



Cloud-Based Oscillation Monitoring

January 21, 2026

Jim Follum

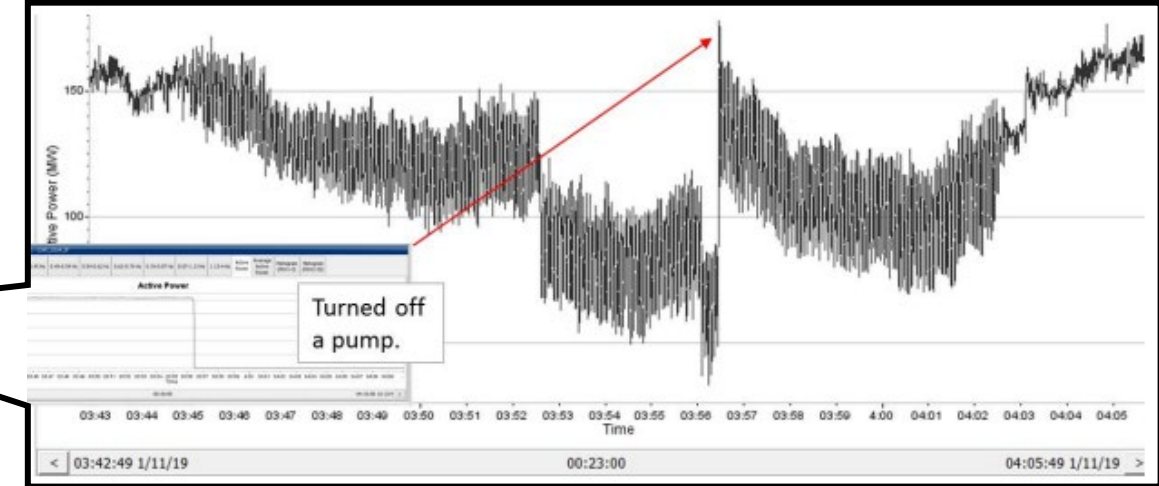
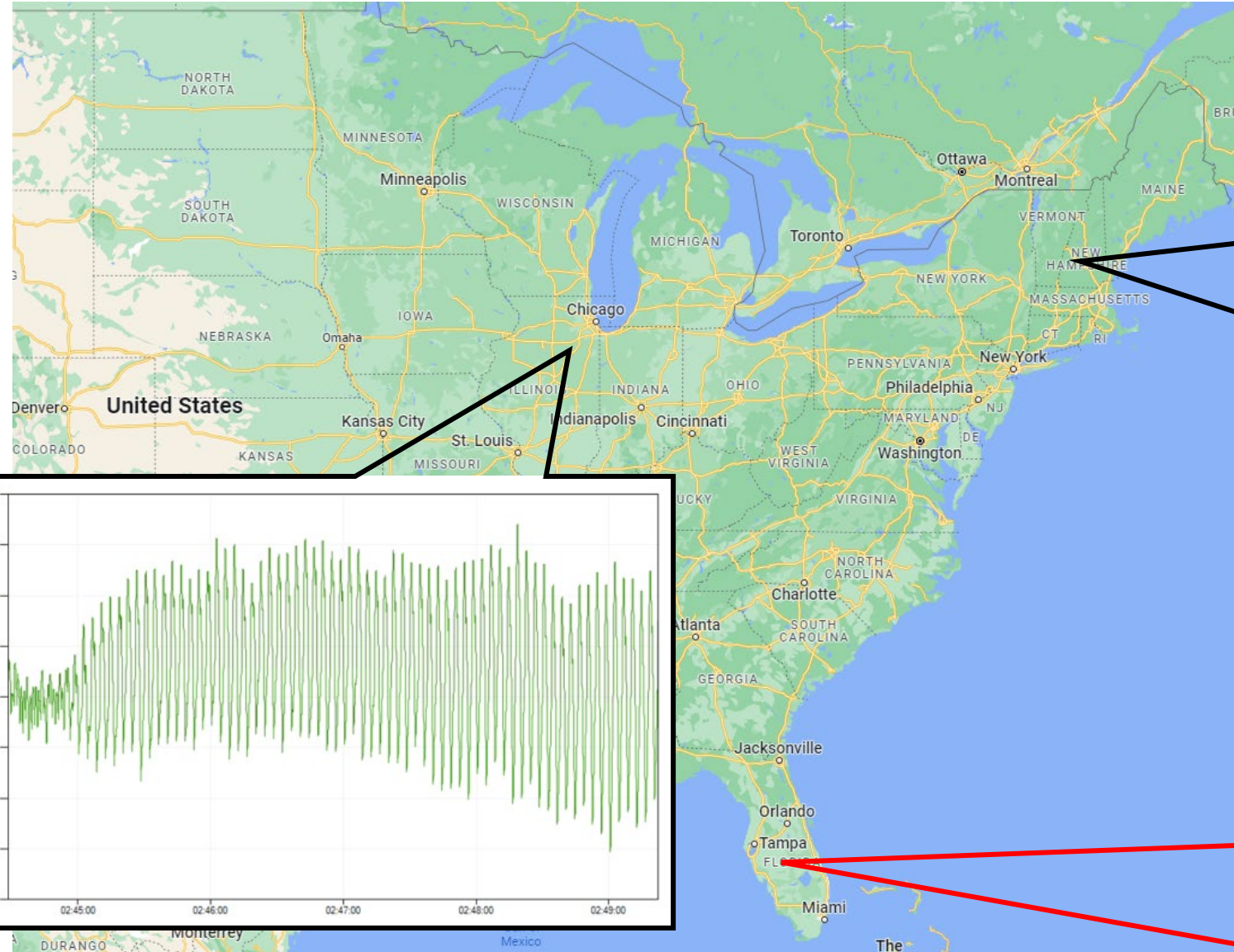


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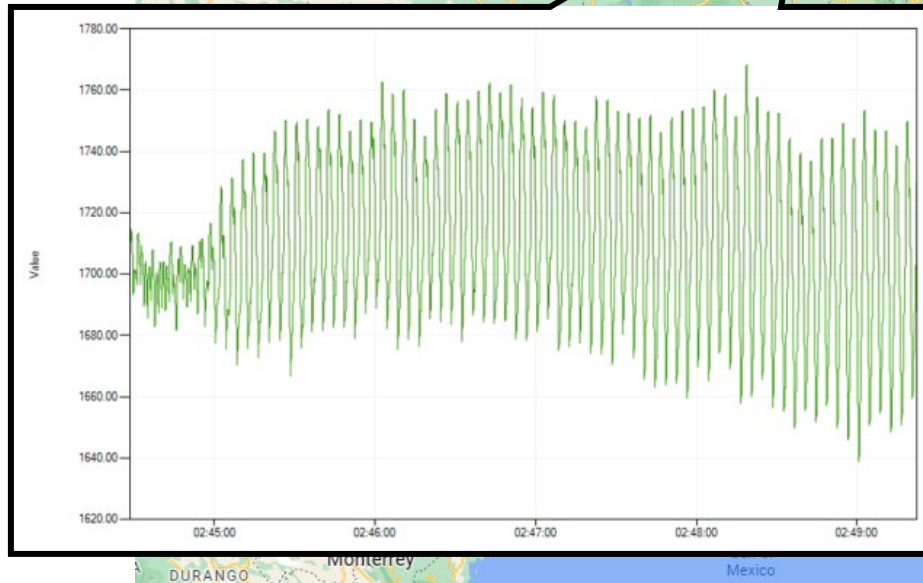
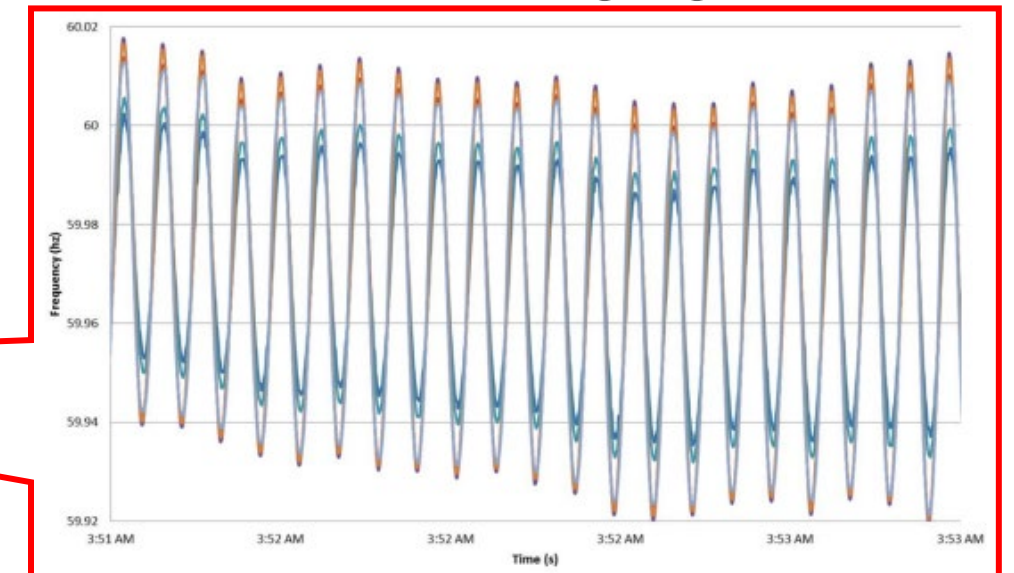
PNNL-SA-219291



Motivation



Oscillation source: single generator



Eastern Interconnection Oscillation Disturbance

January 11, 2019 Forced Oscillation Event

December 2019

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Key Findings

Key findings identified during the analysis of the forced oscillation within the plant include the following:

- A failed PT connection and errored voltage measurement in the PLI turbine controls caused a steam turbine at a combined-cycle power plant to oscillate for around 18 minutes before local plant personnel removed the unit from service.
- While redundancy was built into the plant control and protection system inputs, the turbine controls relied on a single PT measurement. This measurement was different from the protection system input PT measurement. Hence, the protection system was unaffected by the failed PT measurement.
- PLI operation caused the intercept valves of the steam turbine to shut and reopen periodically with a cyclical period of about four seconds. This resulted in oscillatory power output with a frequency of around 0.25 Hz.
- Many different alarms that needed troubleshooting to identify their root causes challenged the plant operators. Prioritization of operator alarms is as much an issue for generator control centers as it is for transmission energy management systems.

Key findings identified during the analysis focused on the wide-area impacts of the oscillation disturbance include the following:

- The 0.25 Hz forced oscillation interacted with the natural system mode near that frequency, causing the entire EI to experience the forced oscillation. Two out of the three conditions required⁴ for a forced oscillation to strongly resonate with a natural system mode were satisfied. The oscillation frequencies between the forced oscillation and the natural system mode matched, and the source location was in a high participation area of the natural system mode. However, the natural system mode was well-damped.
- The generating unit experienced oscillations of around 200 MW peak-to-peak; however, power swings were observed as far as the New England area of about 50 MW.
- RCs were aware of the oscillation event relatively quickly by using both SCADA data and advanced applications and PMU measurements. RCs sought coordination activities, including use of the RC hotline; however, the RC hotline was inoperable due to technical issues. RCs were forced to call neighboring RCs individually that led to misinformation and mischaracterization of the event initially. Wide-area operator action did not contribute to mitigating the oscillation event, and most tools were ineffective at identifying a source location for the oscillation.
- The forced oscillation appears to have grown in energy until the unit (forcing function) was disconnected from the BPS.
- From an interconnection-wide standpoint, the GridEye/FNET system provided one of the most effective means of quickly understanding the extent of the disturbance. Frequency disturbance recorders and SCADA measurements available to NERC helped quickly identify a potential source of the oscillation and the severity of the event.




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Recommendations

Recommendations based on the key findings identified for the forced oscillation within the plant include the following:

- Generator turbine controls, including PLI and other types of controls that could result in a cyclic behavior from the generator, should avoid using a reset timer that has a period close to the reciprocal of the natural system modes (i.e., $T = 1/f$). Generally, this is in the range of 0.1–0.8 Hz; this relates to cyclical timers in the range of 1.25 seconds to 10 seconds. In particular, the frequency of the following dominant interconnection-wide modes should be avoided:
 - Eastern Interconnection: 0.16–0.33 Hz (3.3–6.5 seconds)
 - Texas Interconnection: 0.6–0.75 Hz (1.33–1.66 seconds)
 - Western Interconnection: 0.24–0.42 Hz (2.38–4.17 seconds)
- Turbine controls should not have a single point of failure, including PT and current transformer input measurements that could fail and cause abnormal or unexpected turbine actions.
- The PLI circuit design in the turbine and generator control systems should consider tripping the unit after a short time for these types of persistent alarms to ensure integrity and safety of plant equipment and personnel.
- Training for Generator Operators (GOPs), RCs, Balancing Authorities (BAs), and Transmission Operators (TOPs) outlining root cause analysis and specific actions to take or not to take during oscillation events should be developed and reviewed periodically.

Recommendations based on the key findings focused on the wide-area impacts of the oscillation disturbance include the following:

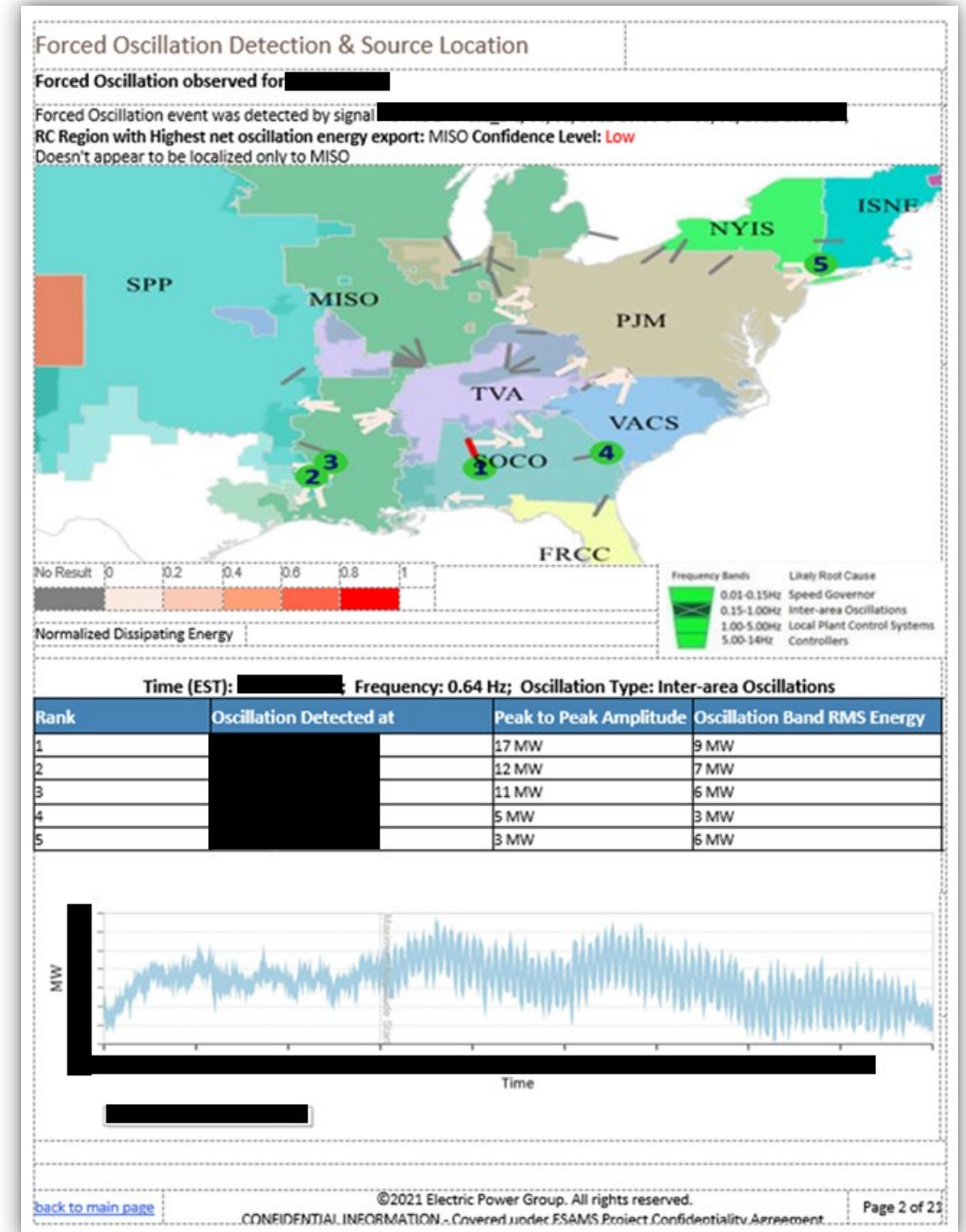
- RCs should have real-time oscillation detection tools in place to identify when oscillations are occurring, determine if it is limited locally within their footprint or across a wider area, and distinguish between forced oscillations and poorly damped natural system modes.
- RCs should improve communication with neighboring RCs in the event of widespread oscillation disturbances on the BPS. Operating procedures could be an effective means of ensuring this coordination upon identification of an oscillation.
- RCs should consider jointly developing interconnection-wide oscillation detection and source location applications using interconnection-wide PMU and SCADA data.
- The industry should develop open-source, publicly available robust tools for performing oscillation analysis that can be used by various entities:
 - The industry should seek improvements to standardized data formats for offline engineering analysis using large volumes of PMU data.
 - The NERC Synchronized Measurement Subcommittee (SMS) should develop guidance on oscillation analysis methods to encourage consistency in monitored quantities and thresholds.
- Based on a survey of RCs, NERC SMS should develop a white paper identifying any potential gaps or areas for improvement in the NERC Reliability Standards pertaining to RC-to-RC coordination and the use of PMU data.
- Commercially available simulation software should develop or improve the capability of simulating forced oscillations such that grid planners can analyze the effects of these oscillations across the BPS.

Eastern Interconnection Situational Awareness and Monitoring System (ESAMS) Concept

- Software tool developed by Electric Power Group (EPG) and PNNL with leadership from LBNL
- Purpose
 - Introduce a common, high-level interconnection-wide view based on synchrophasor information
 - Improve coordination among reliability coordinators
- Core capabilities
 - Analyze Phasor Measurement Unit (PMU) data streamed from across the grid
 - Detect oscillations in power and system frequency impacting a wide area
 - Determine which reliability coordinator the oscillation is originating from
 - Deliver notifications via email

Initial Demonstration

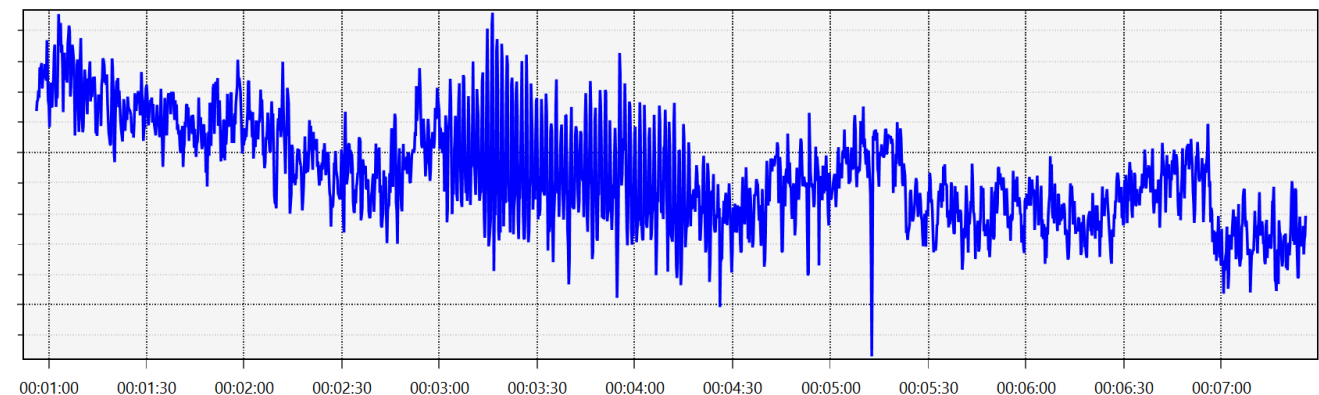
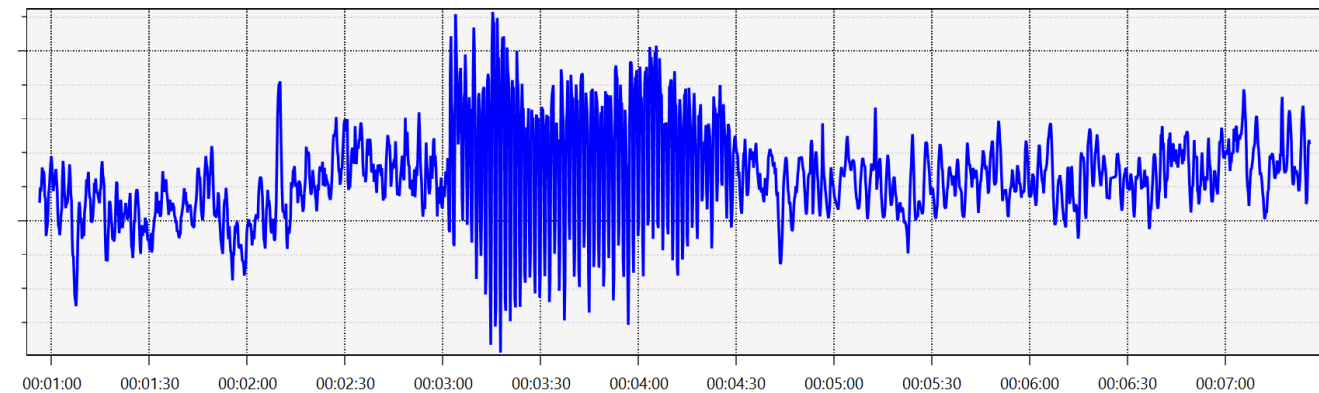
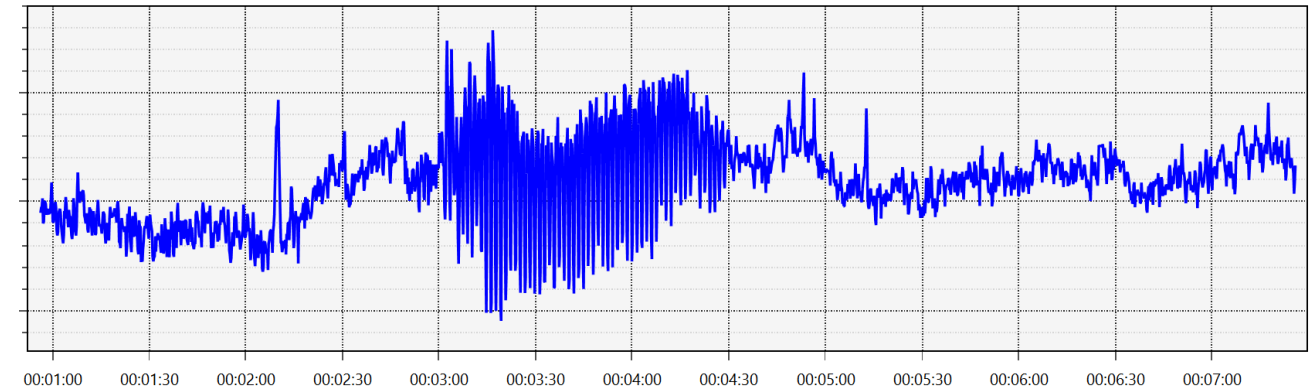
- Hosted by PJM between June 2021 and March 2022
- Daily event reports distributed to seven reliability coordinator participants
- Real-time notifications for oscillations with amplitudes greater than 10 MW



Example of a daily report showing a large forced oscillation

Southern Company Deployment

- Deployed Jan. 2024 – April 2025
- Evaluated the benefits of ESAMS within a reliability coordinator's footprint
 - Monitored interfaces between transmission operators and with neighboring reliability coordinators
- Considered benefits of each of ESAMS's oscillation detectors
 - PNNL's oscillation analysis engine
 - EPG's Real Time Dynamics Monitoring System (RTDMS)



Current Deployment: Cloud ESAMS

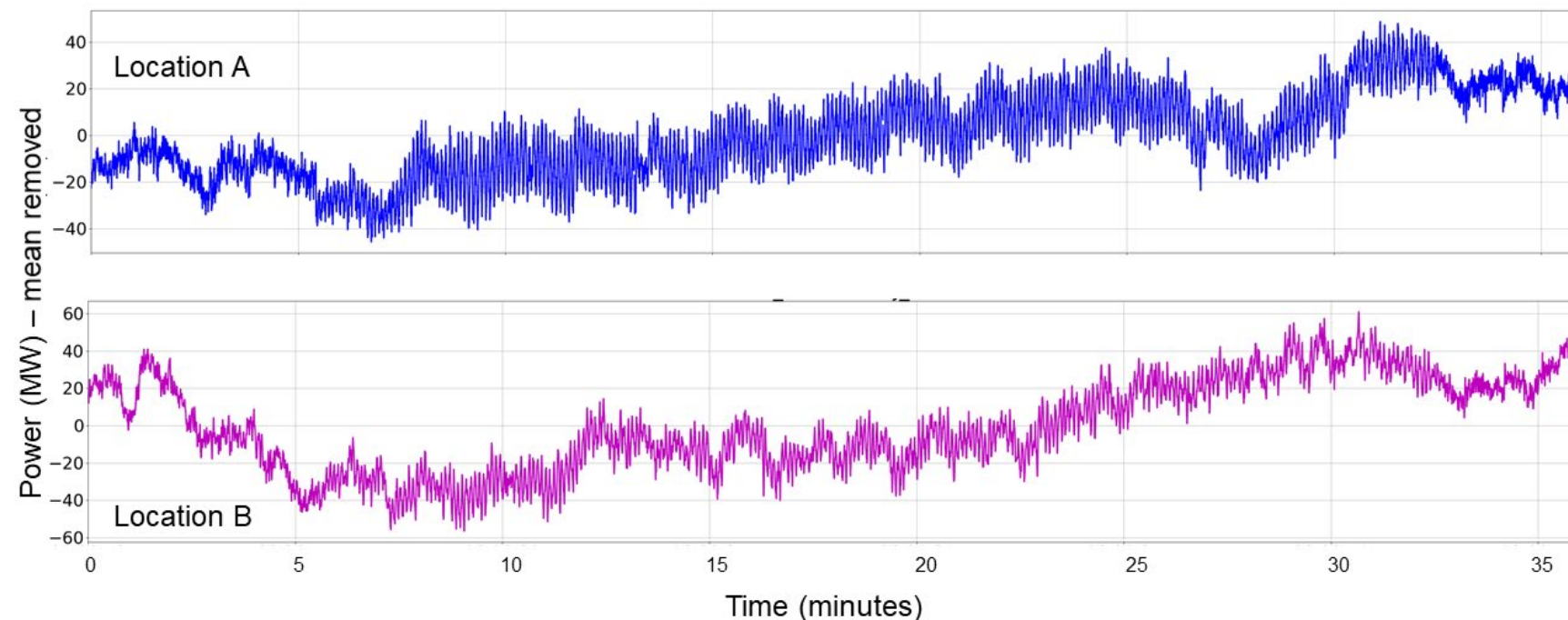
- Long-term hosting is a key challenge for interconnection scale monitoring
- A cloud-based deployment offers:
 - Scalability for new measurement points
 - Excellent reliability
 - Rapid transition to new environments
- Status
 - ESAMS is deployed in ISO-NE's Amazon Web Services cloud environment
 - PMU data streamed from ISO-NE and PJM
 - Considered regions: ISO-NE, New Brunswick, NYISO, PJM, and Eastern Interconnection south and west of PJM
 - Initial 6-month demonstration will conclude March 31
- Planning to share detailed findings and next steps at NASPI in April

Thanks to the Cloud ESAMS Team

- ISO-NE: Xiaochuan Luo, Wenpeng Yu, Slava Maslennikov, & Frankie Zhang
- PJM: Yang Chen & Ed Kovler
- AWS: Song Zhang
- EPG: Neeraj Nayak, Joshua Chynoweth, & Frank Carrera
- PNNL: Tawsif Ahmad & Shuchi Biswas
- And many others from these organizations

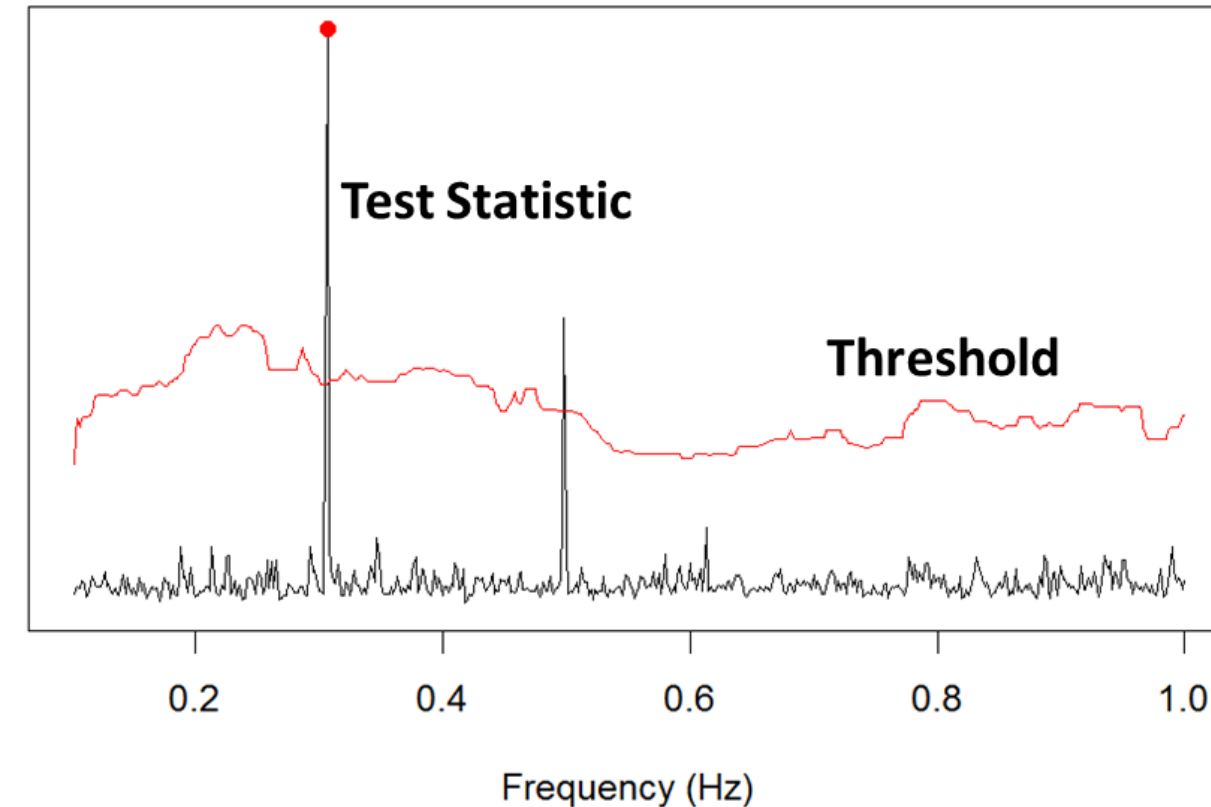
ESAMS's Oscillation Analysis Approach

- Detect that a wide-area forced oscillation is occurring
- Estimate when the oscillation started and stopped
- Estimate the amplitude of the oscillation
- Identify the region containing the oscillation's source



Oscillation Detection

- ESAMS utilizes PNNL's periodogram-based detector
- Test statistic
 - Large value indicates presence of an oscillation at the corresponding frequency
 - Combines measurements from all locations to emphasize wide-area oscillations
- Threshold
 - Does not require baselining on historical data
 - Autonomously designed in real-time using statistics to avoid false alarms



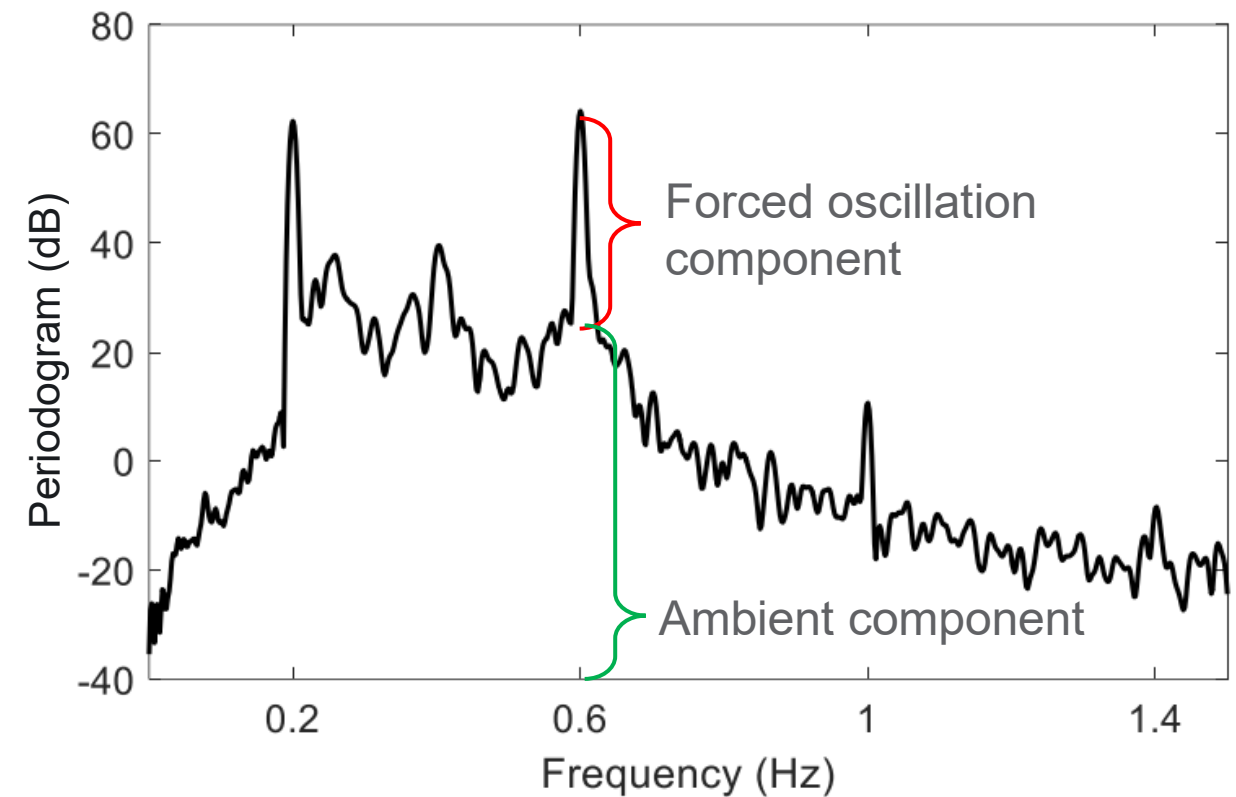
J. Follum and J. Pierre, "Detection of Periodic Forced Oscillations in Power Systems," in IEEE Transactions on Power Systems, vol. 31, no. 3, pp. 2423-2433, May 2016.

J. Follum and F. Tuffner, "A multi-channel method for detecting periodic forced oscillations in power systems," 2016 IEEE Power and Energy Society General Meeting (PESGM), Boston, MA, 2016, pp. 1-5.

J. Follum and F. Tuffner, "Applications of a New Nonparametric Estimator of Ambient Power System Spectra for Measurements Containing Forced Oscillations," 2017 IEEE Power and Energy Society General Meeting (PESGM), Chicago, IL, 2017, pp. 1-5.

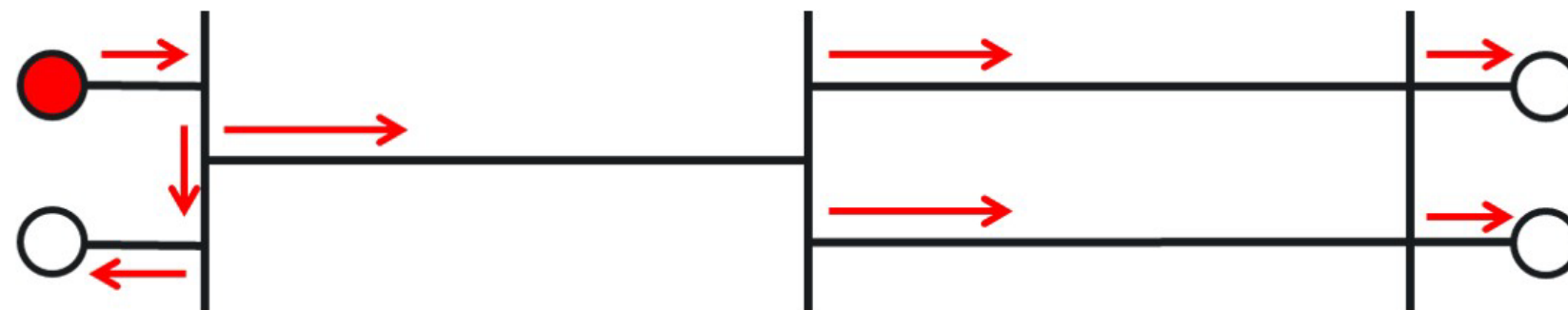
Amplitude Estimation

- The Discrete Fourier Transform is used to estimate each oscillation's amplitude
- Only oscillations with sufficient amplitude included reports
 - Daily reports: 2 MW
 - Real-time notifications: 10 MW



Conventional Source Localization

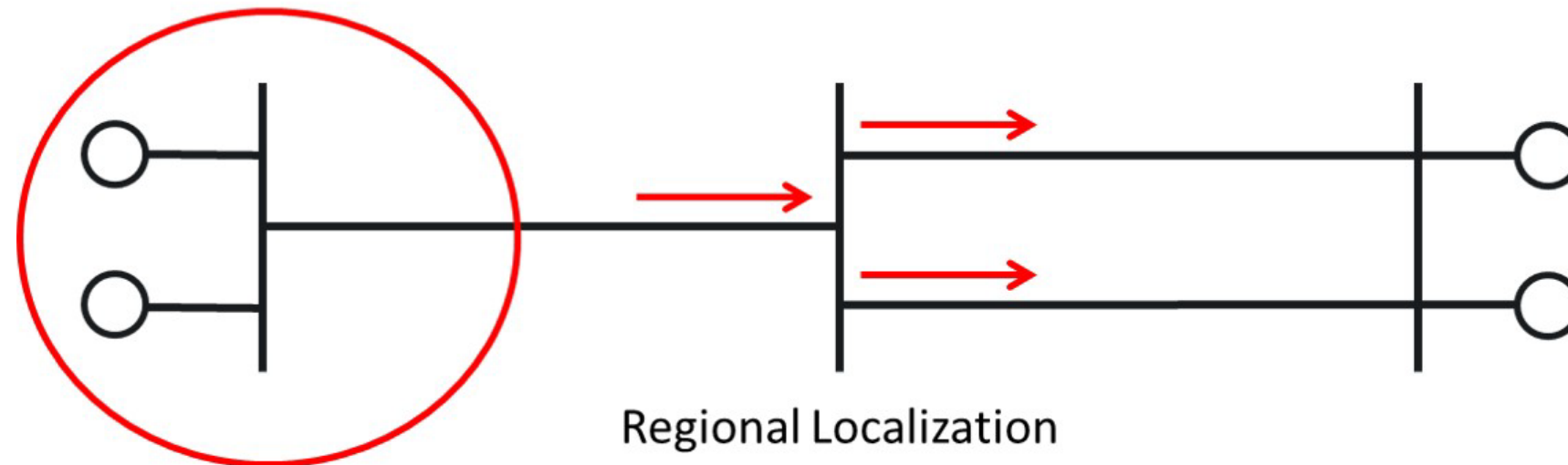
- The Dissipating Energy Flow (DEF) method has become a widely accepted approach for oscillation source localization
- Conventional DEF
 - Bandpass filter applied to limit signal to forced oscillation
 - Oscillation energy calculated by evaluating integrals
 - Flow of oscillation energy traced through network back to the source generator



Equipment Localization

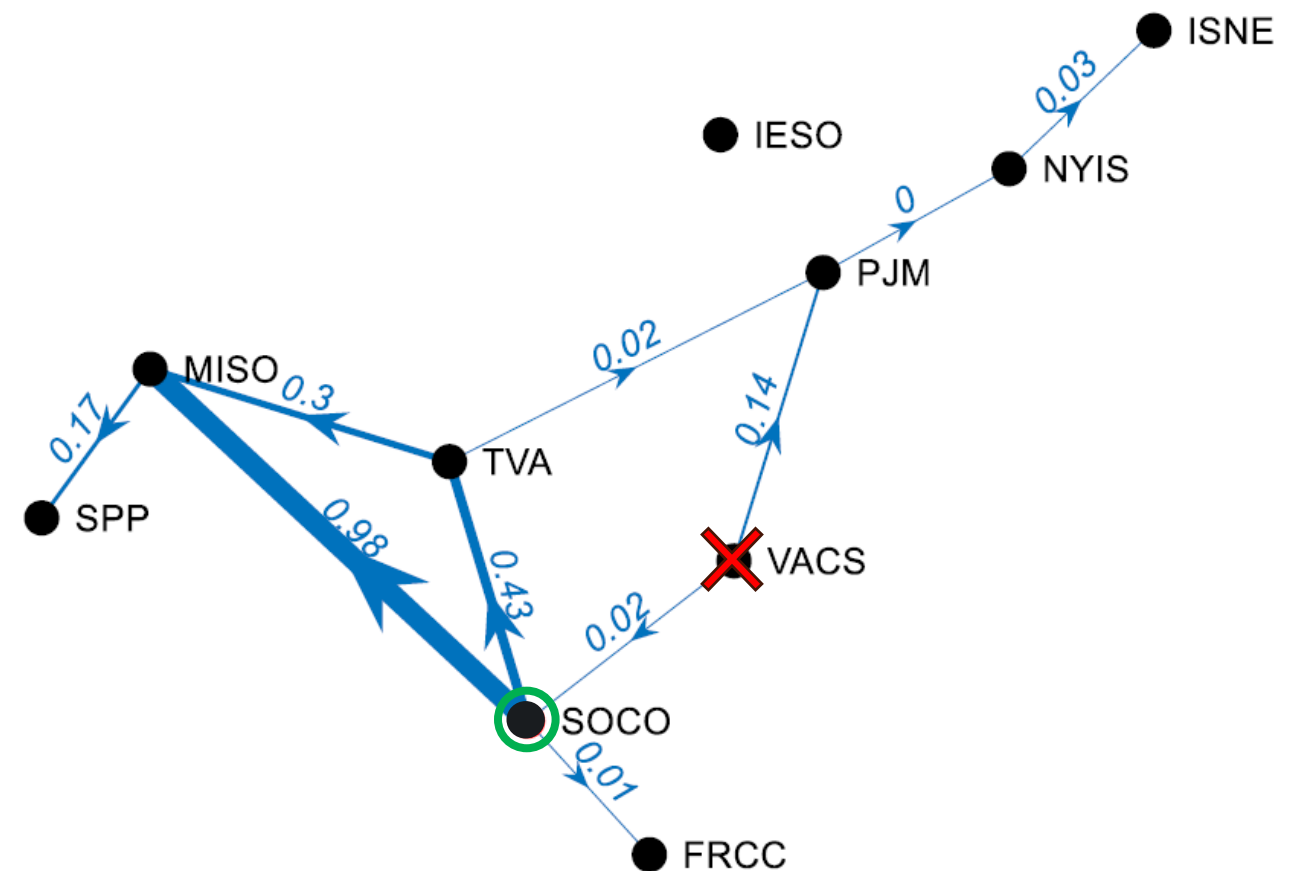
Regional Source Localization in ESAMS

- A mathematically-equivalent frequency-domain expression for DEF is used
 - Calculated using fast Fourier transforms (FFT)
 - Does not require filtering
- Oscillation energy flow between regions is considered
 - Aligned with ESAMS's intended use for coordination among reliability coordinators
 - Only requires measurements at tie lines between regions




Source Localization Criterion

- Ideally, the source region would exclusively export oscillation energy
- In practice, estimation errors can cause this criterion to fail
- Instead, the source is identified as the region with the largest net export of oscillation energy



Ensuring ESAMS Reports are Actionable

- ESAMS is intended to supplement reliability coordinators' internal oscillation monitoring tools, not replace them
- A recent report details how ESAMS notifications can support organizations with various capabilities
 - SCADA
 - PMU-based detection
 - PMU-based localization



PNNL-37162

Interpreting Forced Oscillation Notifications from ESAMS

General Guidance for Reliability Coordinators

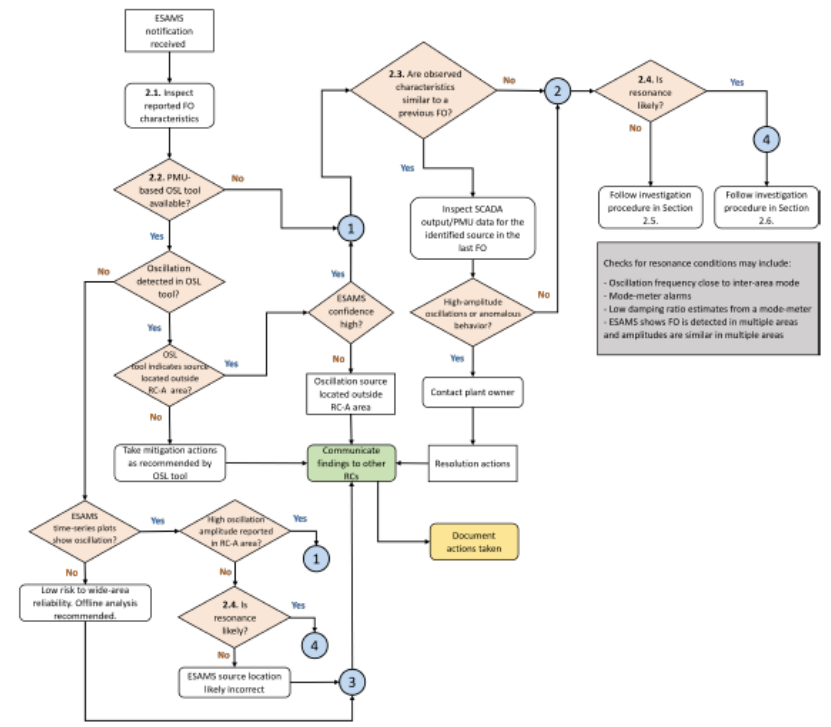
Shuchismita Biswas Jim Follum

U.S. DEPARTMENT OF ENERGY | Prepared for the U.S. Department of Energy Under contract DE-AC05-76RL01630

2.0 Utilizing ESAMS Information in Conjunction with Internal Platforms

The regional source localization capabilities of ESAMS are intended to complement OSL tools deployed by RCs within their footprints. Vendors like Electric Power Group (EPG) and General Electric (GE) offer OSL capabilities in their commercial wide-area monitoring systems (WAMS) platforms, while in-house solutions like the one developed by ISO New England also exist [Maslennikov and Litvinov, 2021]. Actions taken by an RC after receiving notifications from ESAMS will depend on the OSL capabilities they deploy.

Now, let us assume through the rest of this text that 'RC-A' refers to an area identified as the source in an ESAMS notification. For notational convenience, we will use 'RC-B' to refer to any RC area that is not determined to be the source by ESAMS.



```

    graph TD
      Start[ESAMS notification received] --> Step21[2.1. Inspect reported FO characteristics]
      Step21 --> Step22{2.2. PMU-based OSL tool available?}
      Step22 -- No --> Step23{2.3. Are observed characteristics similar to a previous FO?}
      Step22 -- Yes --> Step23
      Step23 -- No --> Step24{2.4. Is resonance likely?}
      Step23 -- Yes --> Step25[Inspect SCADA output/PMU data for the identified source in the last FO]
      Step25 --> Step26{High-amplitude oscillations or anomalous behavior?}
      Step26 -- No --> Step24
      Step26 -- Yes --> Step27[Contact plant owner]
      Step27 --> Step28[Resolution actions]
      Step28 --> Step29[Document actions taken]
      Step29 --> Step30[Communicate findings to other RCs]
      Step30 --> Step31{ESAMS time-series plots show oscillation?}
      Step31 -- No --> Step32[Low risk to wide-area reliability. Offline analysis recommended.]
      Step31 -- Yes --> Step33{High oscillation amplitude observed in RC-A area?}
      Step33 -- No --> Step24
      Step33 -- Yes --> Step34{2.4. Is resonance likely?}
      Step34 -- No --> Step35[ESAMS source location likely incorrect]
      Step34 -- Yes --> Step36[ESAMS confidence high?]
      Step36 -- No --> Step37[Oscillation source located outside RC-A area]
      Step36 -- Yes --> Step38{Oscillation detected in OSL tool?}
      Step38 -- No --> Step39{OSL tool indicates source located outside RC-A area?}
      Step39 -- No --> Step37
      Step39 -- Yes --> Step40[Take mitigation actions as recommended by OSL tool]
      Step40 --> Step30
      Step37 --> Step30
      Step35 --> Step30
      Step32 --> Step30
      Step24 --> Step41{2.4. Is resonance likely?}
      Step41 -- No --> Step42[Follow investigation procedure in Section 2.5.]
      Step41 -- Yes --> Step43[4]
      Step43 --> Step44[Follow investigation procedure in Section 2.6.]
      Step44 --> Step30
  
```

Checks for resonance conditions may include:

- Oscillation frequency close to inter-area mode
- Mode-meter alarms
- Low damping ratio estimates from a mode-meter
- ESAMS shows FO is detected in multiple areas and amplitudes are similar in multiple areas

Figure 5. Decision flow by an RC (RC-A) if ESAMS indicates that a forced oscillation source is located in their area. Numbers within elements indicate corresponding report sections.

Example Event 1

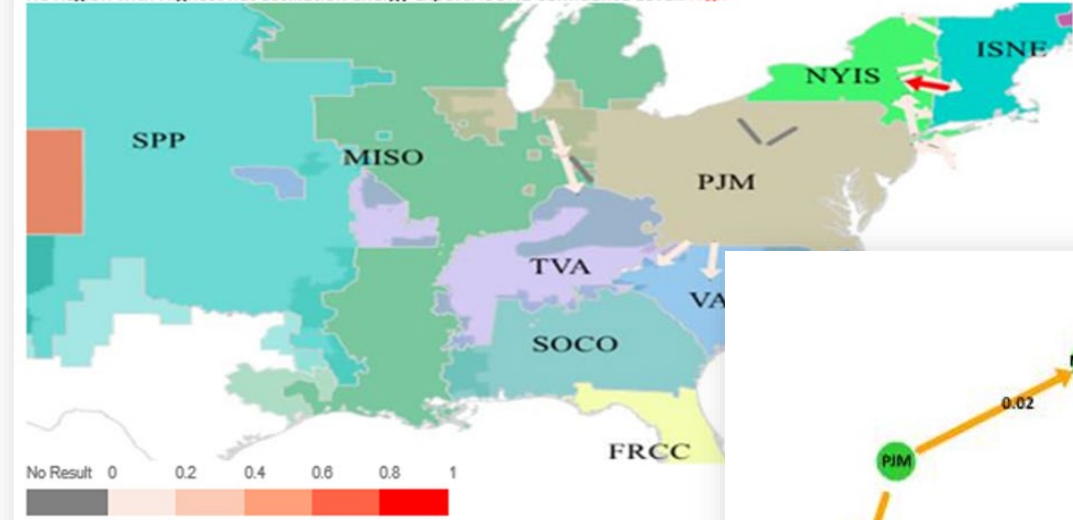
- Recurring oscillation at approximately 1.1 Hz
- 7 MW peak-to-peak
- Not widespread
- Due to a known issue at a power plant
- Not a significant event, but useful for validation

Forced Oscillation Detection & Source Location

Forced Oscillation observed for [REDACTED]

Forced Oscillation event was detected by signal [REDACTED]
UTC,

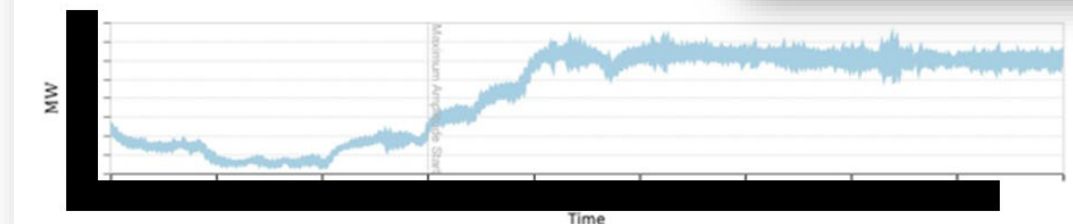
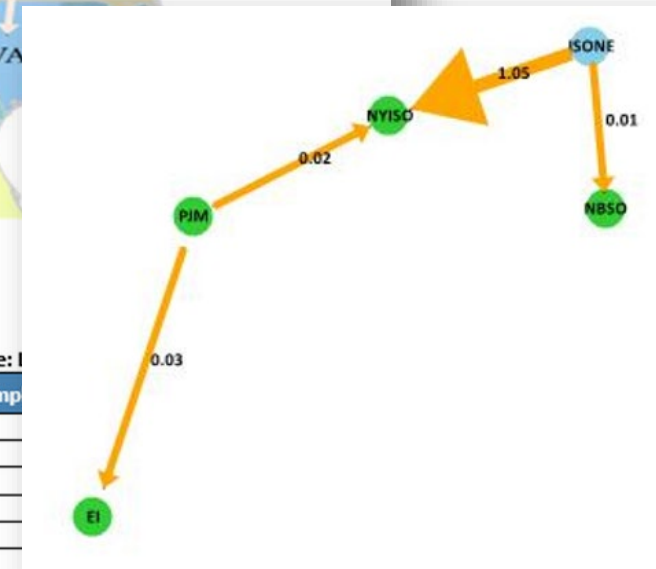
RC Region with Highest net oscillation energy export: ISONE Confidence Level: High



Normalized Dissipating Energy

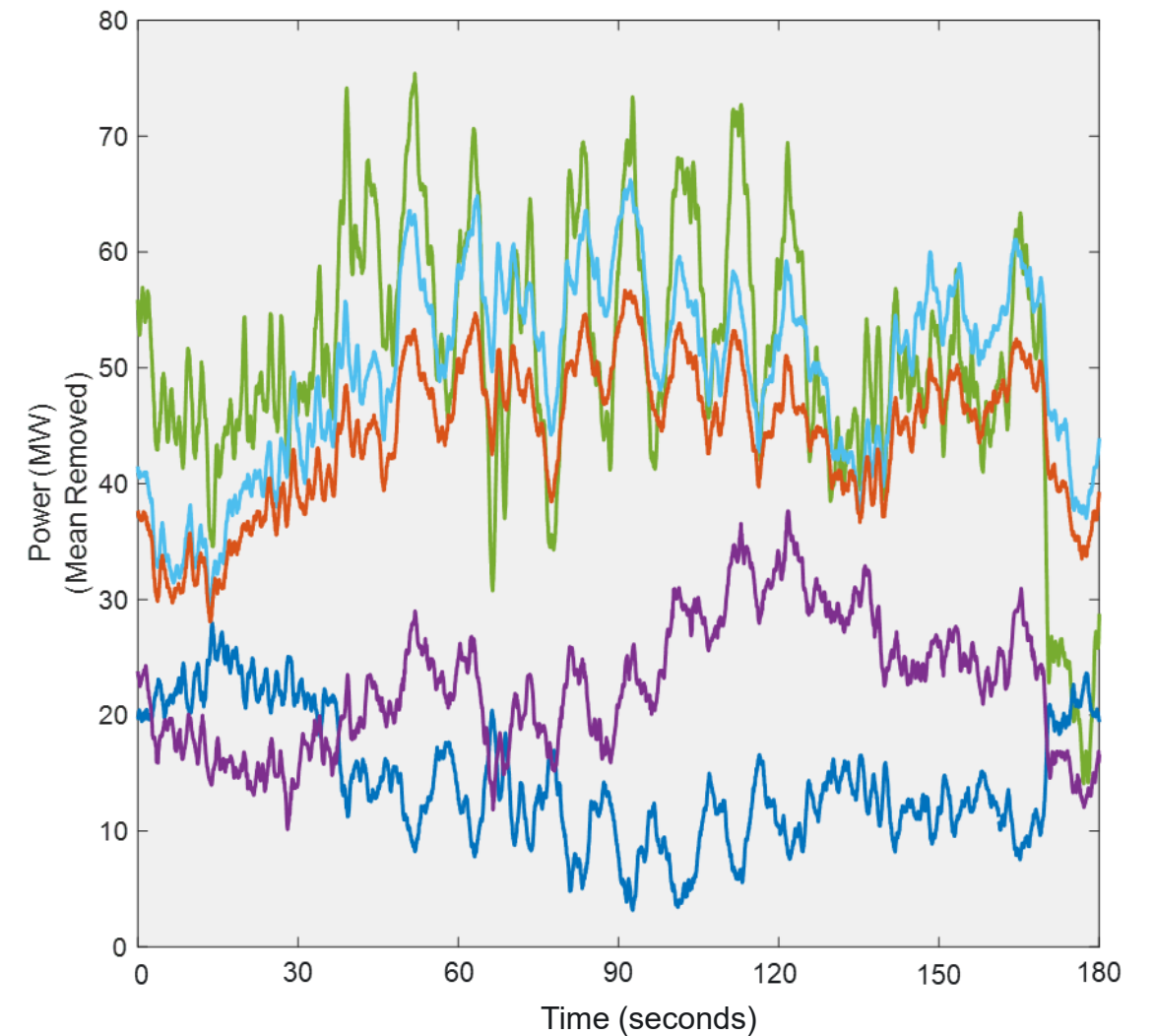
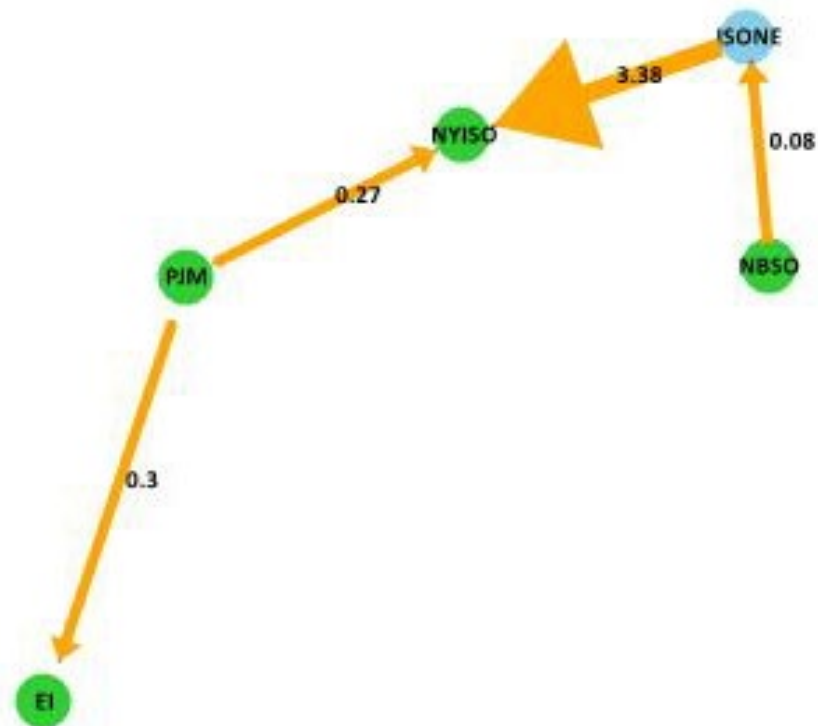
Time (EST): 20:40 - 20:51; Frequency: 1.09 Hz; Oscillation Type: I

Rank	Oscillation Detected at	Peak to Peak Amp
1	[REDACTED]	7 MW
2	[REDACTED]	2 MW
3	[REDACTED]	2 MW
4	[REDACTED]	2 MW
5	[REDACTED]	2 MW



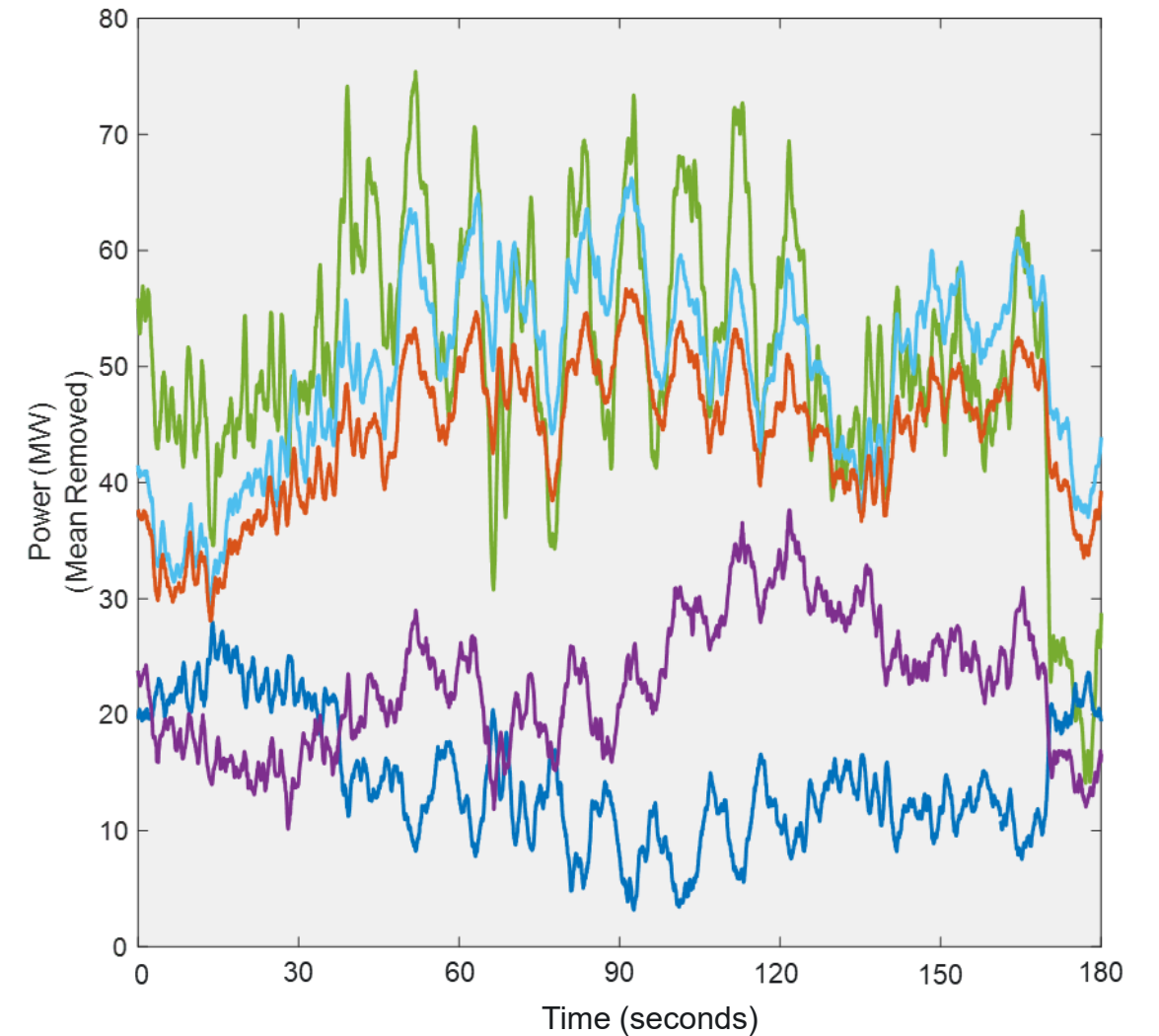
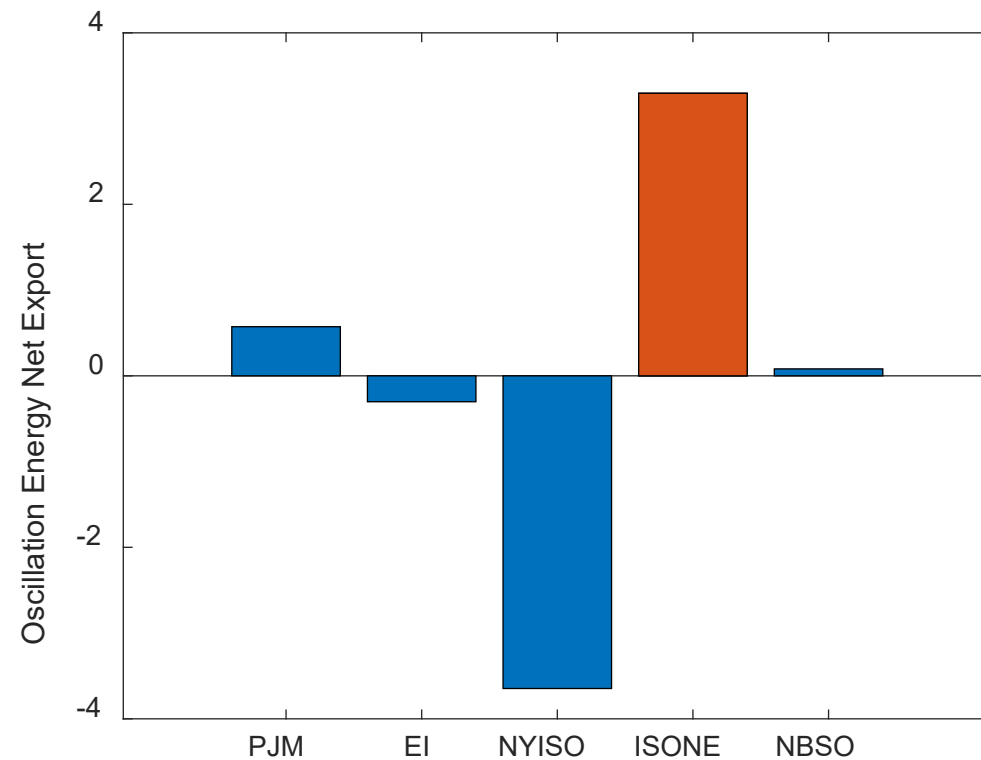
Example Event 2

- Very low frequency: 0.1 Hz
- 25 MW peak-to-peak
 - Greater than 2 MW at 9 locations
- 90 second duration



Example Event 2

- Very low frequency: 0.1 Hz
- 25 MW peak-to-peak
 - Greater than 2 MW at 9 locations
- 90 second duration





Thank you

