DOE/OE Transmission Reliability Program

DOE Eastern Interconnection Situational Awareness Monitoring System (ESAMS) Prototype Demonstration Project

Joe Eto
Lawrence Berkeley National Laboratory
jheto@lbl.gov
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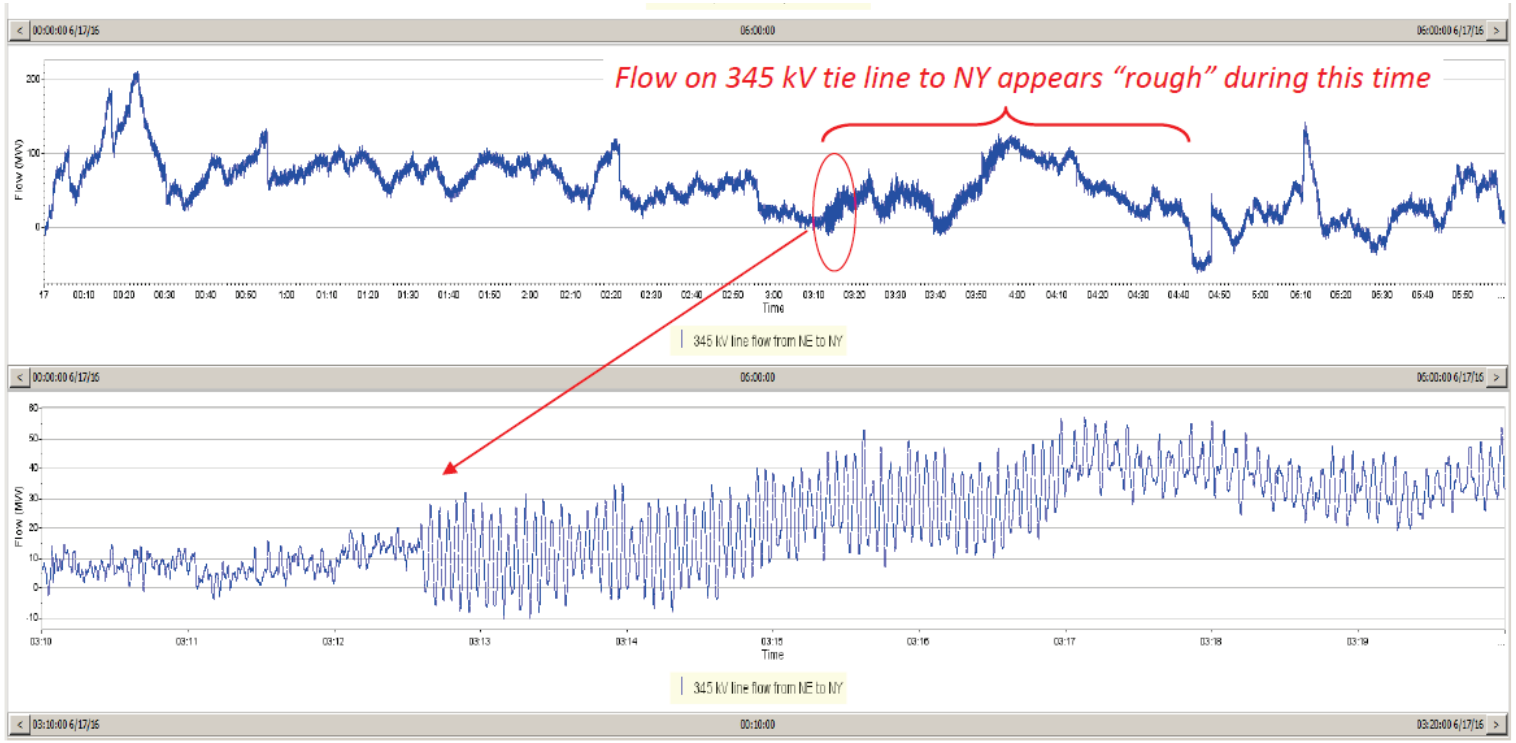
Overview and Motivation

A PMU-based system that provides a common view of interconnection-wide operating conditions—focusing on conditions not currently visible with existing systems

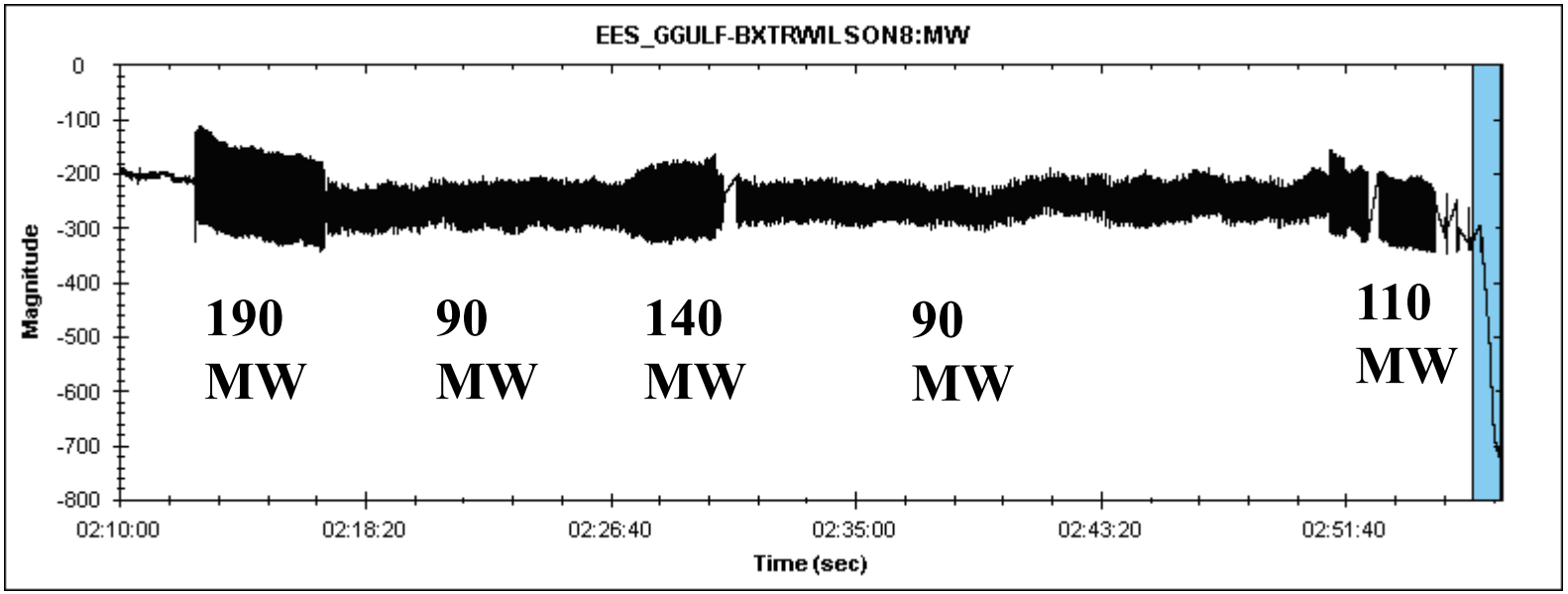
- All entities have excellent visibility of conditions taking place on-system (and well-established tools/procedures to guide responses to them)
- But, currently, we have limited means of gaining visibility of many conditions taking place off-system (with the partial exception of frequency response events, e.g., via FNet)
  - Frequency can tell us whether an off-system generator has tripped; other systems can help us identify the generator
- What additional off-system information might PMUs provide?
  - Source and magnitude of forced oscillations
  - Trends and changes in wide-area phase angle pairs

Oscillations seen in New England: Summer 2016



- 2:12 to 2:17: 40 MW Oscillations seen in a 345 kV NE to NY tie-line

Middle South Generator PMU MW Flow



- 2:12:30 AM CDT: Oscillations started; Amplitude varied between 90 MW and 190 MW
- 2:56:00 AM CDT: Oscillations stopped

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DOE Eastern Interconnection Situational Awareness Monitoring System (ESAMS) Prototype Demonstration

Overall Project Objective:

*To introduce a common, high-level interconnection-wide view based on synchrophasor information in order to foster discussion within and among Eastern Interconnection operating entities**

Key Elements of the initial high-level view will include:

1. Detect and identify forced and natural oscillations
2. Monitor phase angle pairs and identify when values are outside of normal operating ranges
3. Detect atypical behavior from an ensemble of measurements and identify which ones are contributing to the atypicality

Information Delivery Methods (by subscription):

1. Near real-time text message
2. Emailed reports (daily, weekly, monthly)

**The prototype will not duplicate functionalities currently provided by FNet*

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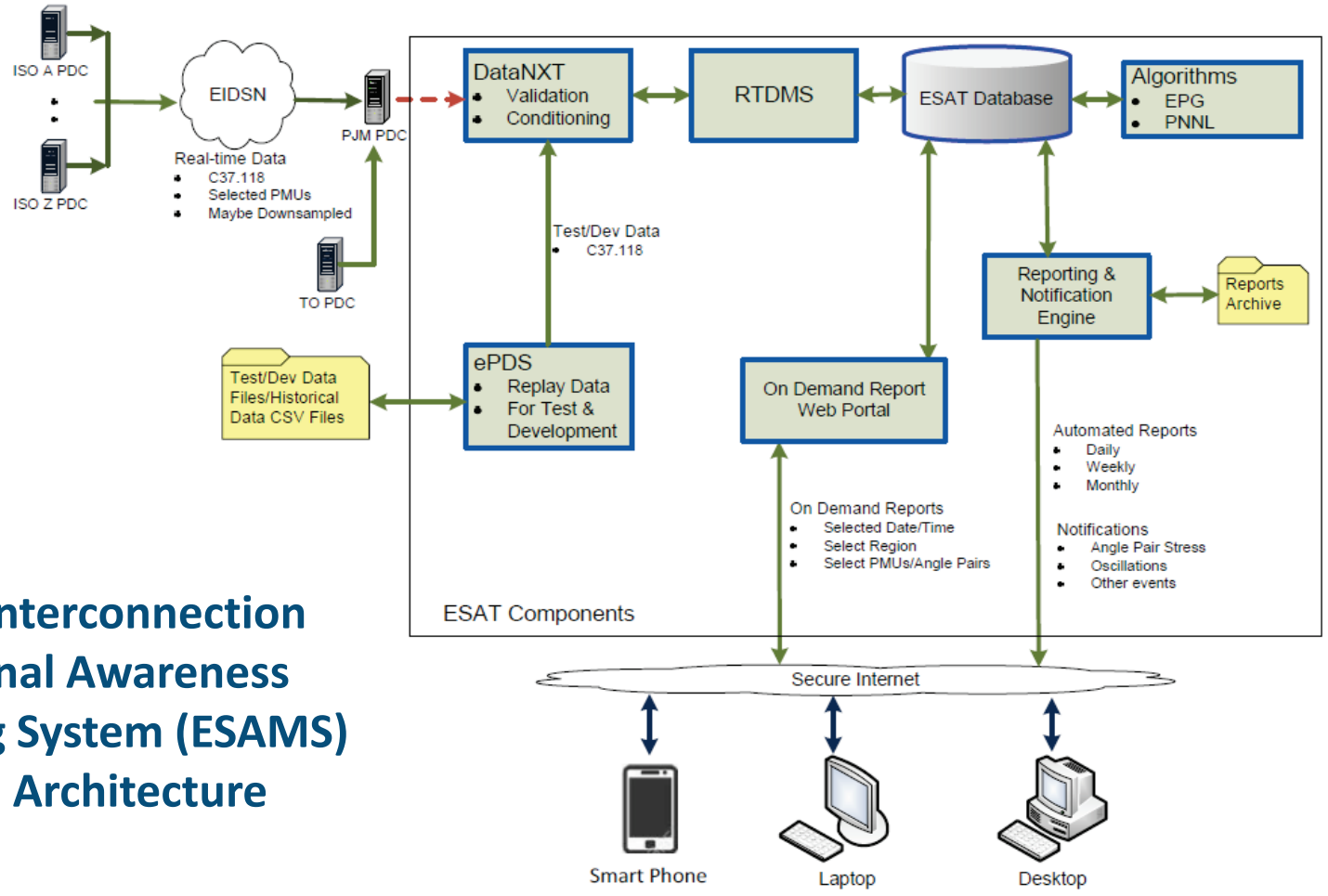
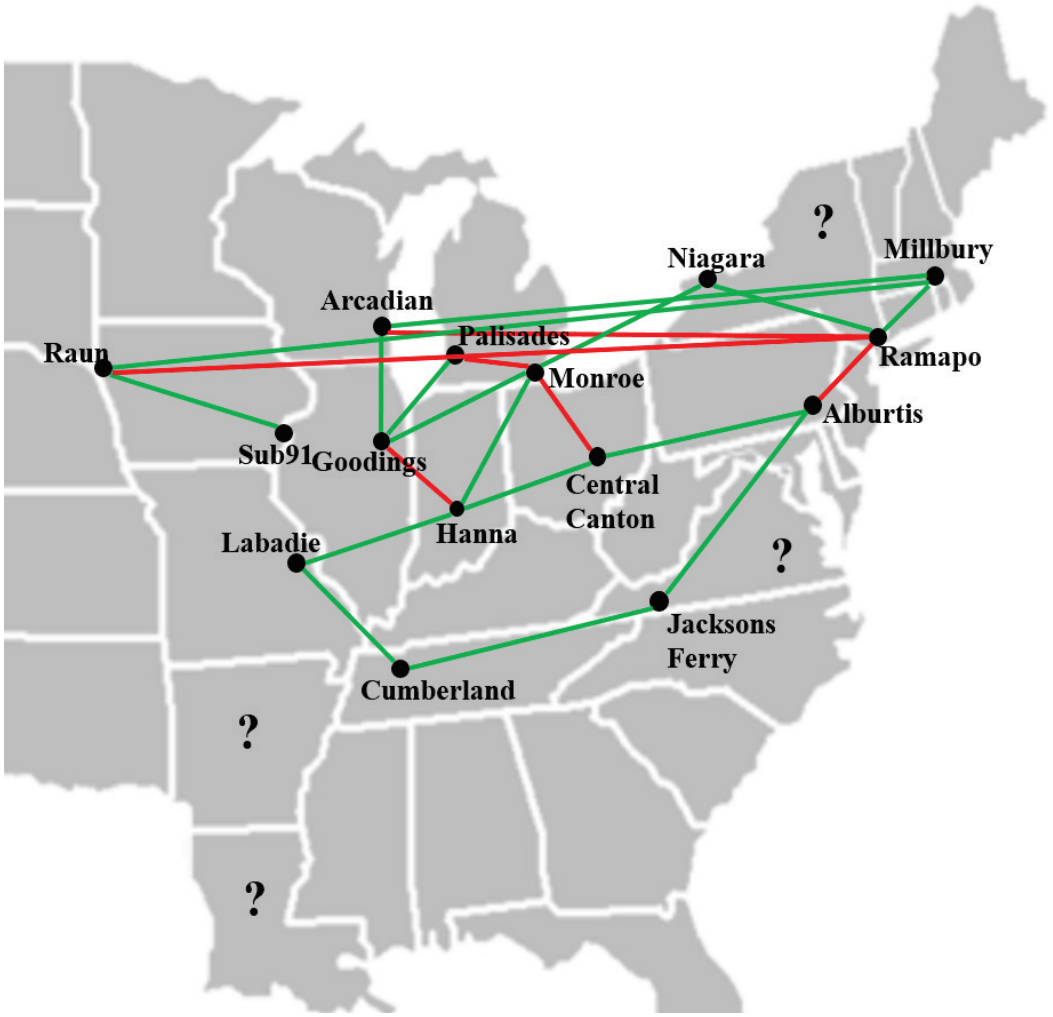
System Architecture for the Prototype System



Eastern Interconnection Situational Awareness Monitoring System (ESAMS) System Architecture

20-25 Phase Angle Pairs will be Included, Initially

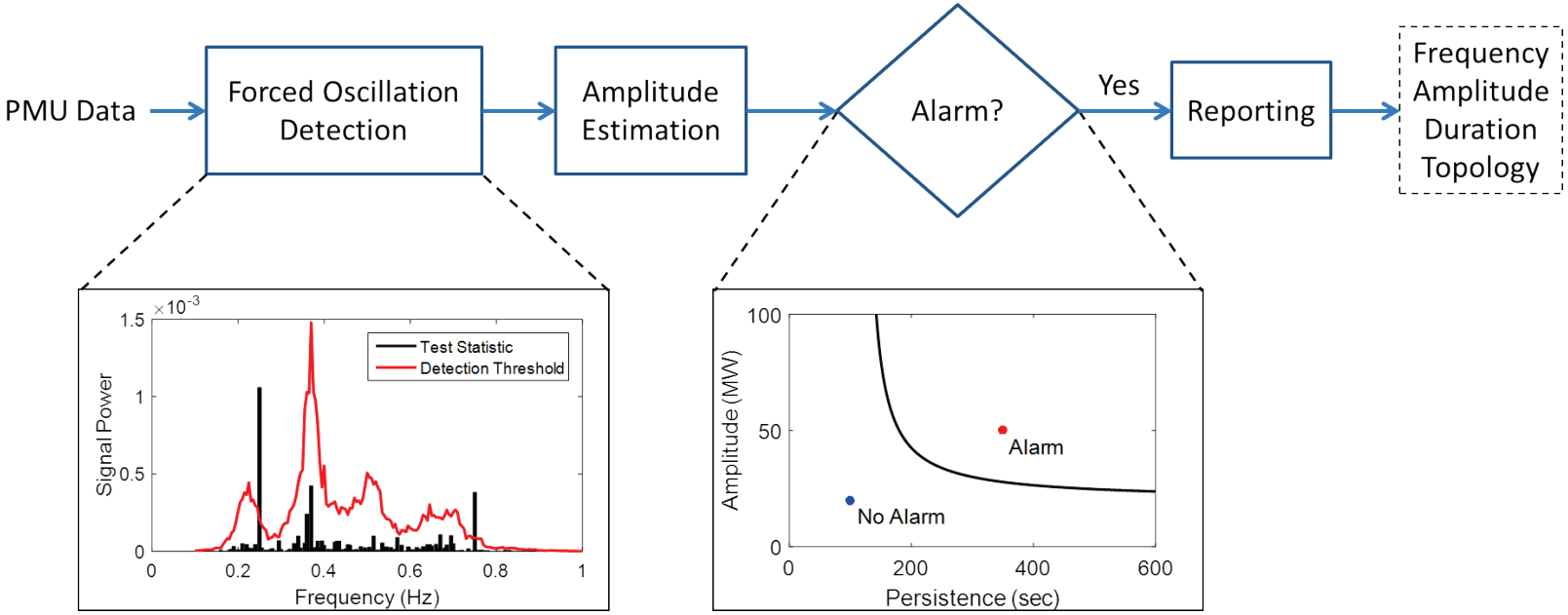
- 22 previously determined phase angle pairs were studied
- 16 pairs (in green) provide good coverage from the phase angles previously included
- 6 of those (in red) were found to be providing redundant information (using clustering and mathematical transitive property)
- We will work with our ISO/RTO partners to discuss inclusion of additional angle pairs involving monitoring locations in Arkansas, Louisiana, New York, and Virginia



Key Element #1:
Oscillatory Event Detection

Event: Forced oscillations

- Oscillations at measurement locations
- Coarse source location possible in many circumstances



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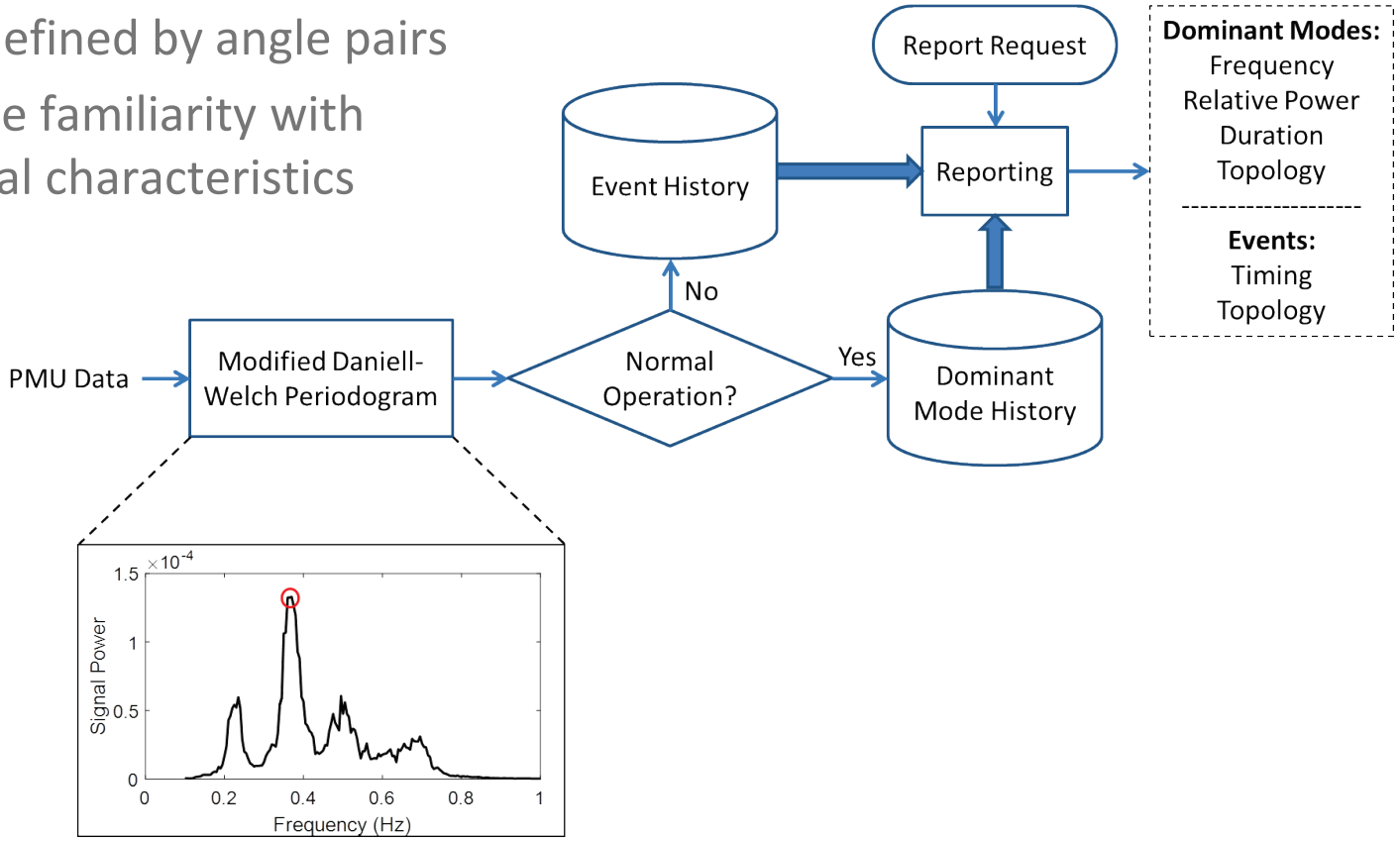
Key Element #1:
Oscillatory Event Detection

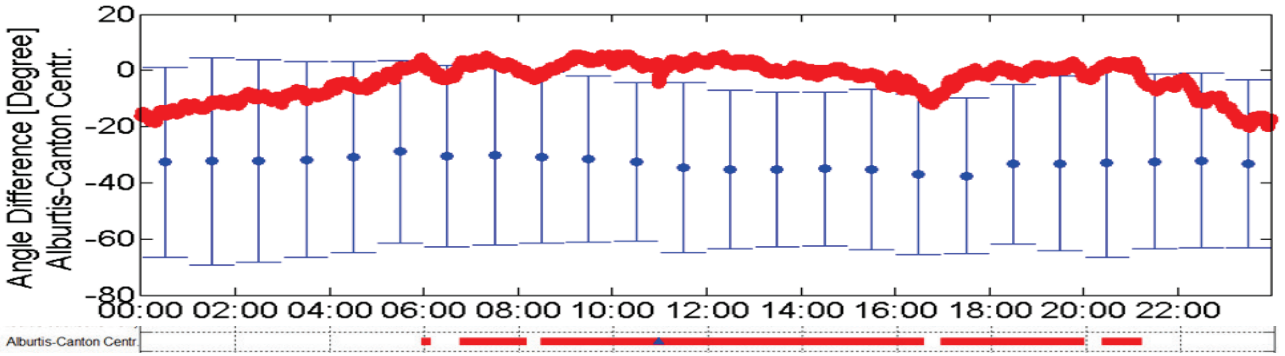
Event: Changes in low-level natural oscillations

- Oscillations between the areas defined by angle pairs
- Increase familiarity with EI modal characteristics

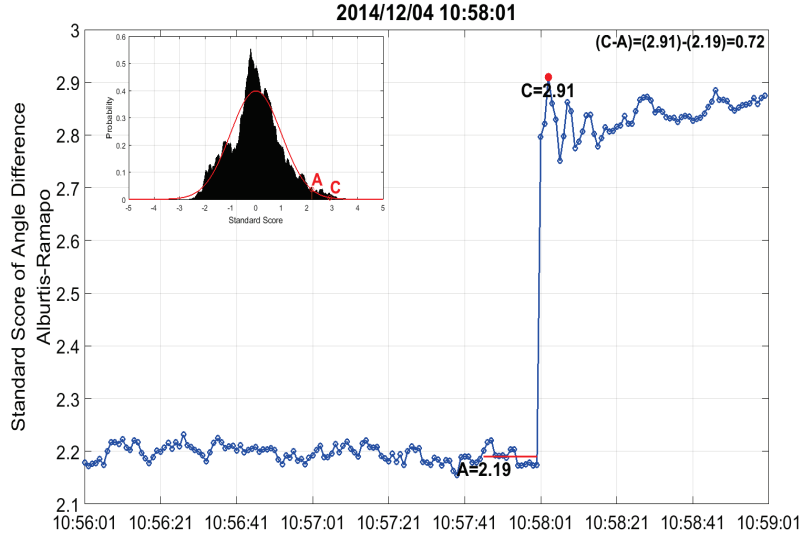


Key Element #2:
Monitor Phase Angle Pairs

- Identify when phase angle pair differences are outside of historically observed normal operating ranges



- Apply control chart methodology to detect significant changes in angle pairs



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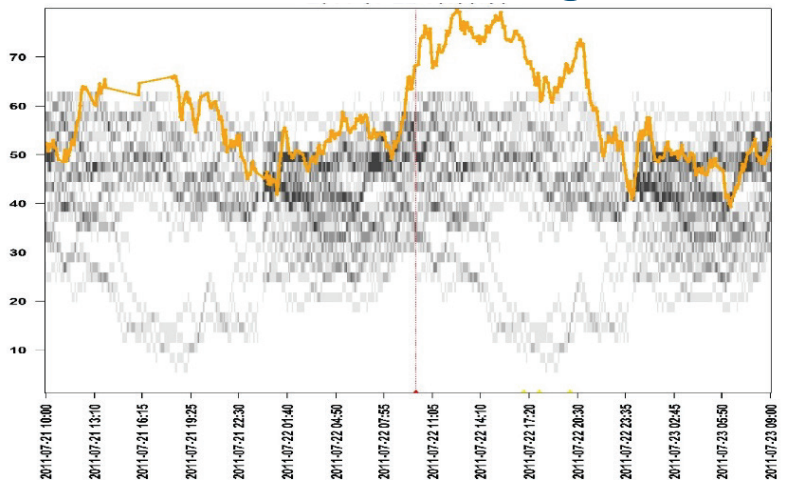
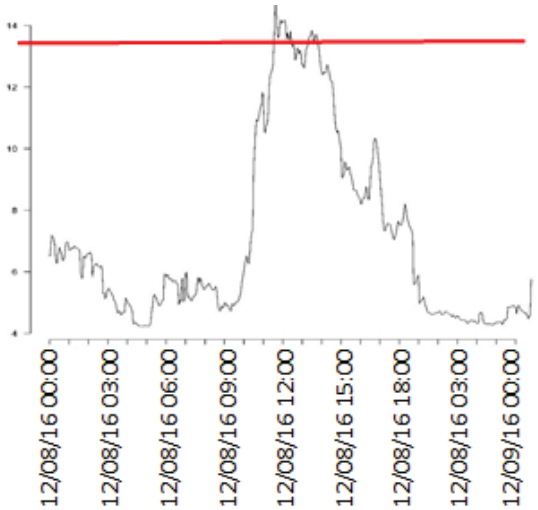
Key Element #3:
Detect Atypical Behavior

- Use multivariate statistical algorithms and past data to define a baseline of normal, observed behavior
- Compare current data to the baseline to determine when and where atypical behavior is observed

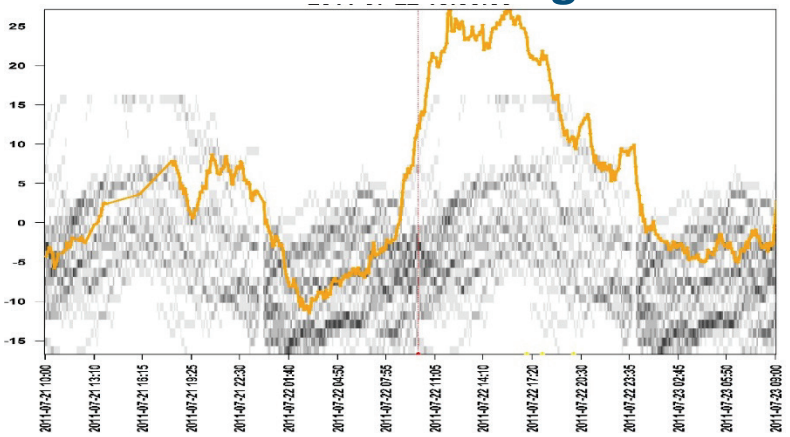
Jackson – Alburtis Angle Pair



Atypical Score



Monroe – Hanna Angle Pair



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Delivery Method #1:
Text Message–Immediate Notification

- **Oscillation examples**
  - A 20 MW forced oscillation began at 14:42 EDT today and has persisted for 20 minutes. It is localized to the PJM territory.
  - A 30 MW sustained oscillation began at 14:42 EDT today and has persisted for 1 minute. It is widespread and possibly natural, indicating a significant threat.
- **Phase angle monitoring examples**
  - Monroe-Hanna angle pair was outside the upper normal operation limit from 08:23 to 08:35 EDT today. Niagara-Monroe angle pair was also outside the lower normal operation limit from 08:22 to 08:38 EDT today.
  - 7 angle pairs detected a wide area disturbance at 10:58 today. The most sensitive angle pair is Alburtis–Ramapo pair.
- **Atypicality example**
  - An atypical event was detected at 09:23 EDT today. The atypical behavior continued for 37 minutes. Monroe-Hanna angle pair values were significantly higher (23.1^{o}) than normal (15.4^{o}). Jacksons Ferry-Alburtis angle pair rate of change was significantly higher (2.3^{o}) than normal (0.02^{o}).

Delivery Method #2:
Emailed Summary–Daily, Weekly, or Monthly

Report (.doc, .pdf, or .xml format) with embedded links that can be selected for additional information and drill down plots. Example first page:

Detected Oscillations
A 20 MW forced oscillation began at 14:42 EDT today and has persisted for 20 minutes. It is localized to the PJM territory.

Click on each link for additional information

Phase Angle Abnormalities
Monroe-Hanna angle pair was outside the upper normal operation limit from 14:45 to 14:52 EDT today.

Atypicalities
An atypical event was detected at 14:23 EDT today. The atypical behavior continued for 47 minutes. Monroe-Hanna angle pair values were significantly higher (23.1°) than normal (15.4°). Jacksons Ferry-Alburtis angle pair rate of change was significantly higher (2.3°) than normal (0.02°).

Issue	Duration	Additional Information
Forced Oscillation	14:42-15:02 EDT 12/08/2016	20 MW forced oscillation localized to the PJM territory
Exceed Normal Operating Limits	14:45-14:52 EDT 12/08/2016	Monroe-Hanna angle pair
Atypical Behavior Detected	14:23-15:10 EDT 12/08/2016	Monroe-Hanna angle pair values Jacksons Ferry-Alburtis angle pair rate of change

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Project Milestones and Schedule

Feedback and direction on initial prototype notifications/summaries w/ISONE, MISO, NYISO, PJM	Completed
Preparation of requirements document	Completed
Establish partnership with ISO/RTO host - scope and place project in queue for 2018 funding for IT support	Completed PJM has offered to host demonstration
Update briefings with partners (ISONE, MISO, NYISO), and outreach (CERTS ILC, EIDSN)	Completed
Finalize initial "look" and factory test prototype with historical data – transfer/test at PJM Synchrophasor Lab	2nd - 4th Q 2017 *In progress*
Initiate field installation at PJM	1st Q 2018
Complete field acceptance tests with PJM	2nd Q 2018
Roll-out to include other 3 original ISO/RTO partners	3rd Q 2018 (after summer operating season)

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Looking Ahead

- Enlarge participation to include additional Eastern Reliability Coordinators (also TOs and TOPs)
- Establish and obtain regular feedback from a working user group
  - Increase number of monitored points
  - Add/test analysis functionalities
- Transition to self-sustaining, industry-supported activity

Preliminary draft for an ESAMS daily report

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1. DATA AVAILABILITY

This section provides data availability and detected errors for selected PMUs in Eastern Interconnection during the reporting period.

Figure below provides the time-based data quality for all monitoring PMUs.

Detected errors could be interpreted using the provided color chart.

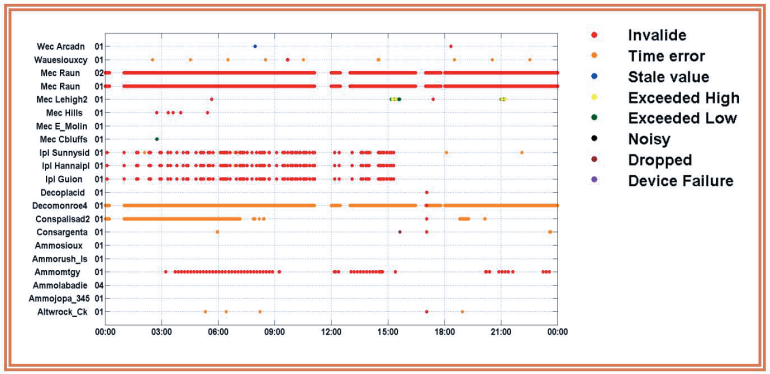


Table below summarizes selected PMUs' availability and detected errors related to bad and uncertain data.

Data Availability and Detected Errors for all Selected PMUs

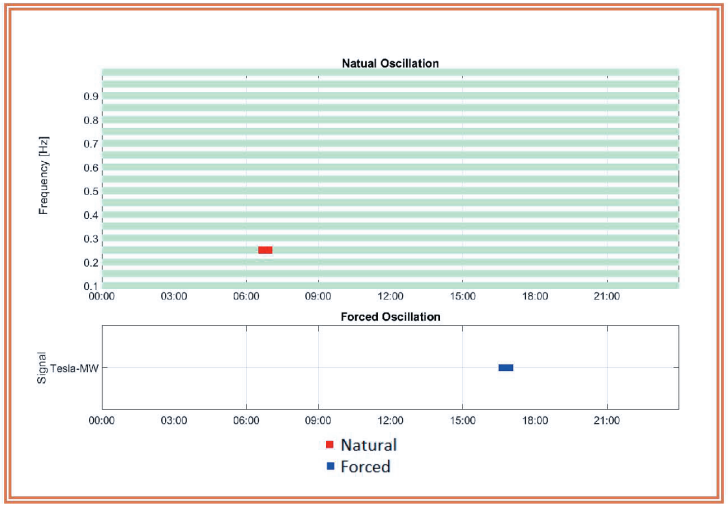
PMU	Good Data (%)	Bad Data (%)					Uncertain (%)					
		All Bad	Dropped	Planned Outage	Device Failure	Others	All Uncertain	Out of Range	Invalid Data	Time Error	Noisy	Others
RAUN	33.86	23.31	9.3	6.47	4.36	3.18	42.83	11.14	4.74	4.45	3.6	18.9
...												

2. OSCILLATIONS DETECTION

This section provides detailed information about detected forced and natural oscillations during the 24hr reporting period.

The red horizontal bar represents the time of the detected natural oscillation with damping less than threshold (5%) and energy greater than specific threshold for peak-peak value (Real Power >1MW, Reactive Power>1MVAR, Frequency>0.010Hz, Voltage Mag>1kV, Current Mag>5A, Angle Difference>0.5deg).

The blue horizontal bar represents the time of the detected forced oscillation. All detected forced oscillations with energy greater than the specific peak-peak energy threshold (Real Power >1MW, Reactive Power>1MVAR, Frequency>0.010Hz, Current Mag>5A, Angle Difference>0.5deg) will be shown.



2.1 NATURAL OSCILLATIONS

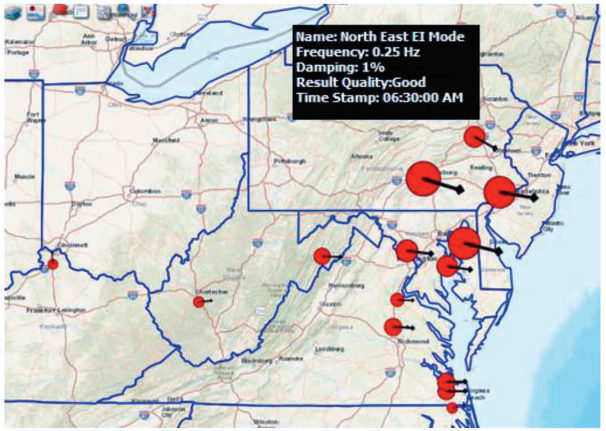
This section provides the information about detected natural oscillations with damping smaller than specific threshold (5%) and energy greater than specific peak-peak threshold (Real Power >1MW, Reactive Power>1MVAR, Frequency>0.010Hz, Voltage Mag>1kV, Current Mag>5A, Angle Difference>0.5deg).

Table below summarizes the information for natural oscillations detected during the 24hr reporting period

Start Time	End Time	Mode Name	Frequency	Damping	Maximum Peak-Peak Amplitude
6:30:10 am	7:05:00 am	North East EI Mode	0.25 Hz	1%	20 MW

Mode shape visualization on geospatial map is provided for each listed natural oscillation.

1. NORTH EAST EI MODE FREQUENCY 0.25HZ FROM 6:30-7:05



2.2 FORCED OSCILLATIONS

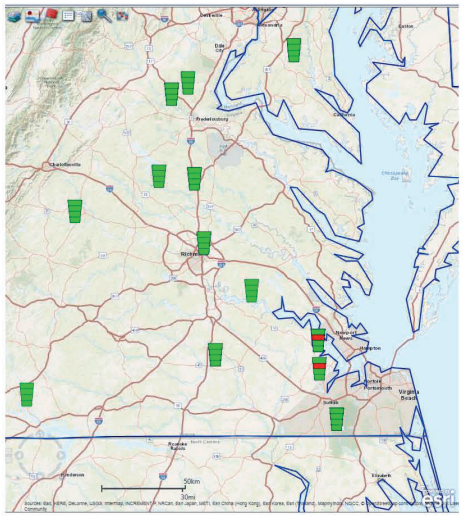
This section provides the information about detected forced oscillations based on specific peak-peak energy threshold (Real Power >1MW, Reactive Power>1MVAR, Frequency>0.010Hz, Voltage Mag>1kV, Current Mag>5A, Angle Difference>0.5deg.

Table below summarizes the information for forced oscillations detected during the 24hr reporting period

Start Time	End Time	Location	Signal	Frequency	Maximum Peak-Peak Amplitude
4:30:10 pm	5:05:00 pm	Tesla	Power (MW)	3.3 Hz	100 MW

Geospatial map display indicating location of oscillations is provided for each detected forced oscillation.

1. Forced Oscillation Found in Voltage of PMU Surry with 0.46Hz from 4:30pm-5:05pm



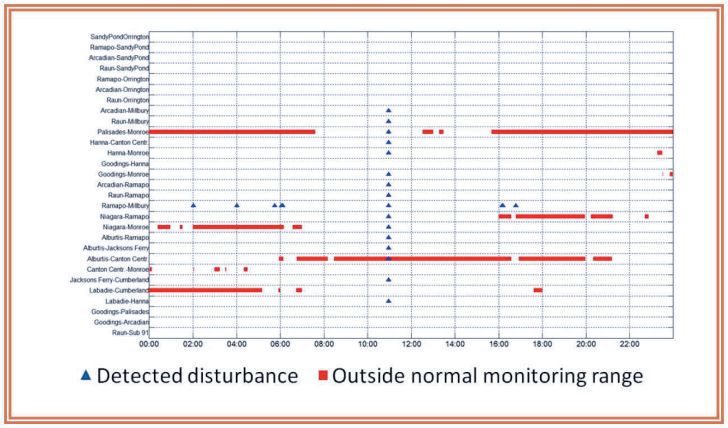
3. STRESS AND DISTURBANCE DETECTION

This section summarizes behavior of angle pairs from the standpoint of detection of system stress and system disturbances. Figure below shows detected angle pair difference stress situations and detected angle pair difference disturbances for the reporting period.

The red horizontal bar represents the time duration of an angle pair outside of the normal +/- 3sigma monitoring range - which is an indication the system stress.

The blue triangle indicates the time of system disturbance detected by observing an angle pair difference change range which is outside of +/- 25 sigma monitoring range.

Angle Pairs outside Normal Monitoring Range and Detected Disturbances

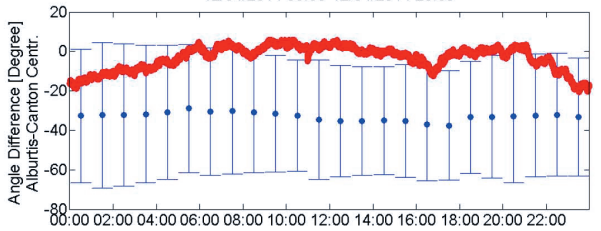


3.1 STRESS DETECTION

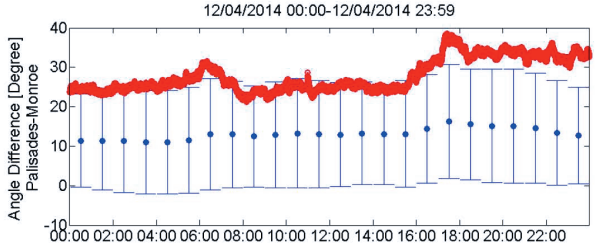
This section provides the plot of angle pairs outside the normal monitoring range for more than 5 hours.

Angle Pair Difference Monitoring Upper/Lower Bounds Hourly Reference Mean Value

1. ALBURTIS-CANTON CENTR. OUTSIDE NORMAL MONITORING RANGE 08:00-16:00



2. PALISADE -MORNE OUTSIDE NORMAL MONITORING RANGE 0:00-6:00 AND18:00-22:00

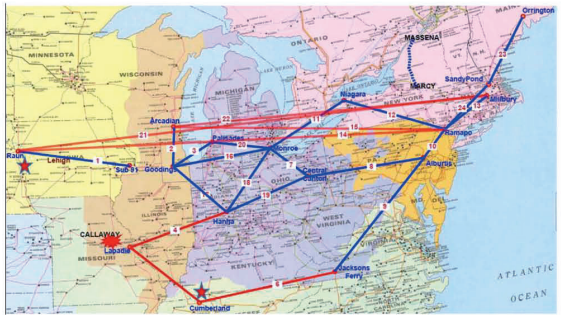


3.2 WIDE AREA DISTURBANCE DETECTION

This section presents disturbances detected by more than 7 angle pairs.

1. DISTURBANCE AT 10:58 WAS DETECTED BY 7 ANGLE PAIRS

The angle pairs detected the event shows in the following geographic map.



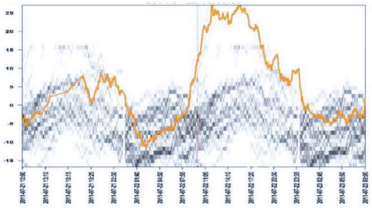
The angle pairs which contributed to the event detection are shown in the following table. The Z score change during the event indicates the angle sensitivity to the disturbance. The most sensitive angle pair is listed at the top of the table below.

From	To	Angle Pair Sensitivity to the Detected Disturbance (Z-Score Change, 0 means no change during the event, the higher absolute value means higher sensitivity)
Labadie	Hanna	-1.08
Labadie	Cumberland	-1.07
Jacksons Ferry	Cumberland	0.68
Raun	Ramapo	-0.39
Arcadian	Ramapo	-0.33
Raun	Milbury	-0.26
Arcadian	Milbury	-0.23

4. ATYPICALITY

A multivariate-based atypical event was detected at 14:23 and continued until 15:10. The atypicality score began to trend upward at 13:45. The Monroe-Hanna angle pair and Jacksons Ferry-Alburtis angle pair contributed most to this atypicality.

Jacksons Ferry – Alburtis Angle Pair



Monroe – Hanna Angle Pair