Field Demonstration of Cloud-Based Oscillation Monitoring in the Eastern Interconnection

April 14, 2026

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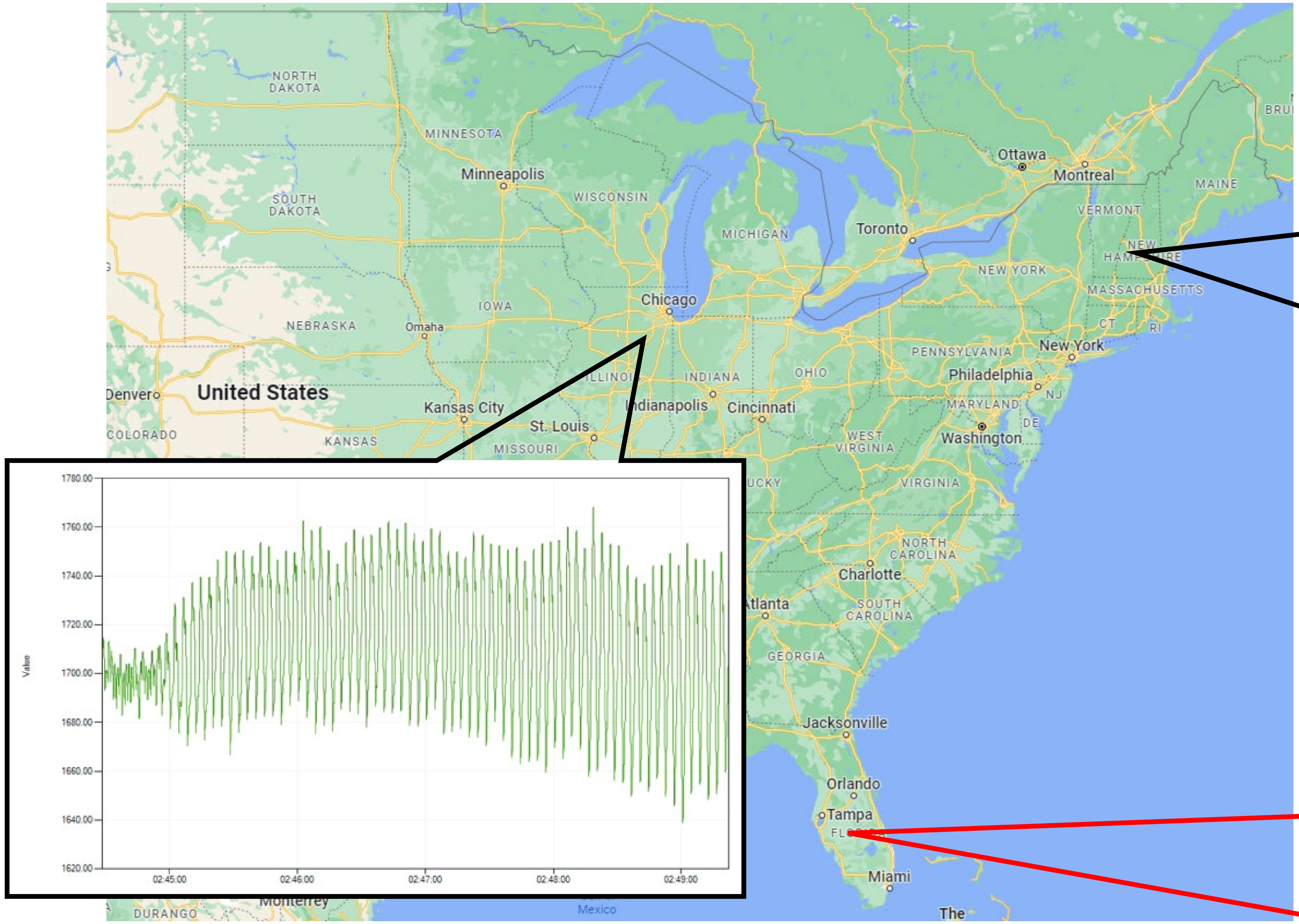
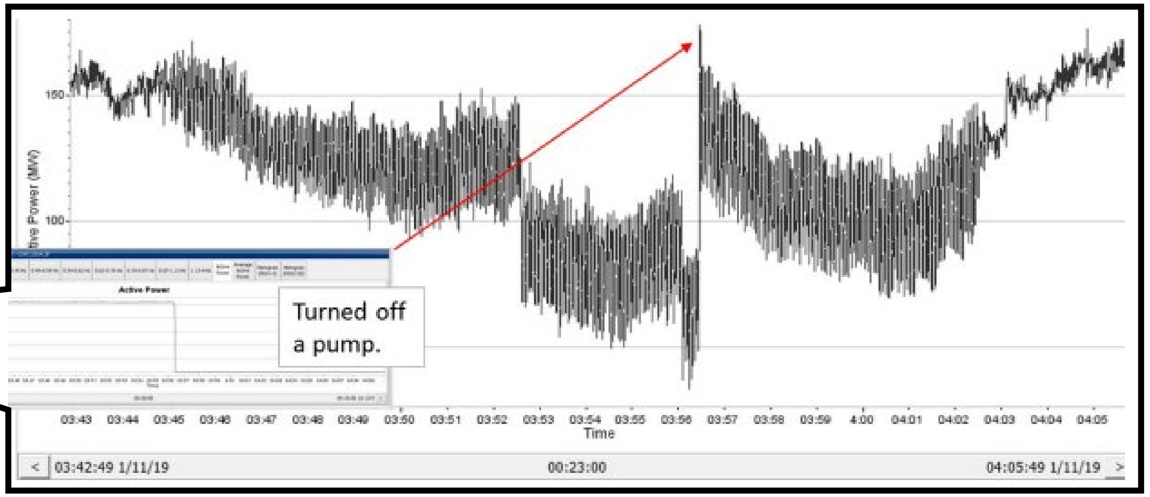
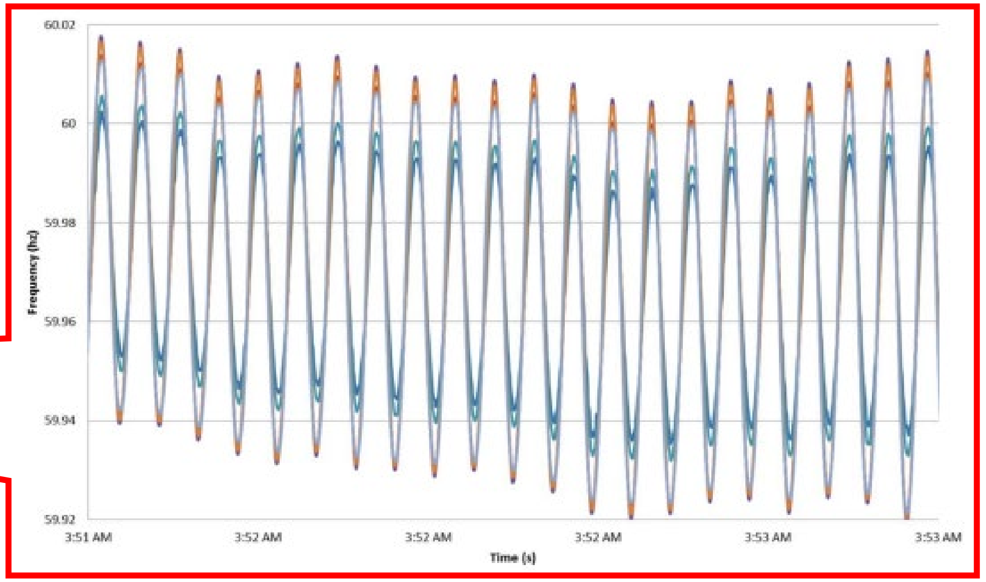
PNNL is operated by Battelle for the U.S. Department of Energy

Motivation:
11 January 2019 Forced Oscillation Event





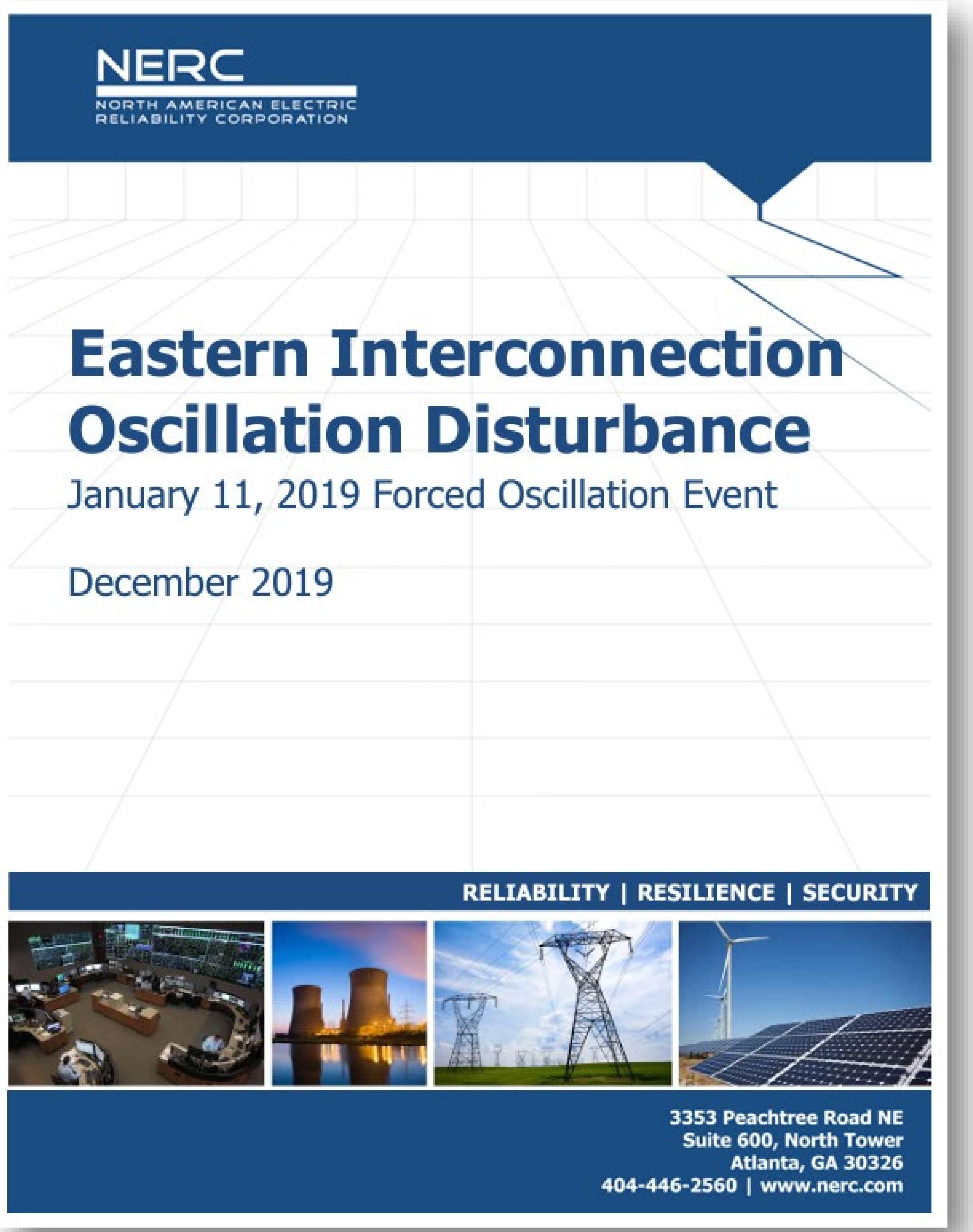
Oscillation source: single generator



Images: https://www.nerc.com/pa/rrm/ea/Documents/January_11_Oscillation_Event_Report.pdf

NERC Recommendation

"[Reliability Coordinators] should consider jointly developing interconnection-wide oscillation detection and source location applications using interconnection-wide PMU and SCADA data."


NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Eastern Interconnection Oscillation Disturbance

January 11, 2019 Forced Oscillation Event

December 2019

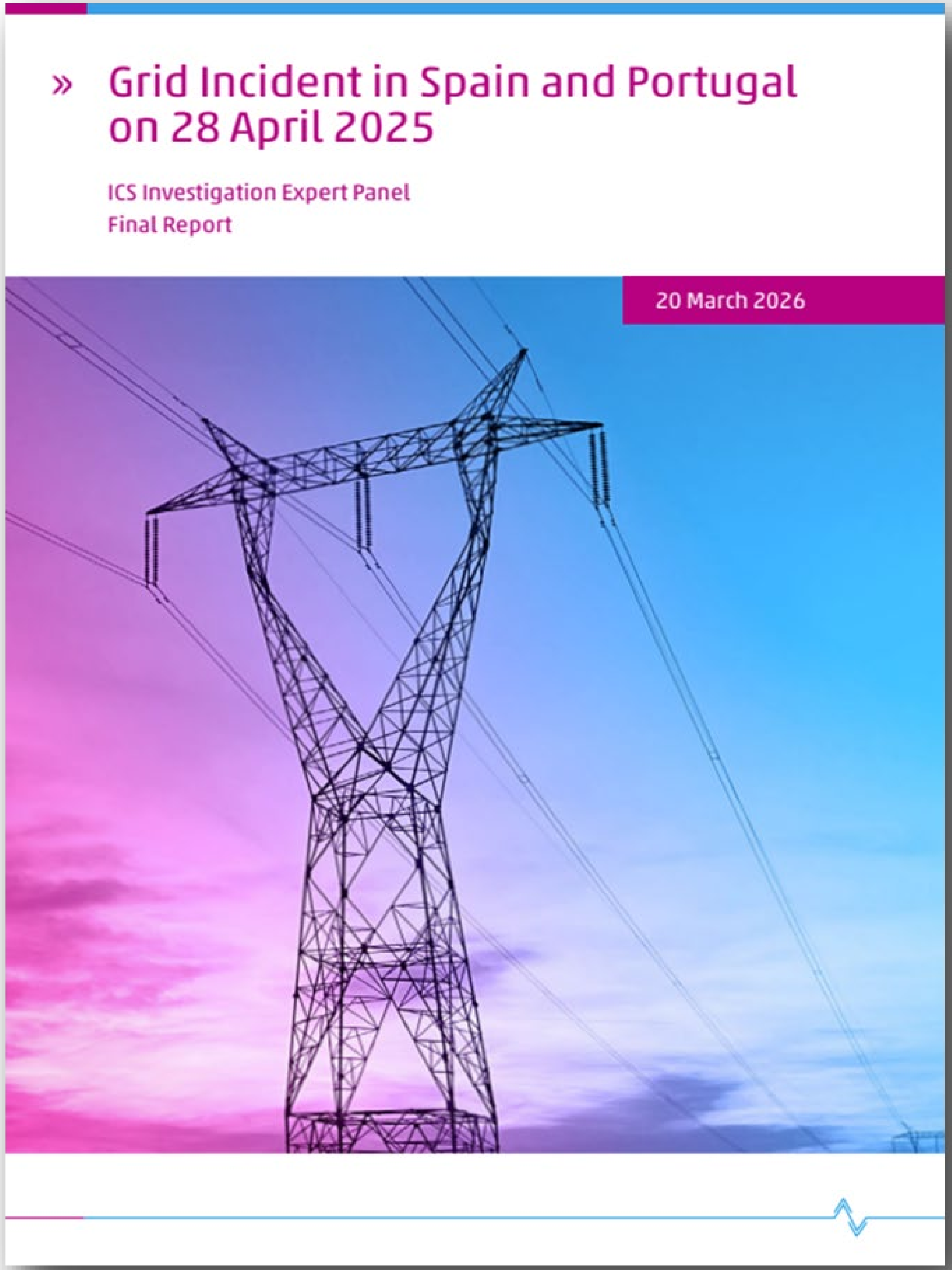
RELIABILITY | RESILIENCE | SECURITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

Motivation:
28 April 2025 Iberian Peninsula Blackout

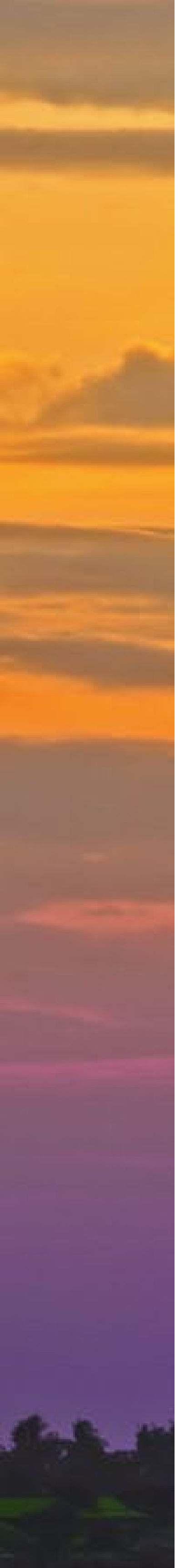
High-priority recommendation:

"Implement automatic detection systems and effective early-warning tools to identify oscillations in a timely manner…, locate their source in case of forced oscillation, and support prompt corrective actions…"



Introducing ESAMS: The Eastern Interconnection Situational Awareness and Monitoring System

- Developed by Electric Power Group (EPG) and the Pacific Northwest National Laboratory (PNNL)
- Core capabilities
  - Analyze PMU data streamed from across the grid
  - Detect oscillations impacting a wide area
  - Determine which reliability coordinator the oscillation is originating from
  - Deliver notifications via email
- Initial demonstration (June 2021 – March 2022)
  - Hosted by PJM with streaming measurements from seven reliability coordinators
  - Successes: Distributed daily event reports for 2 MW oscillations and real-time notifications for 10 MW oscillations
  - Challenge: Hosting an interconnection-wide tool within a single RC’s on-premises environment posed challenges for scalable long-term deployment



Advantages of a Cloud-Based Deployment

Elastic Scalability

Infrastructure scales dynamically to match ingestion. No manual capacity planning.

Reduced Overhead

Offloads server maintenance, patching, and backups.

Resilient Deployment

Blue/green deployments with automated rollbacks and multi-zone high availability.

Usage-Based Costs

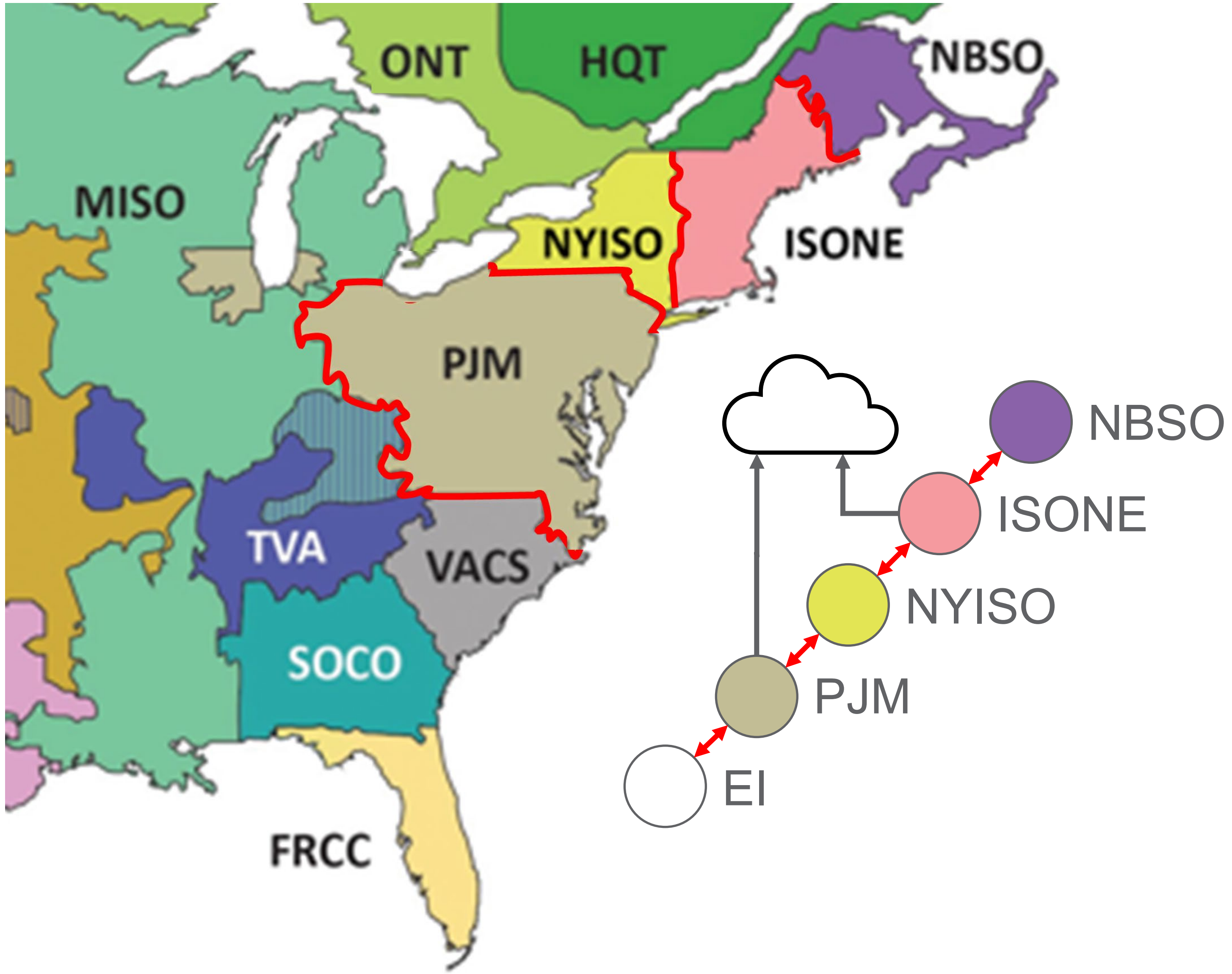
Pay-as-you-go pricing aligns costs with consumption.

Enterprise-Grade Security

Comprehensive controls aligned with utility industry requirements.

Cloud ESAMS Demonstration

- Hosted in ISO-NE's AWS cloud environment
- PMU data streamed from 73 transmission elements in ISO-NE and PJM
- Observable regions: New Brunswick, ISO-NE (with DC ties to HQT), NYISO/ONT, PJM, and the rest of the Eastern Interconnection
- Went live October 1, 2025

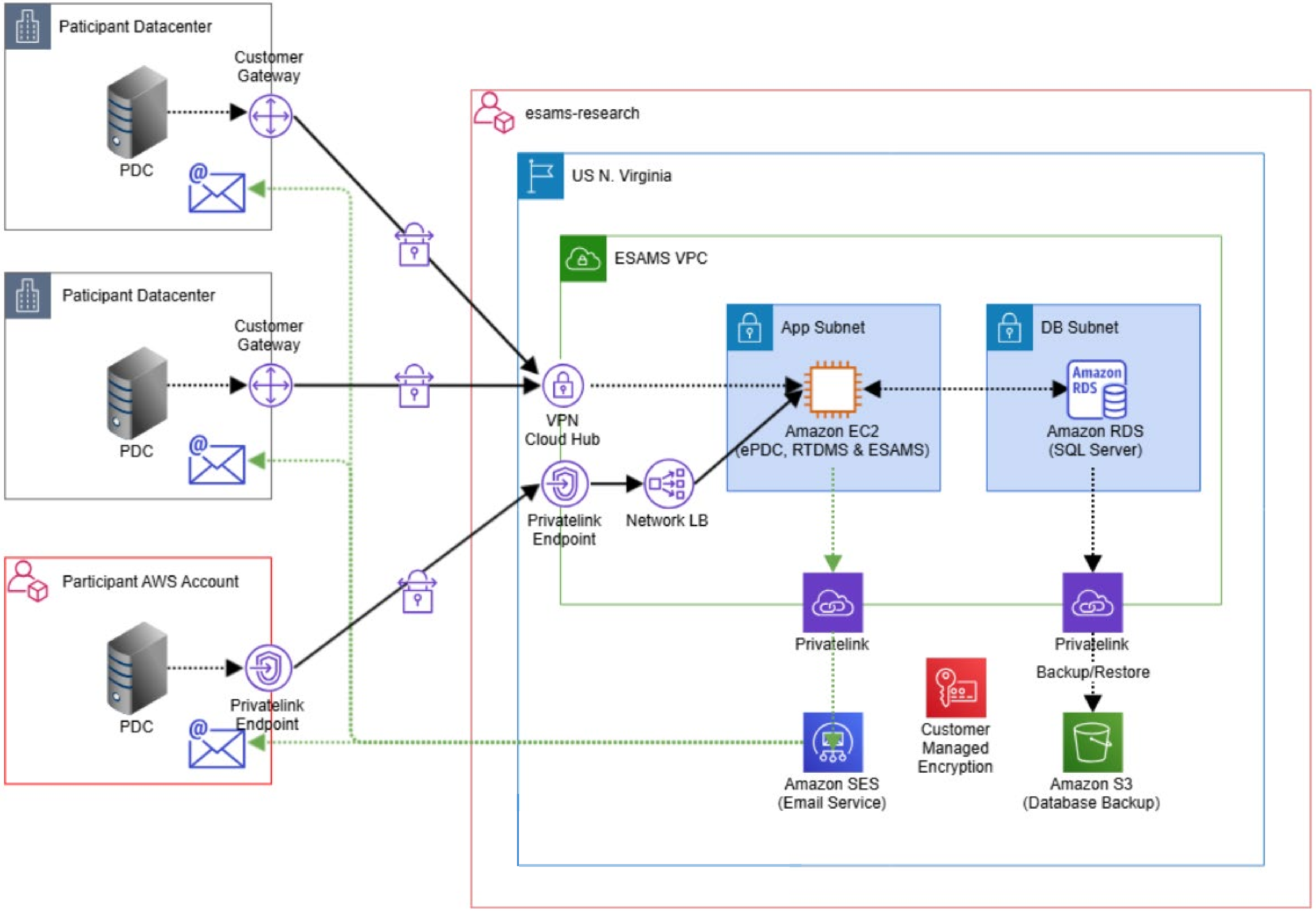


Cloud ESAMS Overall Architecture

Other entities
(streaming data via
site-to-site VPN)

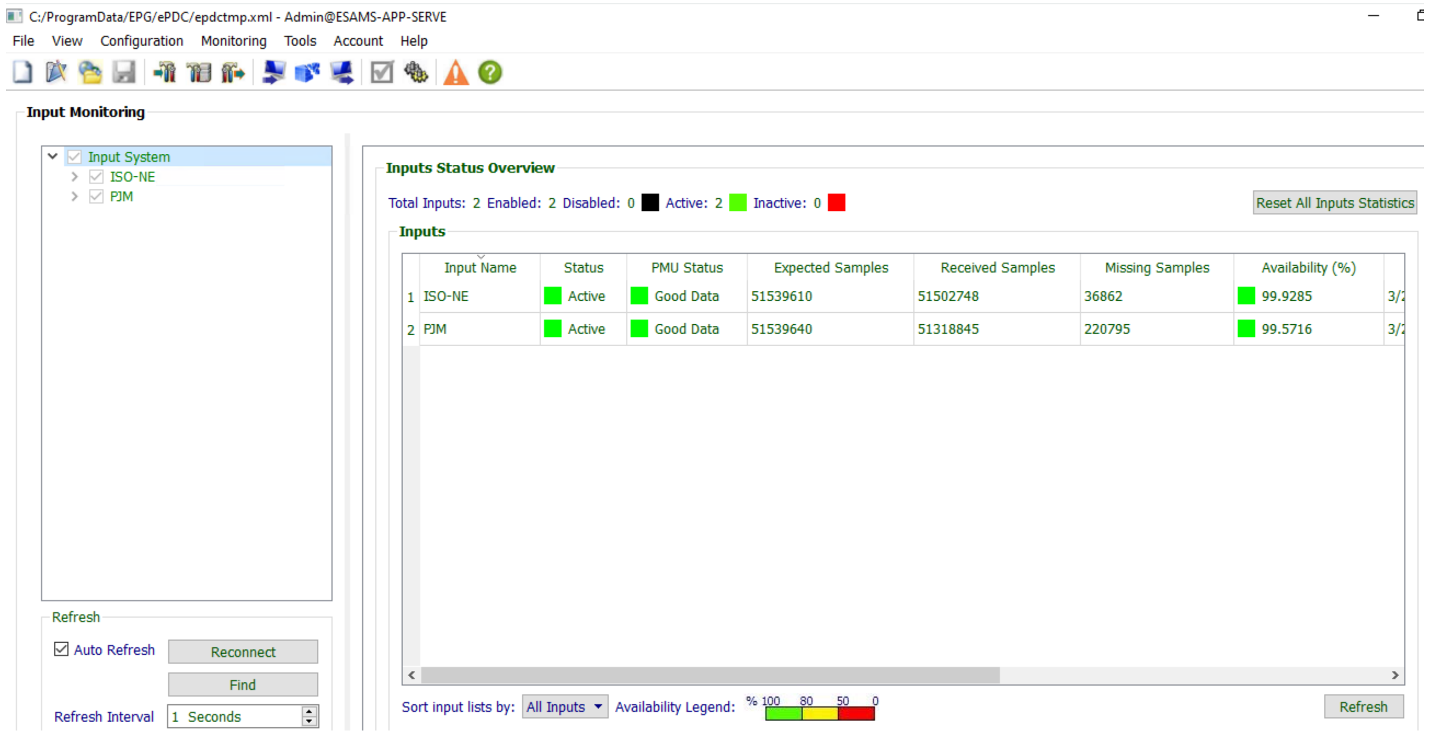
PJM
(streaming data via
site-to-site VPN)

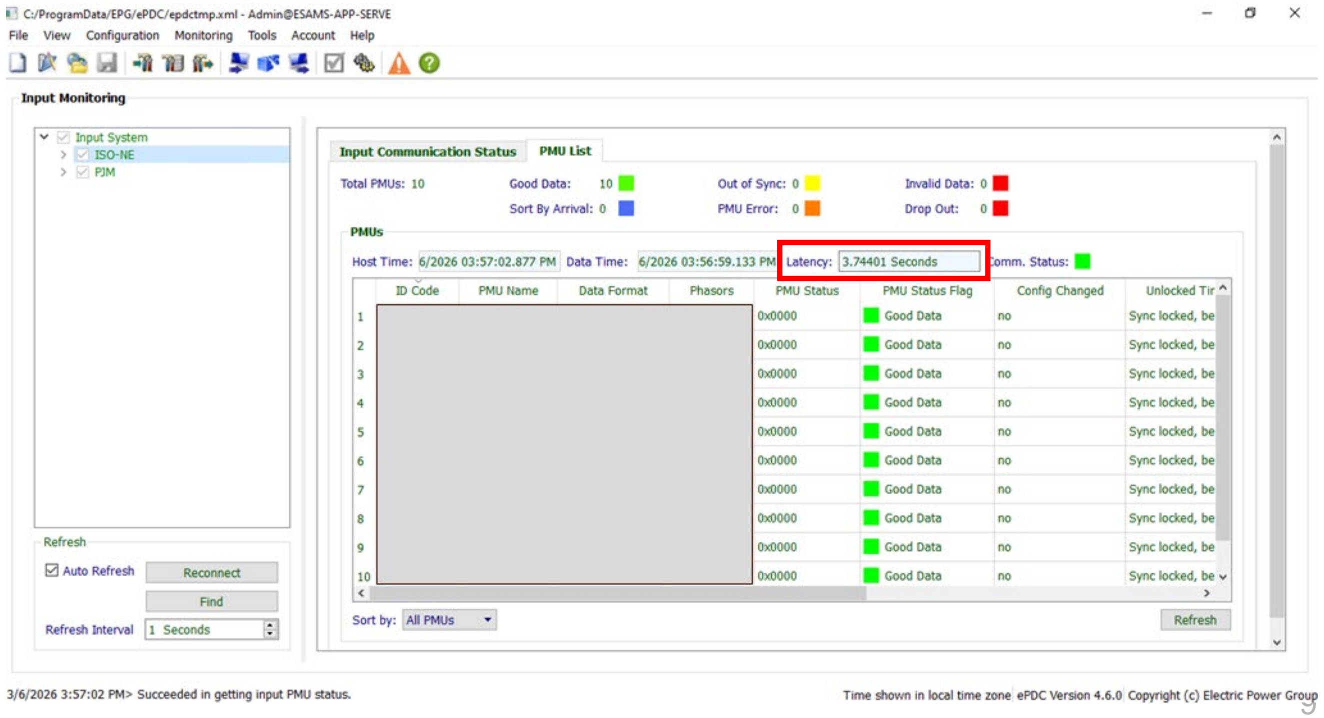
ISO-NE
(streaming data via
AWS Direct Connect)



Cloud ESAMS Server Aggregates PMU data from ISO-NE and PJM by ePDC

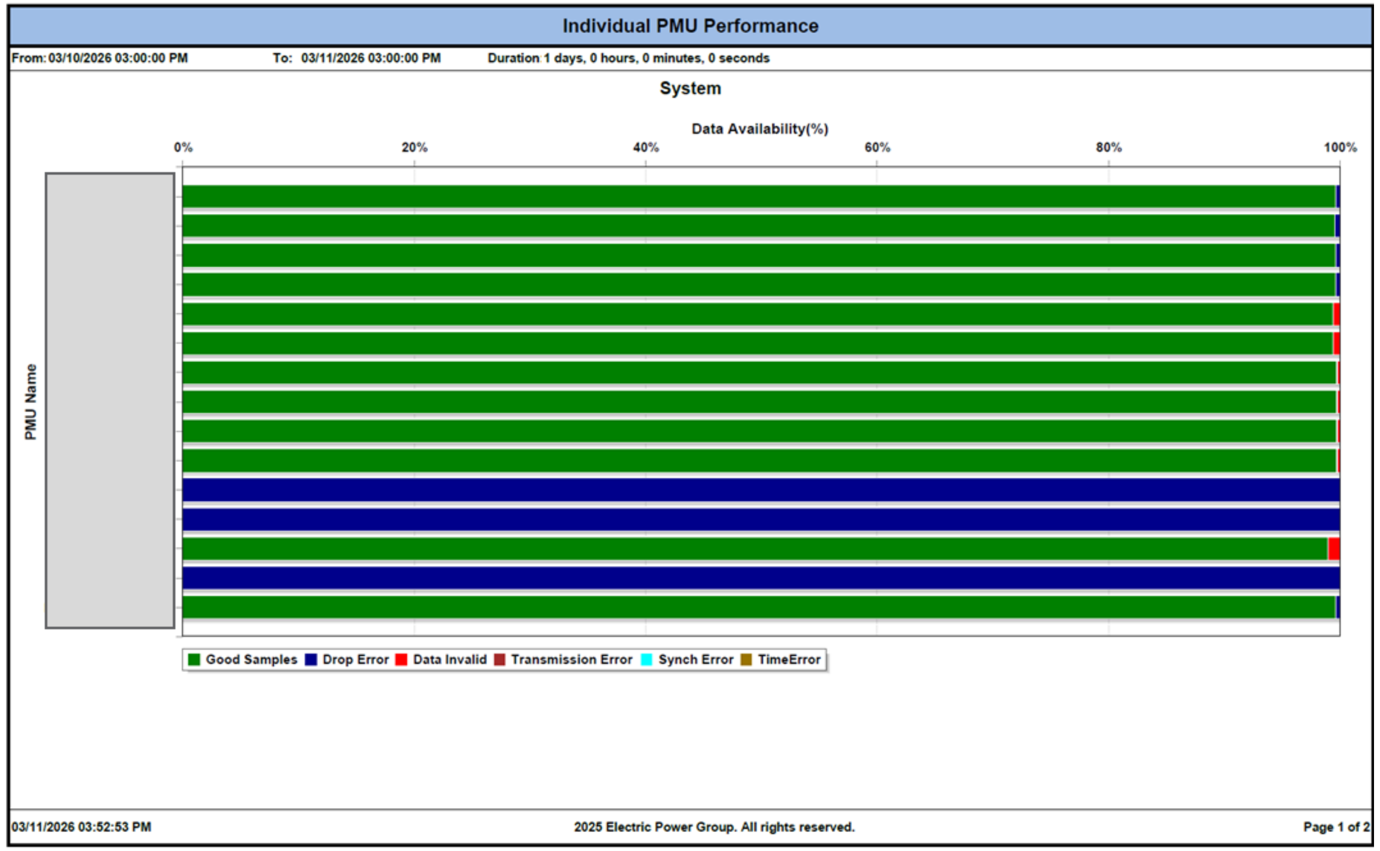
- Left - each region's incoming PMU status, data availability
- Right - individual PMU ID, name, number of phasors, status flag
- The ISO-NE input PMU data latency is 3.74 seconds
  - End-to-end transit time from the field measurement to the cloud, including buffering and processing delays of two intermediate PDCs
  - The transit time from on-premises ISO-NE and PJM PDCs to the cloud is ~150-200ms



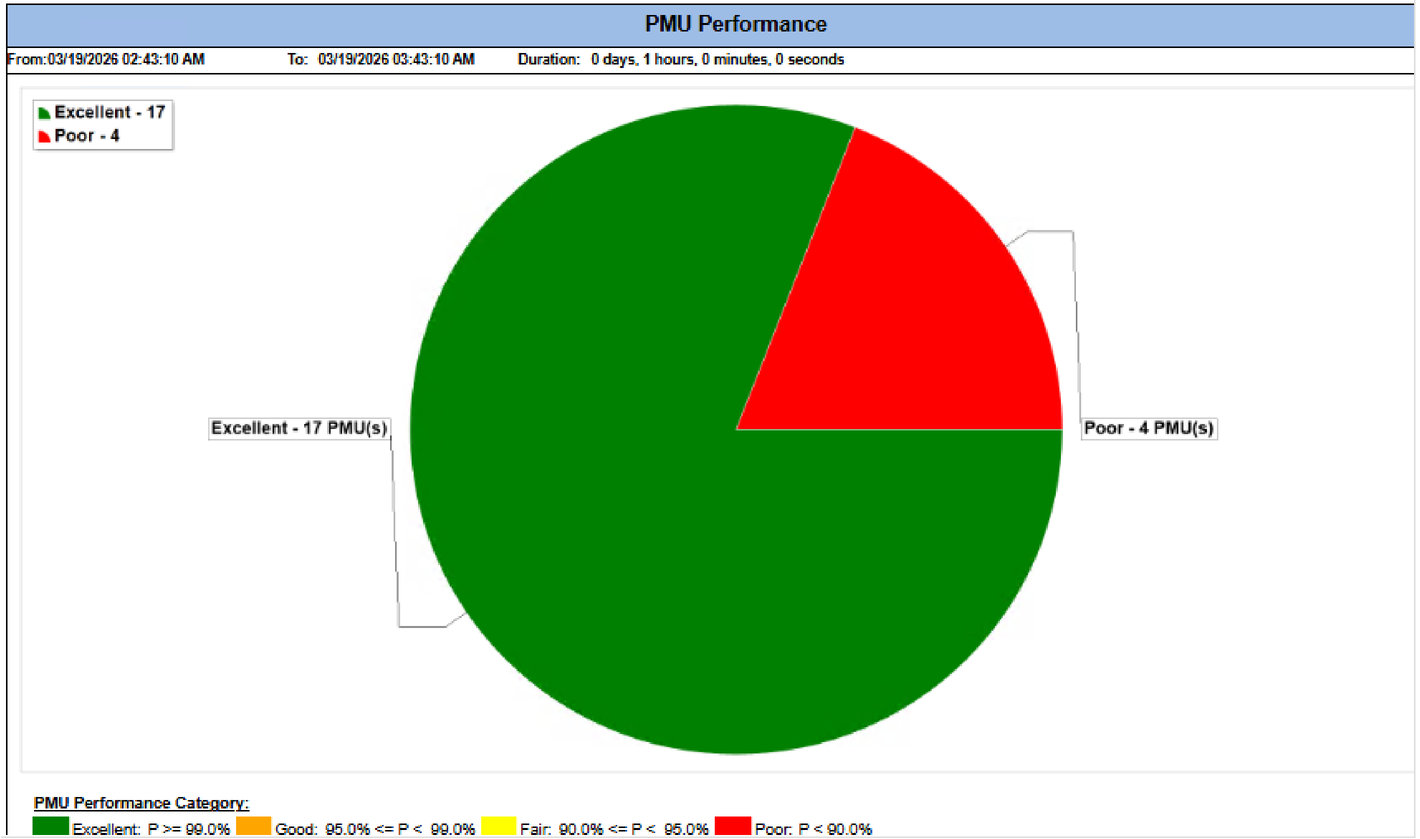


PMU Performance

Individual PMU Performance



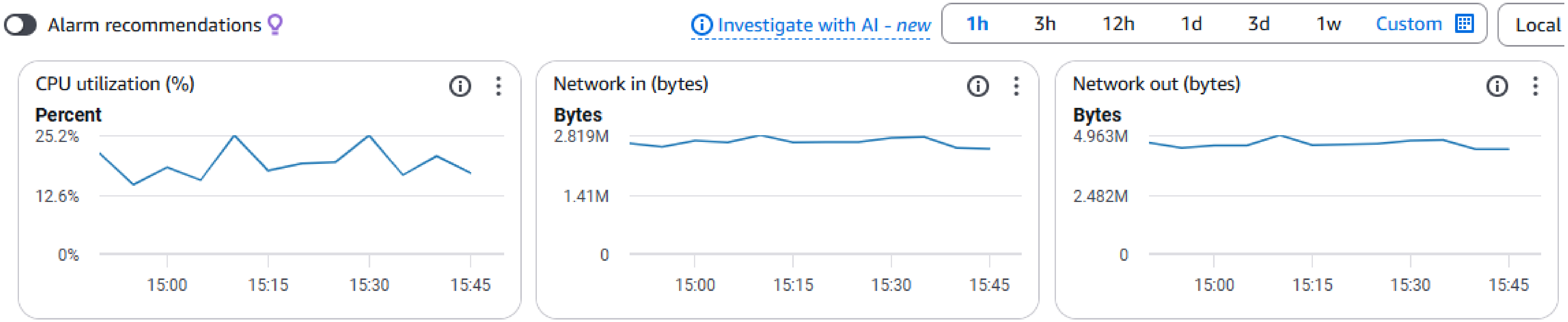
Overall PMU Performance



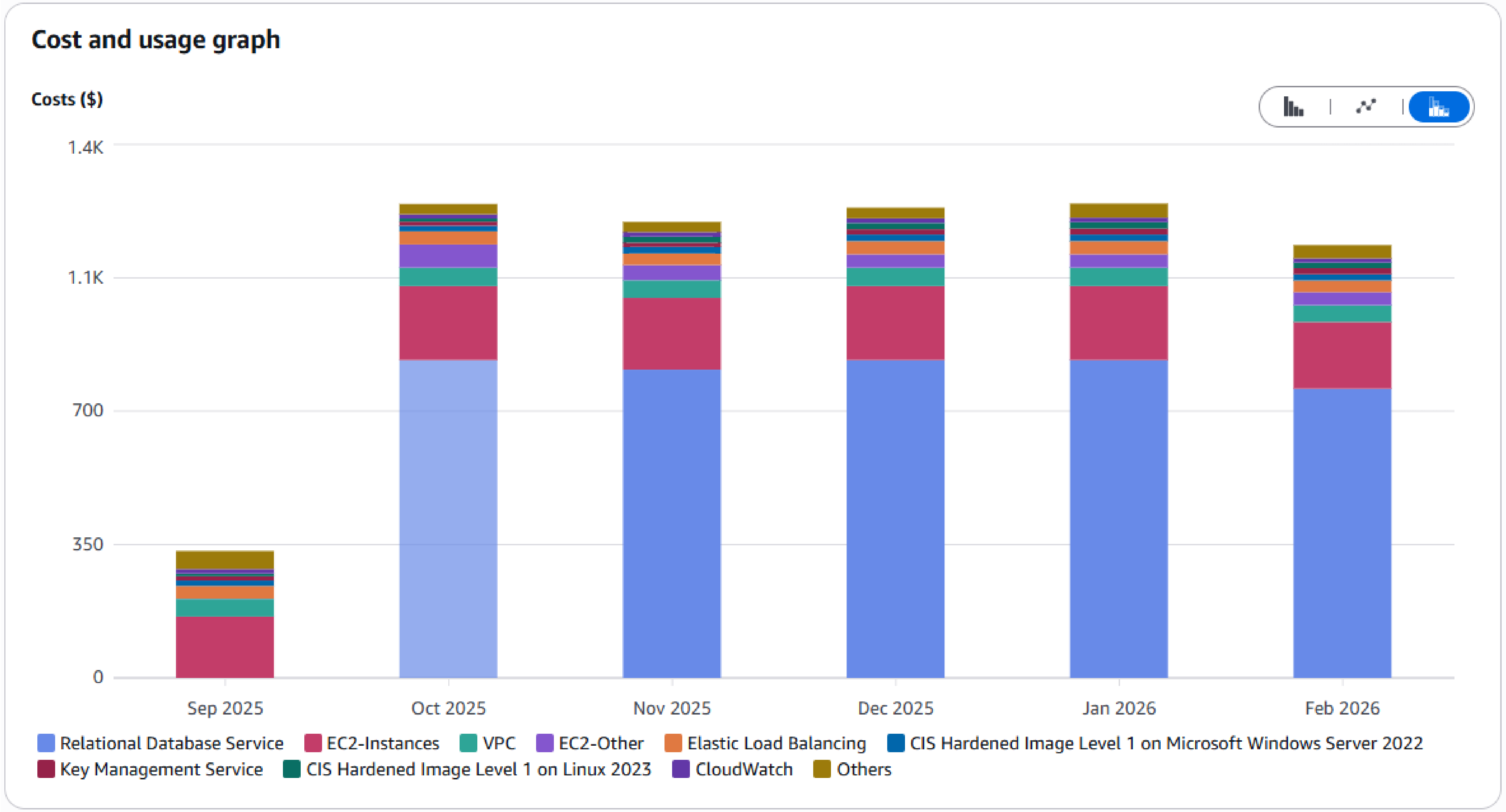
The research team verified that data availability problems originated before transfer to the cloud

Network Traffic Statistics for the ESAMS Server

- Network inbound: ~2.5MB every 5 minutes
  - Only tie line PMU data from ISO-NE & PJM
- Network outbound: ~4.3MB every 5 minutes
  - From ESAMS server to the RDS database
  - Including additional calculated data like P, Q, oscillation, etc.
- Minimal network traffic even scaling the current system to include other RCs



Average Cost of Cloud ESAMS



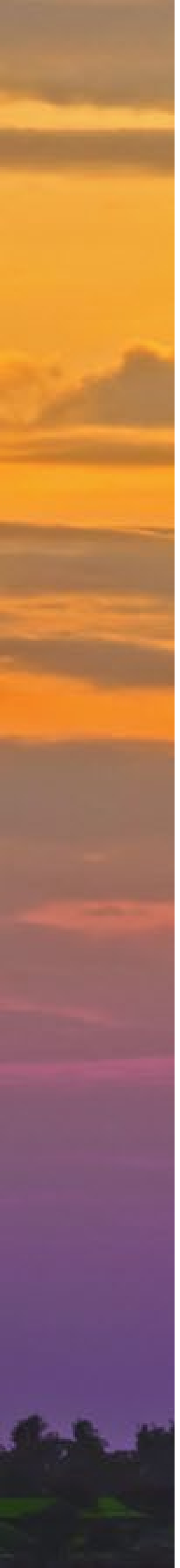
Average total:
$1200/Month

- RDS: ~$**800.00**
- EC2: ~$200.00
- VPC: ~$50.00
  (~$37 for S2S VPN;
  ~$11 for IPv4)

Two EC2 Instances:

- Windows: t3.xlarge
- Linux: t3.small

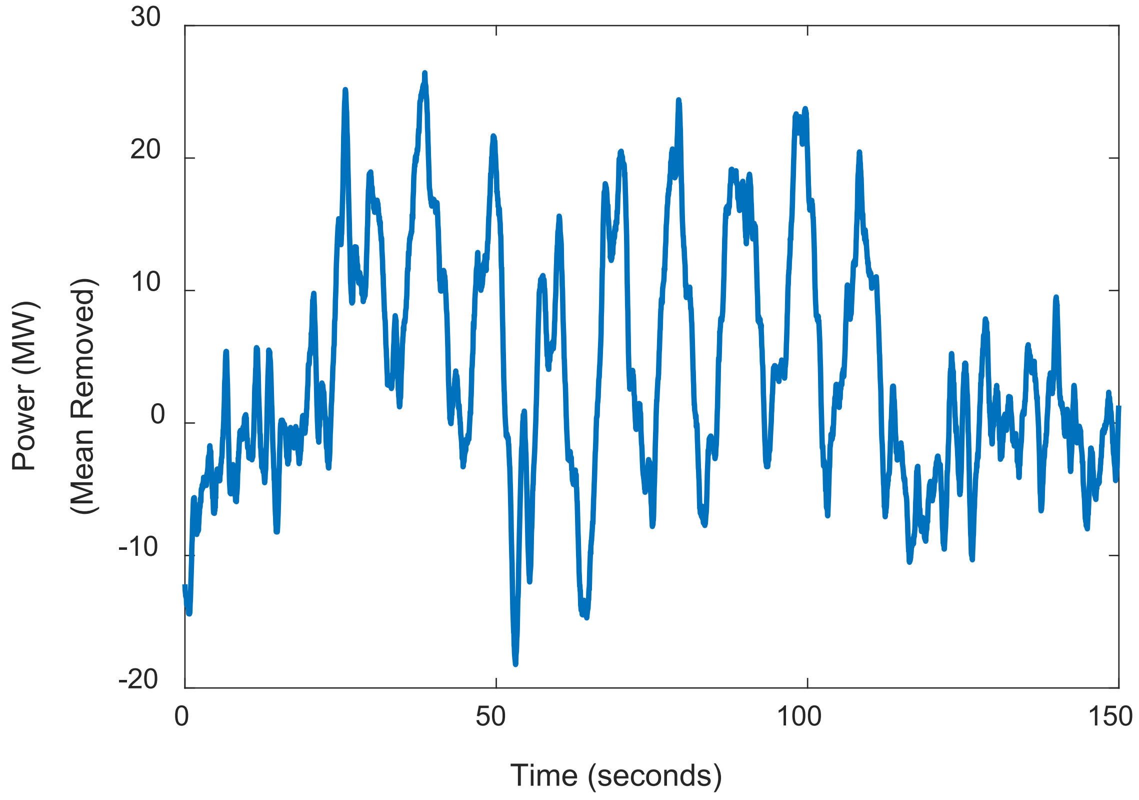
The cloud operating cost is very affordable, even we scale it to include other RCs

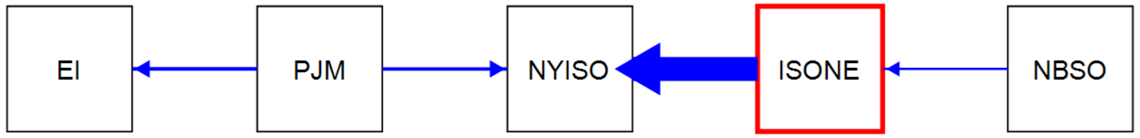


Summary of Detected Oscillations

Frequency (Hz)	Max Peak-to-Peak Amplitude	Duration (minutes)
0.39	2.1 MW	7
0.42	3.3 MW	4
0.10	24.7 MW	1.5
0.33	3.7 MW	3
0.23	5.1 MW	4
0.10	5.7 MVAR	11
1.11	2.2 MW	21
0.29	5.7 MW	10
0.14 0.20 0.31	20.8 MW 11.5 MW 14.5 MW	3
0.40	7.4 MW	4
0.50	6.3 MW	4
1.48	21.3 MW	3
1.51	7.3 MW	78 (intermittent)
0.37	4.7 MW	26
0.83	5.6 MW	1
0.50	6.4 MW	5
0.23	6.7 MW	2
0.40	6.9 MW	6
0.73	2.2 MW	6
0.40	6.5 MW	6
2.63	3.4 MW	677 (intermittent)
0.47	2.2 MW	5
0.54	10.5 MW	2

Oscillation Example 1





Boundary Oscillation Energy Flows

Frequency (Hz)	Max Peak-to-Peak Amplitude	Duration (minutes)
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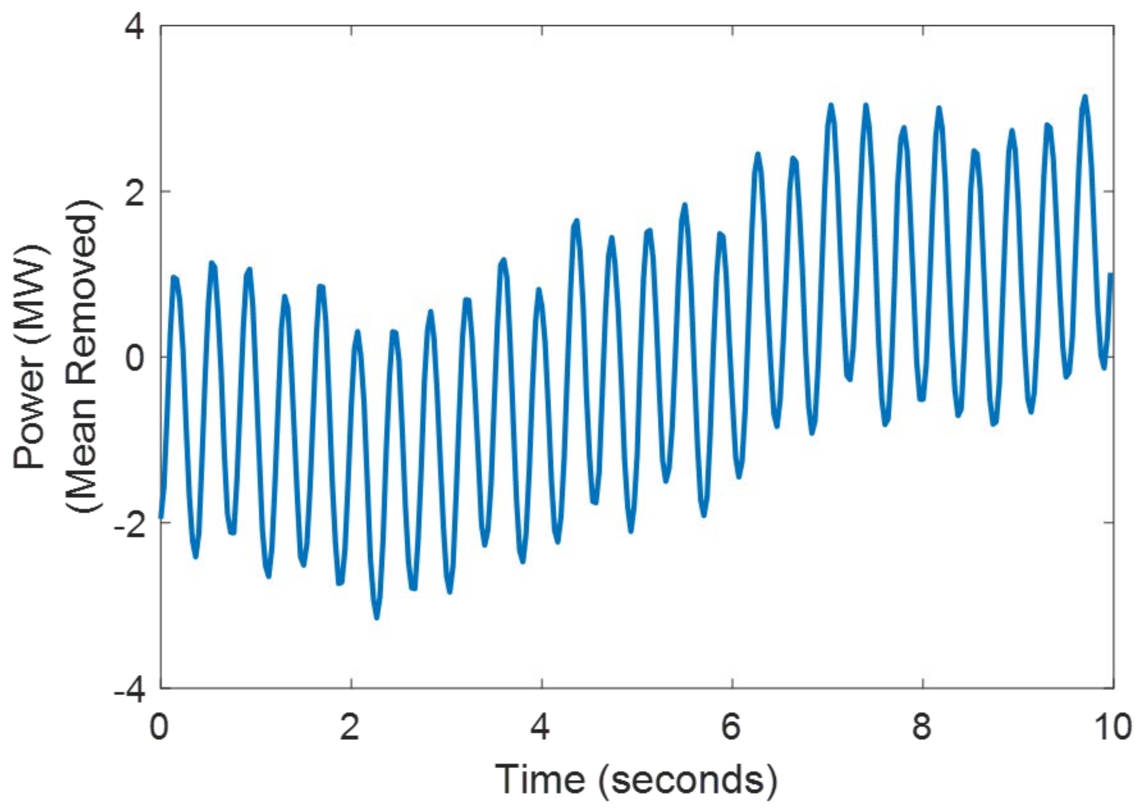
0.40	6.5 MW	6
2.63	3.4 MW	677 (intermittent)
0.47	2.2 MW	5
0.54	10.5 MW	2

Oscillation Example 2



Boundary Oscillation Energy Flows

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1.11	2.2 MW	21
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0.83	5.6 MW	1
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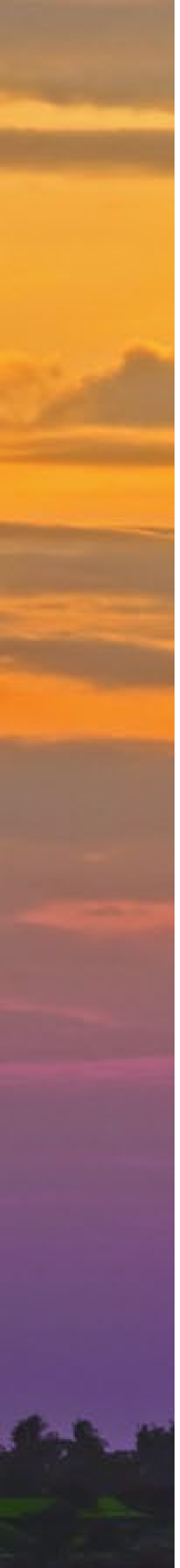
0.23	6.7 MW	2
0.40	6.9 MW	6
0.73	2.2 MW	6
0.40	6.5 MW	6
2.63	3.4 MW	677 (intermittent)
0.47	2.2 MW	5
0.54	10.5 MW	2

Value of Participation

- Common interconnection-wide view based on synchrophasor data
- Complements existing tools
- Provides actionable information
- Cost effective
- Managed by a third party (for example, EPG)
  - Participants don’t have to plan for on-premises hardware and software upgrades, network management, storage, etc.
- Scalable platform

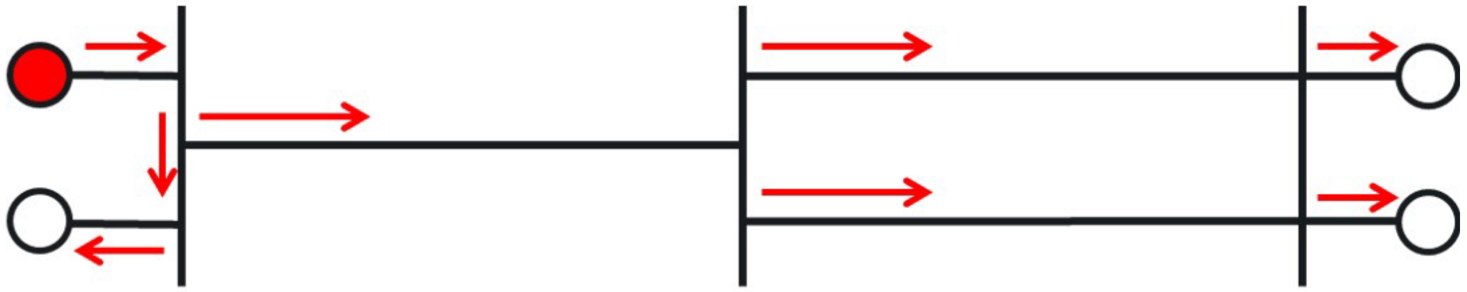
Call for RCs Participation to Realize Interconnection-Wide Value



Thank you

Conventional Source Localization

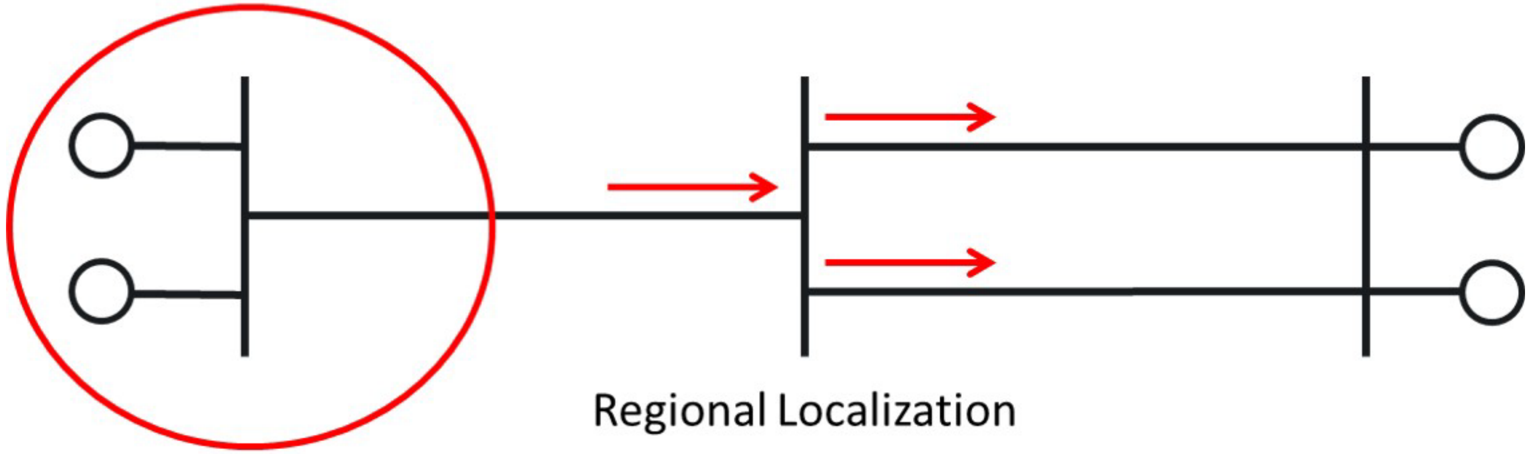
- The Dissipating Energy Flow (DEF) method has become a widely accepted approach for oscillation source localization
- Conventional DEF
  - Bandpass filter applied to limit signal to forced oscillation
  - Oscillation energy calculated by evaluating integrals
  - Flow of oscillation energy traced through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

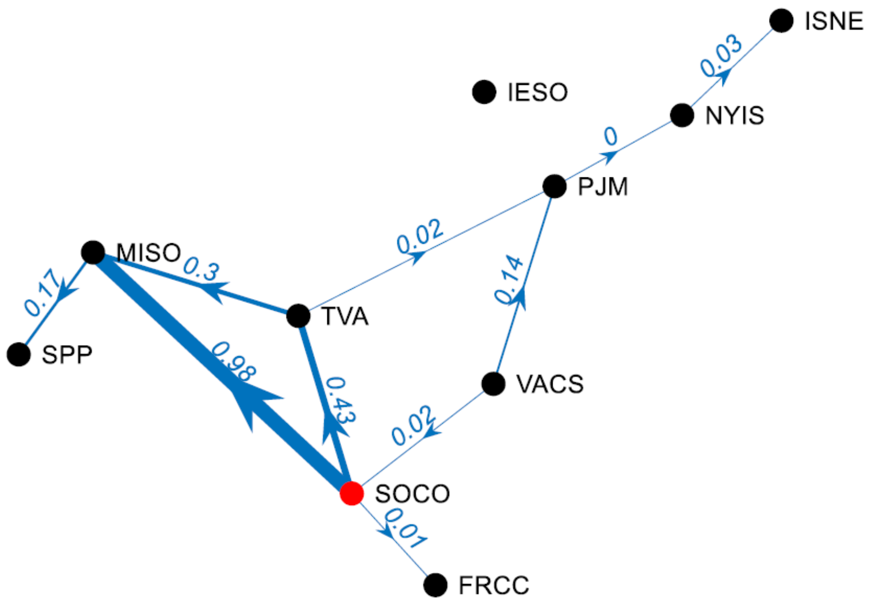


Equipment Localization

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





J. Follum, "Statistical Evaluation of New Estimators used in Forced Oscillation Source Localization," Hawaii International Conference on System Sciences (HICSS), 2020.
S. Biswas, J. Follum and J. H. Eto, "Confidence Assessment for Regional Forced Oscillation Source Localization: Formulation and Field Validation," in IEEE Transactions on Power Delivery, doi: 10.1109/TPWRD.2023.3284418.

Example Event 3

Frequency	Amplitude	Duration
0.83 Hz	5.6 MW	1 minute