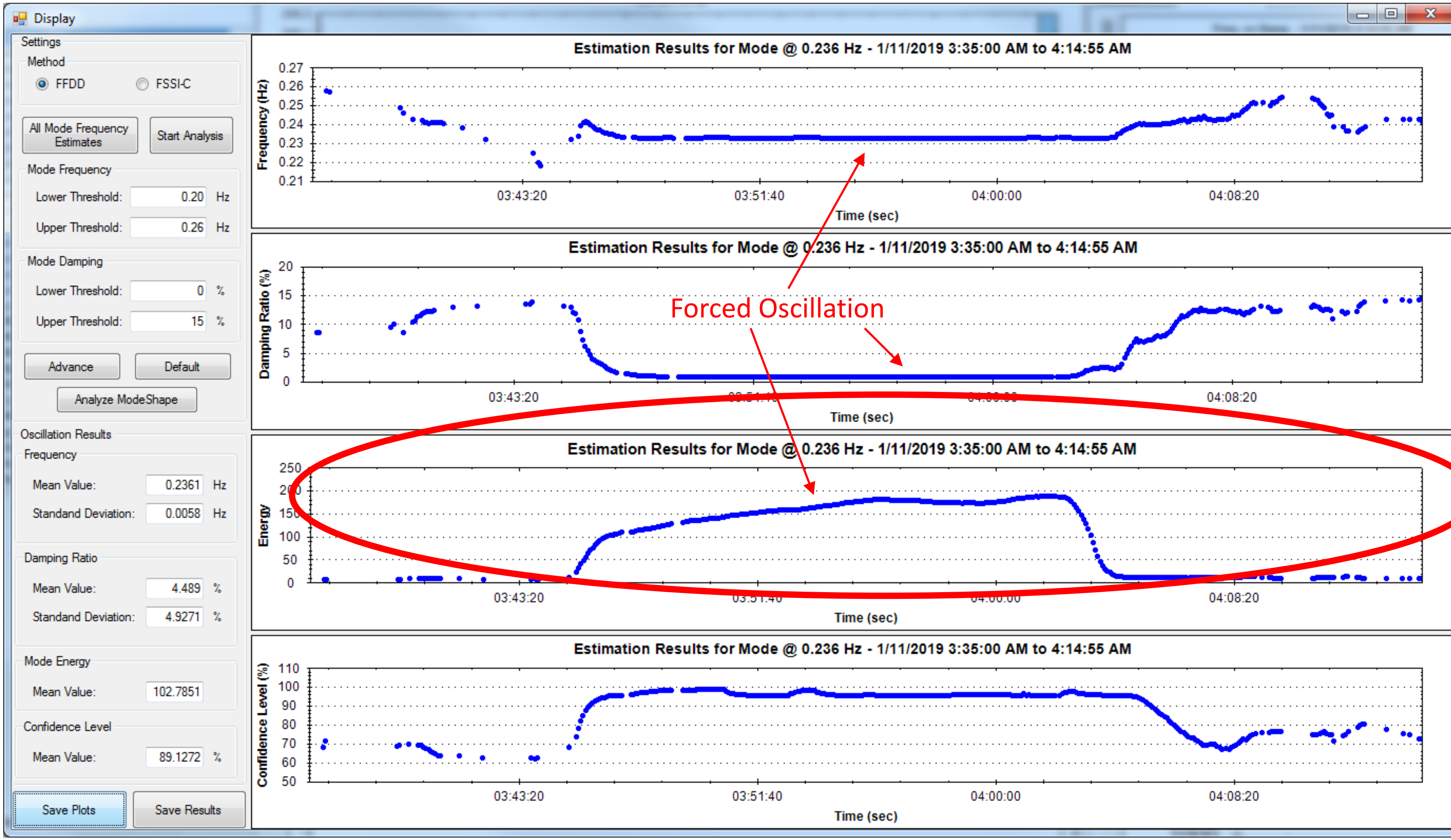
Observed Oscillation



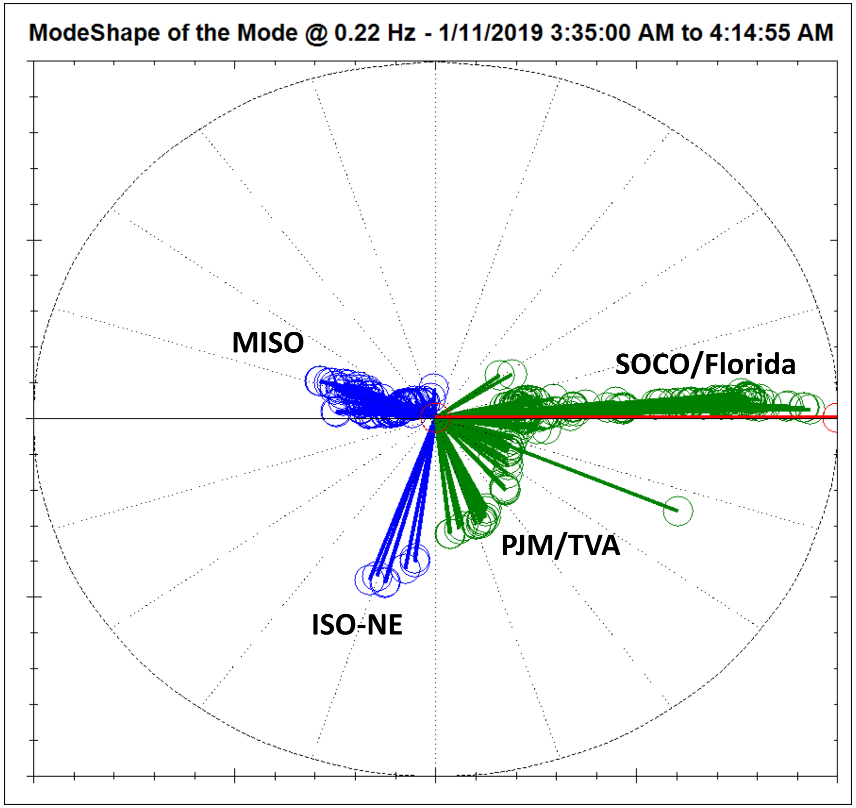


January 11, 2019 Forced Oscillation
Oscillation Analysis

0.236 Hz Natural Mode Summary



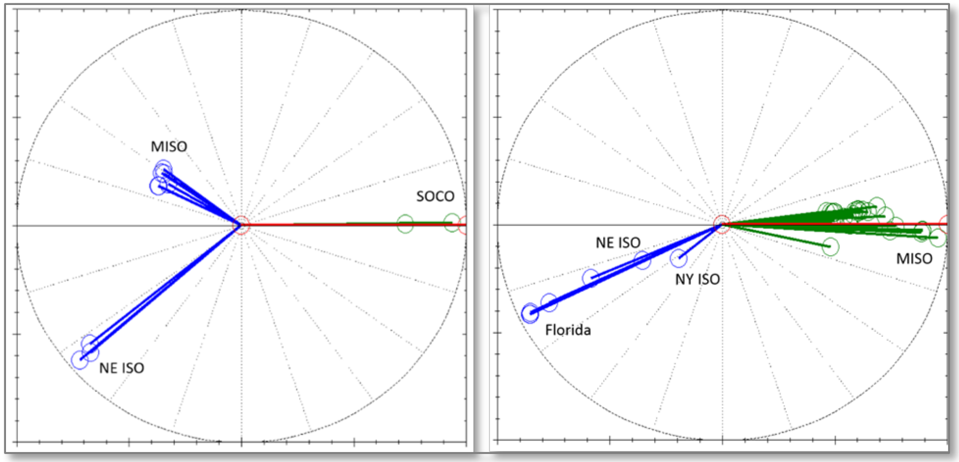
Comparison with Oscillation Report



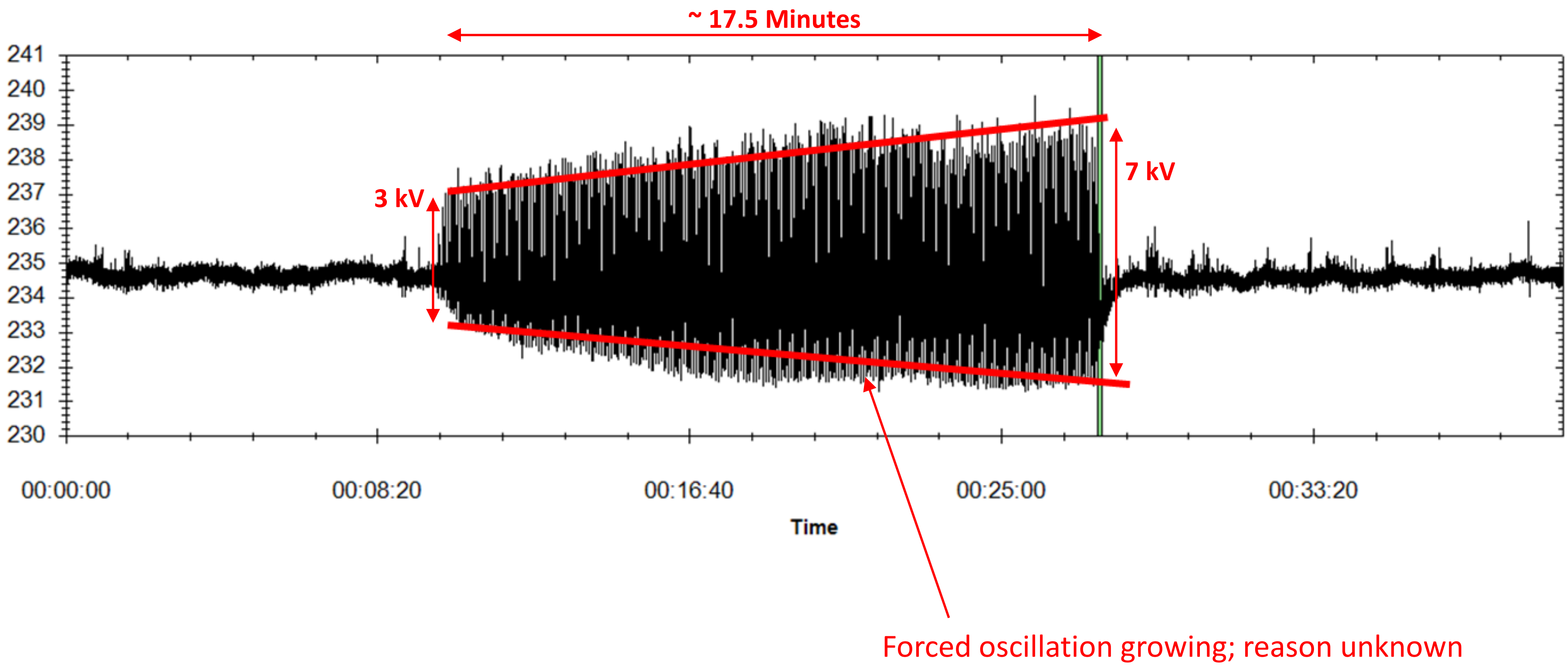
January 11th Forced Oscillation Analysis

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

From Oscillation Analysis Report



Sustained (Growing) Oscillation



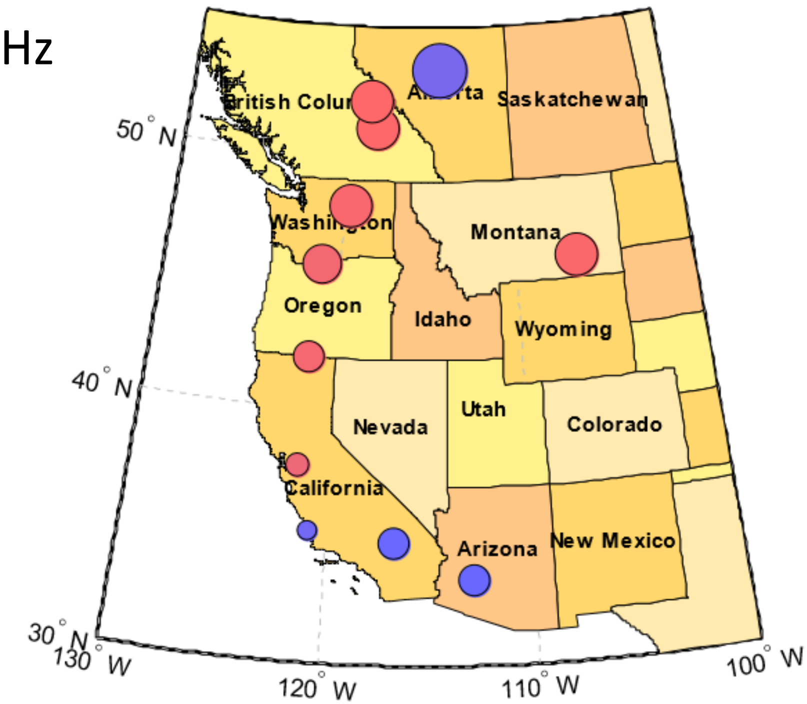
Key Findings and Recommendations

- RCs should ensure coordination with neighboring RCs regarding how to handle wide-area oscillation events.
  - Industry agrees that more visibility and communication is needed for these type of events
  - Utilities need better understanding of these types of events, and how to identify and respond appropriately
- RCs should incorporate oscillation events and appropriate operating procedures into their operator training
- NERC Reliability Standards should be reviewed for communication during these types of events

Western Interconnection Oscillation Activities

WECC Electromechanical Modes

- 2013 WECC JSIS* report described known modes
  - North–South A ~ 0.23 Hz
  - North-South B ~ 0.4 Hz
  - North-South (AB disconnected) ~ 0.32 Hz
  - East-West A ~ 0.45 Hz
  - British Columbia ~ 0.6 Hz
  - Montana ~ 0.8 Hz
- Confirmed in NERC Oscillation Analysis report



North-South B Shape

*JSIS: Joint Synchronized Information Subcommittee

Ongoing Activities

- Update to WECC modes report
  - Led by WECC JSIS Oscillation Analysis Working Group (OAWG)
  - Scope
    - Using GE PSLF base cases and snapshot cases to perform planning studies
    - Model-based small signal analysis to validate known modes
    - Measurement-based analysis using PMU data
- Dynamic System Tests
  - Probing signal injection with the Pacific DC Intertie (PDCI)
  - Insertion of the Chief Joseph dynamic brake to create ringdown events

Ongoing Activities

- Managing the Peak RC wind-down
  - CAISO now receiving live PMU data from entities for oscillation monitoring
  - Peak RC and Washington State University (WSU) supporting CAISO to set up their tool for forced oscillation source localization
- WECC is beginning study on correlation between system inertia and inter-area oscillations
- Peak RC observed interactions between forced oscillations and the Montana and British Columbia modes – further study planned

Wrap Up:

Key Takeaways and Recommendations

Key Takeaways

Oscillation Analysis:

- Dominant modes in EI, TI, and WI identified

Interconnection	Mode Name	Mode Frequency Range (Hz)	Mode Average Damping Ratio (%)
Eastern	NE–S	0.16–0.22	9.70
	NW–S	0.29–0.32	16.45
	NE–NW–S	0.23–0.24	12.80
Texas	N–SE	0.62–0.73	9.26
Western	NS Mode A	0.37–0.42	12.71
	NS Mode B	0.24–0.27	13.525

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

January 11 Forced Oscillation:

- Interactions between forced oscillations and system modes occurred multiple times – recurring theme
- Failure at combined cycle plant involving PLU control
- Interaction with system mode – observed across entire EI

Oscillation Analysis Recommendations

- TPs, PCs, and RCs should continue oscillation studies to understand current and future system modes
  - Current modes: real-time operations
  - Future modes: planning assessments, changing resource mix, dispatch patterns, technologies, etc.
- Improved observability of inter-area oscillations
  - Additional PMUs in certain areas needed (being added)
- Standardized data formats for off-line engineering analysis

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

January 11 Oscillation Event Recommendations

- PLU and other cyclic controls should not be set to coincide with reciprocal of system mode frequency ($f = 1/T$)
- Redundancy in turbine control system inputs needed
- Operator training – appropriate actions during oscillation events
- Operating procedures for taking appropriate action to mitigate or eliminate sustained/undamped oscillations
- Interconnection-wide oscillation tools needed
  - Interconnection-wide PMU-quality data set needed
  - Timely/effective source location is crucial for mitigation
- RC coordination with neighboring RCs and GOPs
  - Review NERC Reliability Standards
- Industry education of system modes and forced oscillations

Technical References

- NERC Reliability and Security Guidelines:
  https://www.nerc.com/comm/Pages/Reliability-and-Security-Guidelines.aspx
- NERC Reliability Guideline: Forced Oscillation Monitoring and Mitigation:
  https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Reliability_Guideline_-_Forced_Oscillations_-_2017-07-31_-_FINAL.pdf
- NERC Oscillation Analysis Technical Report:
  https://www.nerc.com/comm/PC/SMSResourcesDocuments/Interconnection_Oscillation_Analysis.pdf
- NERC Oscillation Analysis Detailed Report:
  https://www.nerc.com/comm/PC/SMSResourcesDocuments/Detailed_Event_Analysis.pdf
- NERC Synchronized Measurement Subcommittee (SMS) Webpage:
  https://www.nerc.com/comm/PC/Pages/Synchronized-Measurement-Subcommittee-(SMS)-Scope.aspx
- WECC Oscillations Analysis Work Group (OAWG) Webpage:
  https://www.wecc.org/RAC/Pages/OAWG.aspx
- WECC JSIS 2013 Oscillation Analysis Report:
  https://www.wecc.org/Reliability/WECC%20JSIS%20Modes%20of%20Inter-Area%20Oscillations-2013-12-REV1.1.pdf

Questions and Answers