Inverter-Induced Forced Oscillation Source Location Estimation Using Synchrophasors: SRP Case Study

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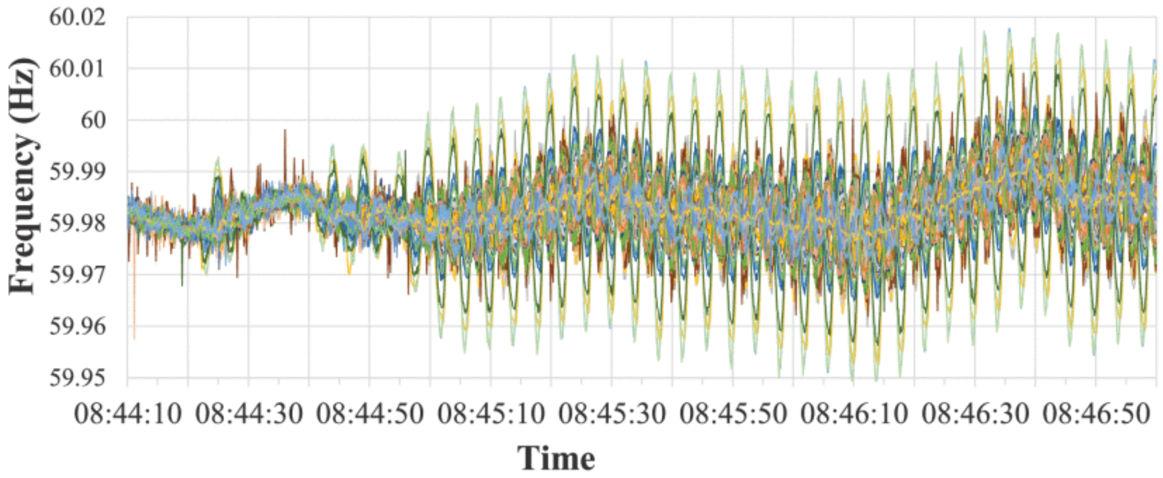
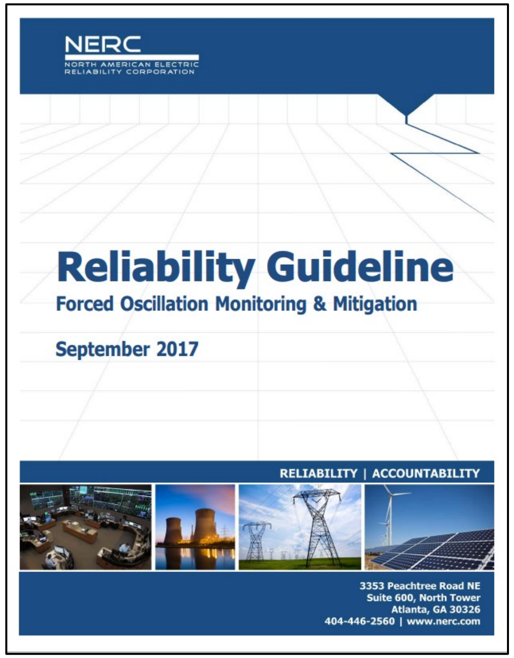
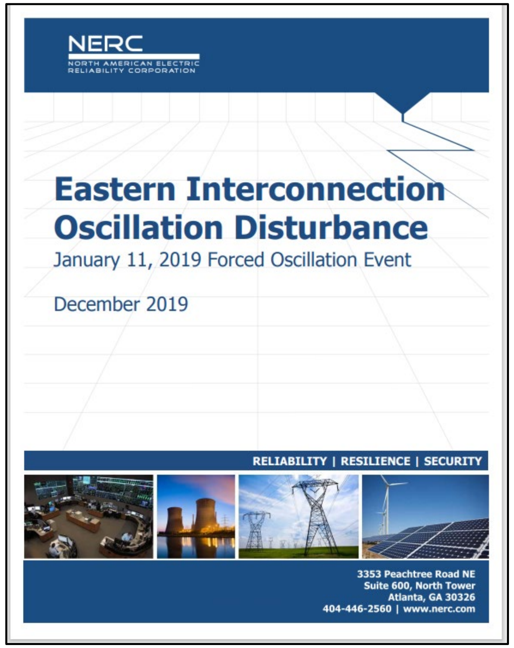
Background: Forced Oscillations

- Sustained oscillations due to equipment failure, inadequate control designs, and abnormal generator operating conditions.
- PMUs are critical in the ability to identify, monitor and mitigate forced oscillations.
- 24 major forced oscillation events reported in "NERC Reliability Guideline: Forced Oscillation Monitoring & Mitigation".
- Example events:
  - EI, 01/11/2019: 0.25 Hz, synchronous generator in Florida
  - WECC, 01/27-28/2022: 0.25 Hz, battery energy storage in Southern CA
  - WECC, 09/20, 11/2-3/2023: 0.20 Hz or 0.25 Hz, battery energy storage in Arizona







Multiple BESS-Induced Forced Oscillations Events in SRP

- During PV/BESS commissioning
- Interacted with WECC NS-A mode
- Forced oscillations observed across major Western Interconnection

September 20, 2023 IBR1 BESS Oscillation Summary

Figure Source: Matt Rhodes and Daniel Goodrich, "Recent BESS Oscillations: Root Cause Analysis and Wide-Area Impacts," NASPI Webinar, 7/10/2024

Date	WECC Impact	Root Cause	Source Type
09/20/2023	• NS-A mode • Oscillations across major WI	• Error in metering loss compensation methodology (Divided by zero)	Active power control issue
11/02/2023	• NS-A mode • Oscillations across major WI	• Differences in start-up timing across GSUs • GSU-level inverter setpoint polarity inversion	Active power control issue
11/03/2023	• NS-A mode • Oscillations across major WI	• PV output hardcode to 0 for testing (not actual PV output) leading to meter switching logic error	Active power control issue

NERC Recommended Practices & Mitigation Measures

- Three-phase, five-step approach to mitigate forced oscillations
- Source location and source type estimation are critical for system operators to mitigate forced oscillations

Phase I: Detection Oscillation

- **Step 1: Detect the Forced Oscillation**

Phase II: Characterizing Oscillation

- **Step 2: Determine Oscillation Frequency and Magnitude**
- **Step 3: Determine Extent of Oscillation**

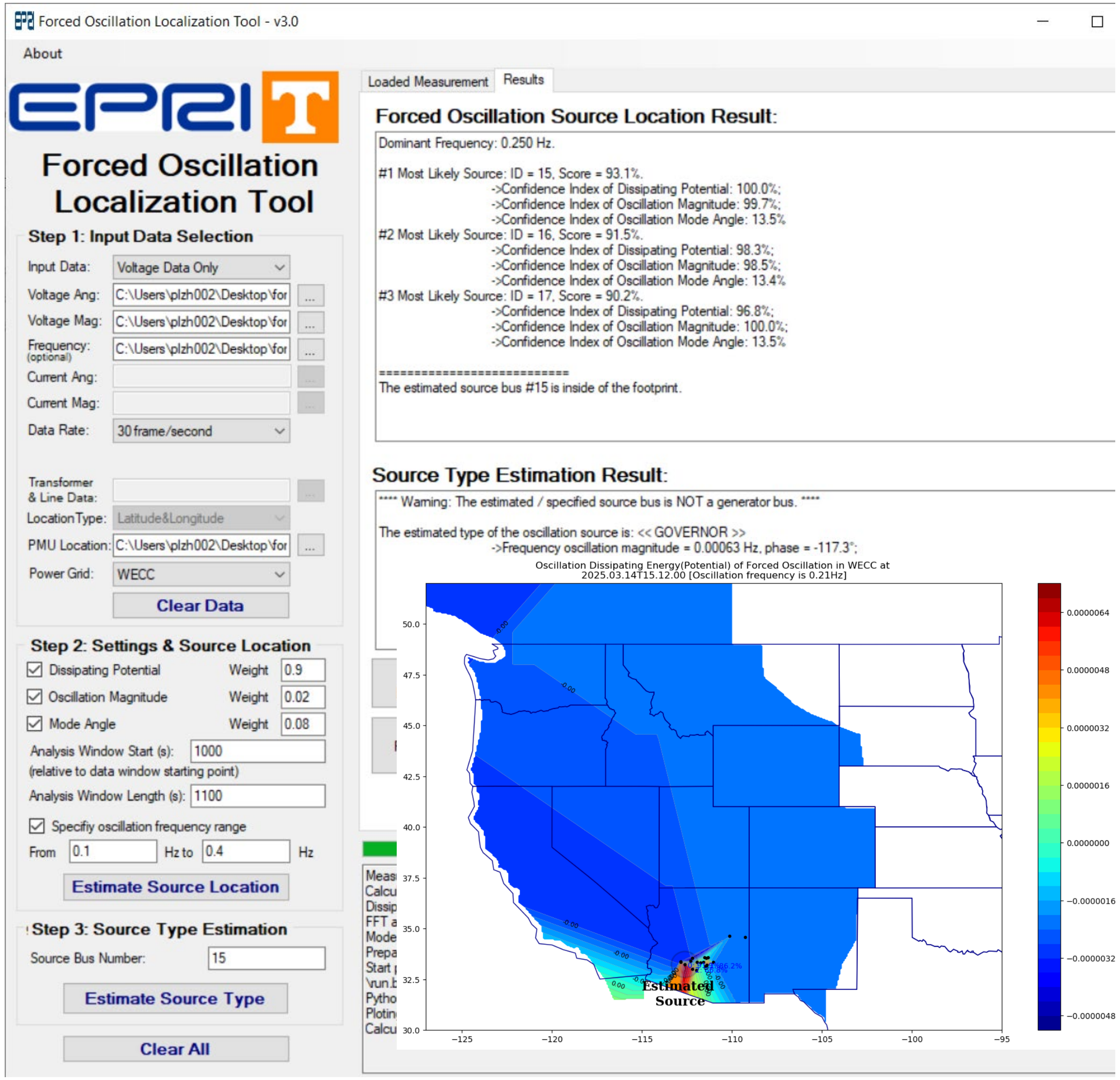
Phase III: Identifying Oscillation

- **Step 4: Determine Location or General Proximity of Oscillation**
- **Step 5: Determine Specific System Component Causing Oscillation**

Source: NERC Reliability Guideline: Forced Oscillation Monitoring & Mitigation Sept. 2017

Forced Oscillation Localization Tool (FOLT)

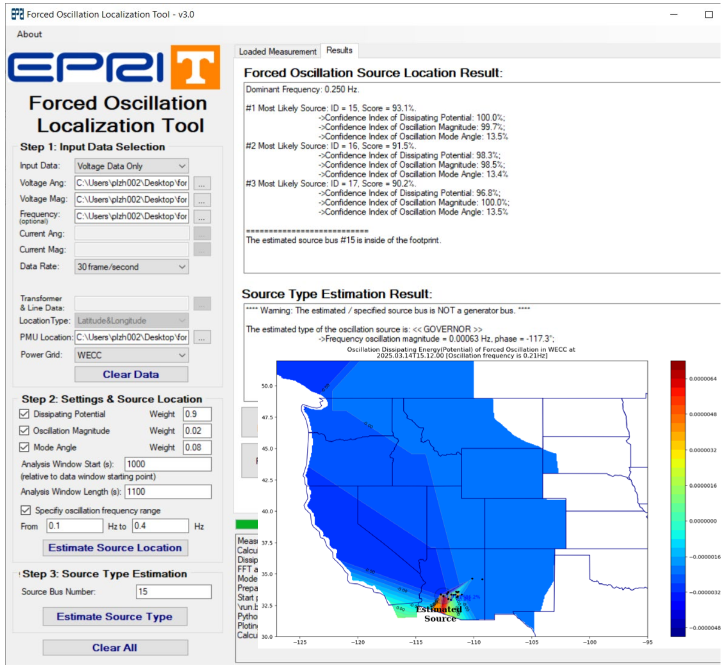
- Wide-band frequency oscillations (< 0.1 Hz to 15 Hz)
- Three different methods for oscillation source location
  - Dissipating Potential method
  - Oscillation Magnitude method
  - Oscillation Mode Angle method
- Source location estimation with confidence index
- Source type estimation: Active or reactive power control issue
- Inside/outside territory identification
  - Usually for interconnection wide forced oscillations
- Does not rely on system topology
- Does not require full grid PMU observability



Forced Oscillation Localization Tool (FOLT)

- Synthetic or recorded synchrophasor measurements as input

Configuration:
- Method selection and weight
- Data reporting rate
- Data window selection
- Frequency range selection



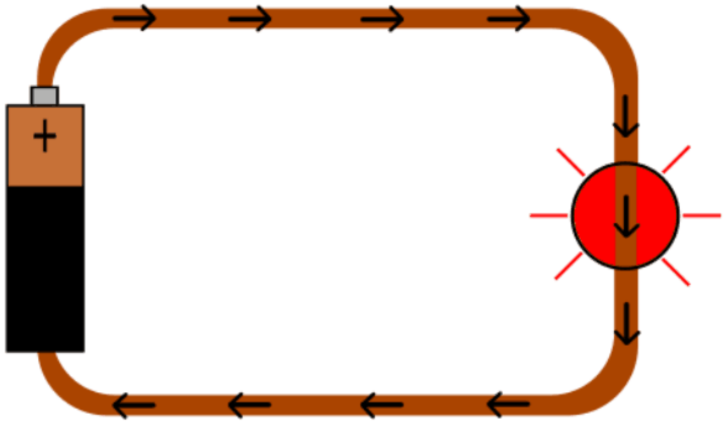
Input:
- **Voltage magnitude & angle**
- **Frequency**
- **PMU location: GPS coordinates/zip code/county name**
- Current magnitude & angle (optional)
- Line parameters (optional)

Output:
- Estimated source location with confidence index
- Estimated source type
- Inside/outside territory
- Other intermediate results, e.g., FFT analysis results

Dissipating Potential-Based Source Location Method

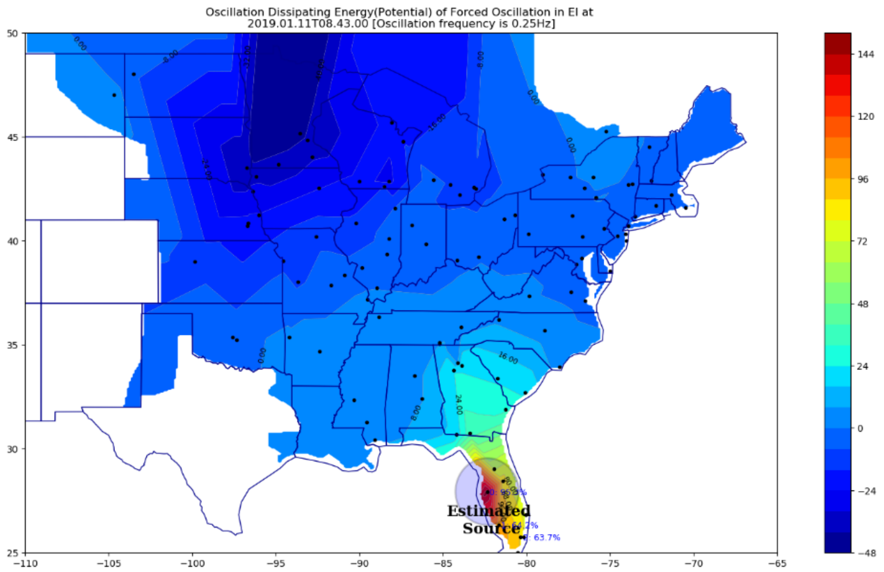
- Dissipating Potential (DP) method
  - Generated Dissipating Energy (DE) flows from source to other areas.
  - Estimate DE flow on virtual lines according to PMU locations with frequency and angle.
  - Estimate DP based on the estimated dissipating energy flow.
  - Dissipating energy flows from high DP area to low DP area. Source identified in bus with highest relative potential.
  - Method is assigned highest weight

Dissipating Energy (DE) flows from source to other areas



DC circuit: High voltage to Low voltage

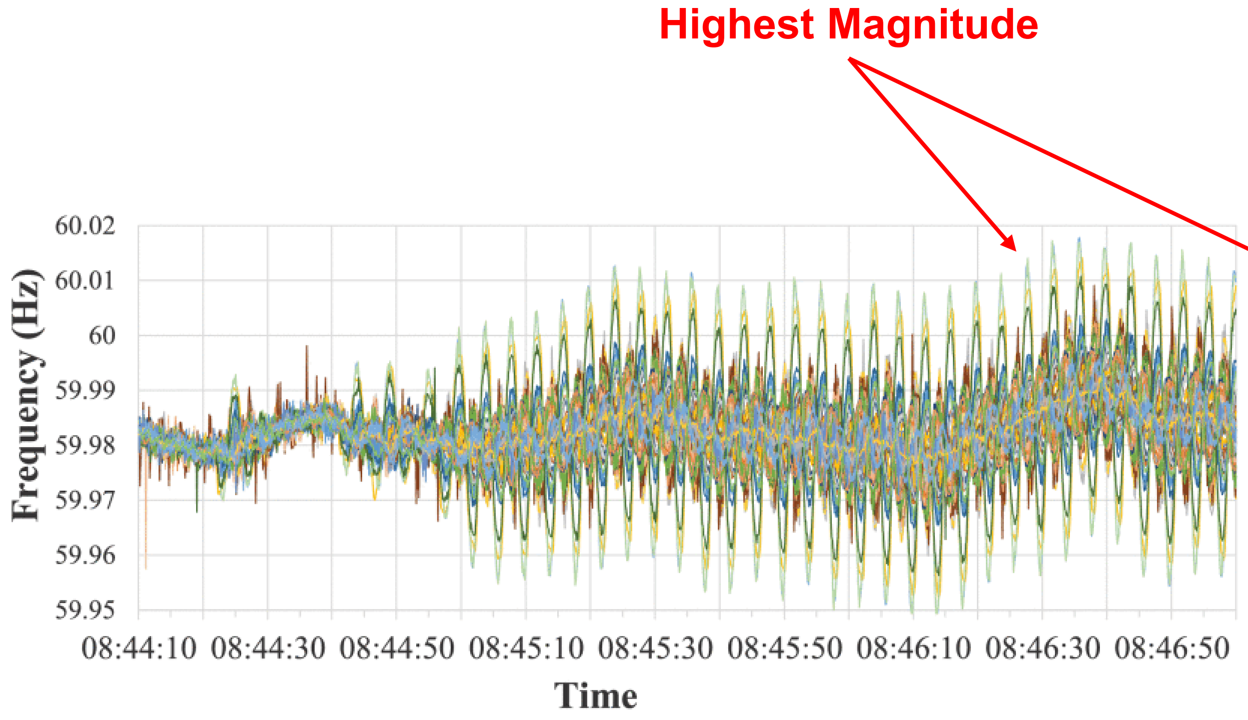
High DP

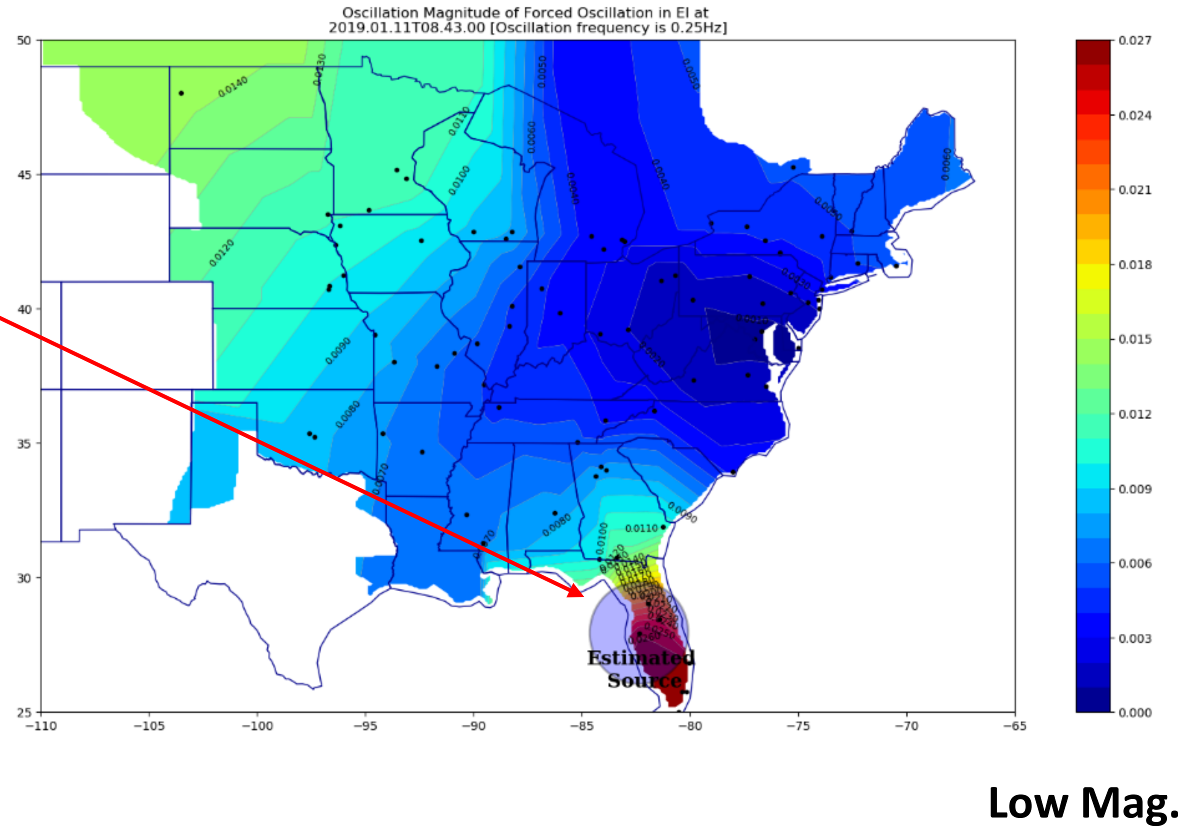


Low DP

Oscillation Magnitude-Based Source Location Method

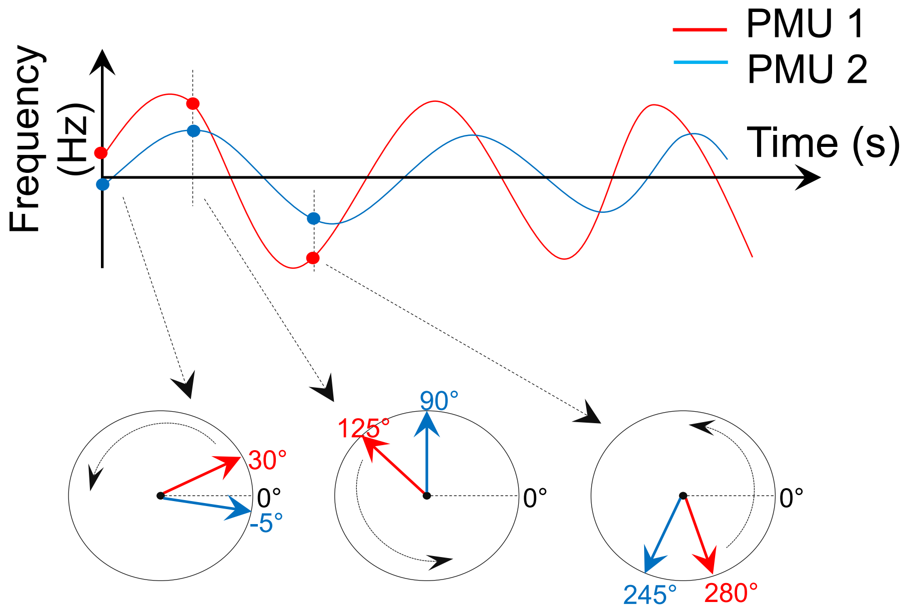
- Observations
  - Source area usually, but not always, has the highest oscillation magnitude
  - Method is assigned lowest weight



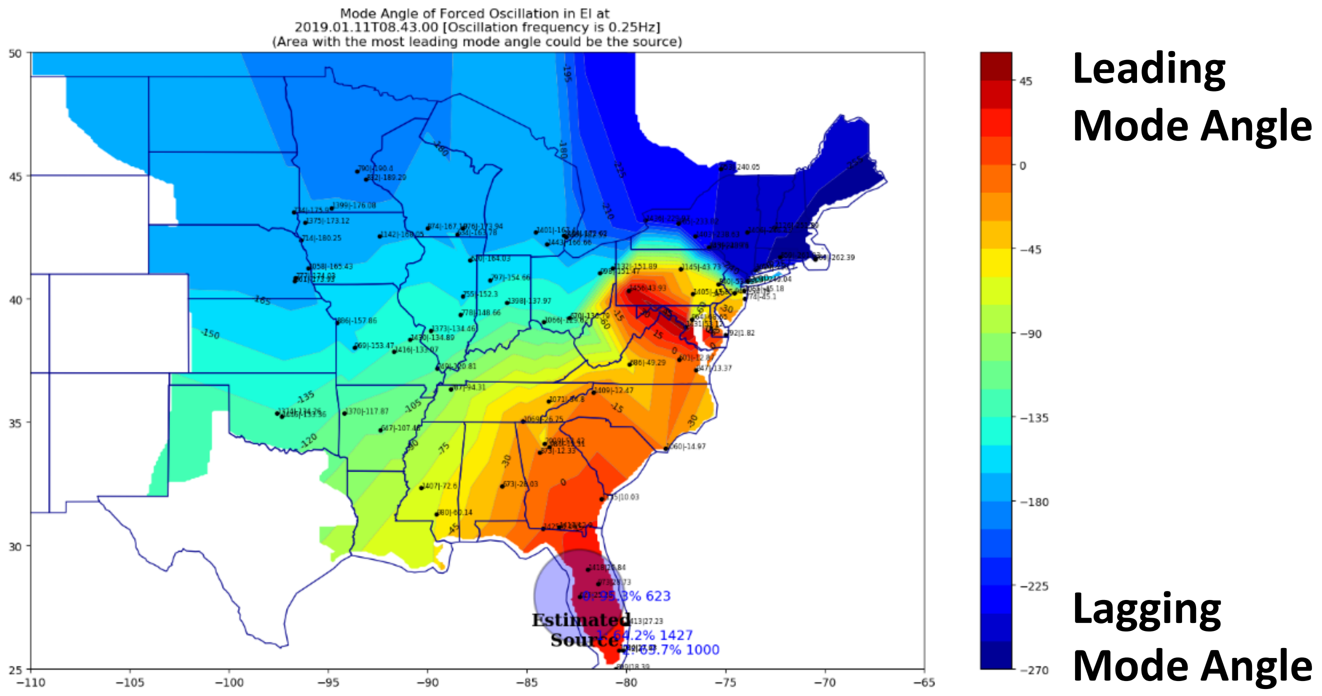


Oscillation Mode Angle-Based Source Location Method

- The dissipating energy flows from the oscillation mode angle leading area to the oscillation mode angle lagging area.
- Method does not require topology information and power measurements
  - Mode angle can be calculated from different types of measurements, e.g., frequency, voltage mag.
- Method is assigned intermediate weight.

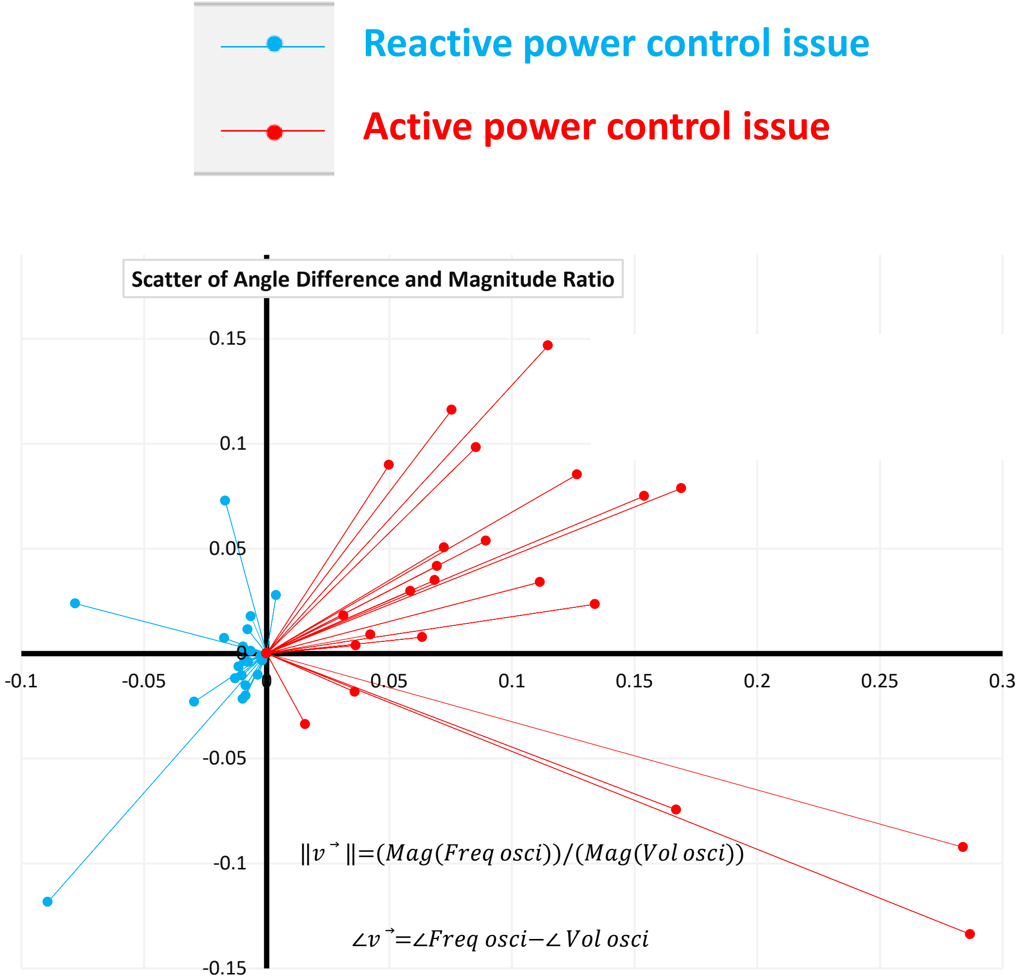


Oscillation Mode Angle
(PMU1 is leading PMU2 by 35°)



Source Type Estimation

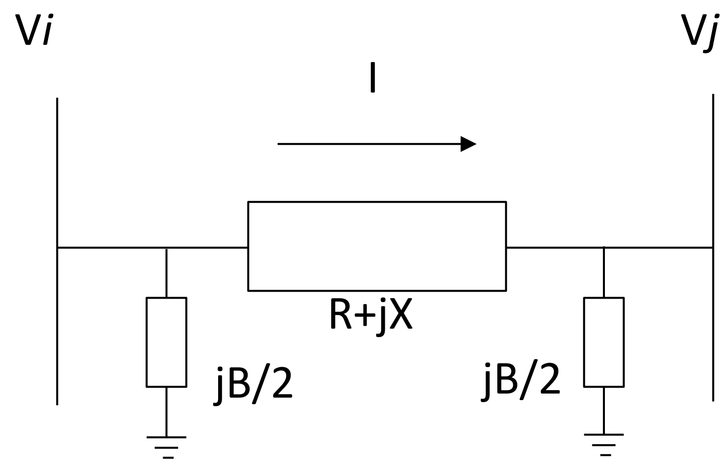
- Based on angle difference and magnitude ratio between frequency and voltage measurements
  - **Active power control issue (e.g., governor):**
    - Oscillation magnitude in frequency > voltage magnitude
    - Oscillation mode angle in frequency leading voltage
  - **Reactive power control issue (e.g., exciter):**
    - Oscillation magnitude in frequency < voltage magnitude
    - Oscillation mode angle in frequency lagging voltage



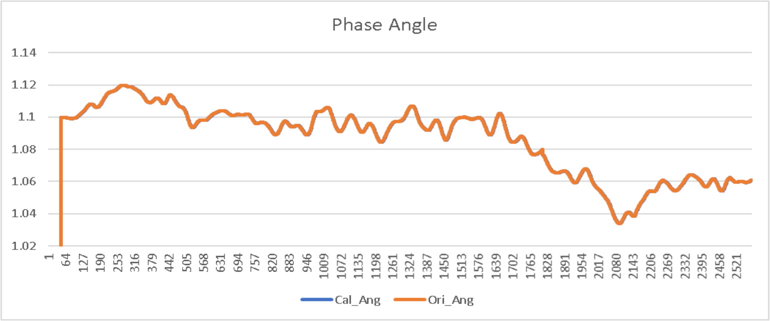
Angle difference and magnitude ratio between frequency and voltage measurements

Grid Observability Expansion Using Linear State Estimation

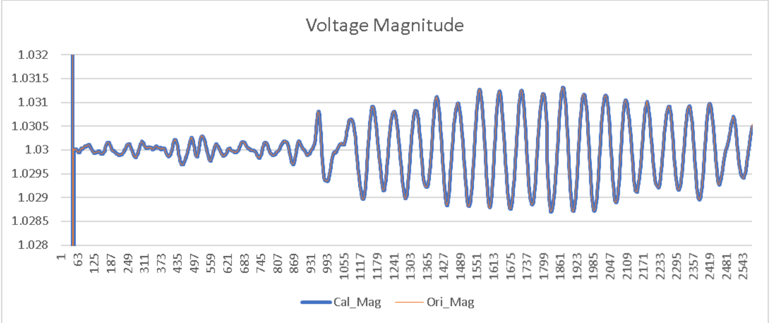
- **Improve grid observability by linear state estimation**: Estimate voltage magnitude and angle of unmonitored bus using voltage and current measurements from PMUs



Linear State Estimator
- Known: V*i*, I, R, B, X
- Unknown: V*j*

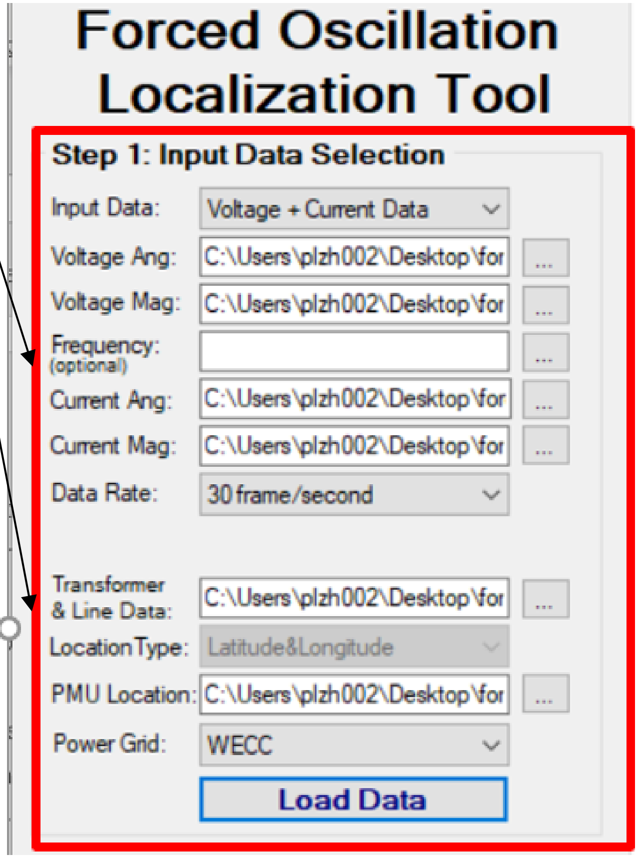


Voltage angle:
Estimated(blue) vs. actual(orange)



Voltage Magnitude
Estimated(blue) vs. actual(orange)

- Current measurements
- Line & Transformer data



SRP Case Study

- Received data from SRP
  - Actual PMU data of two actual oscillation events on 11/03/2023 and 09/20/2023
  - GPS coordinates of substations
- Data preprocessing was performed

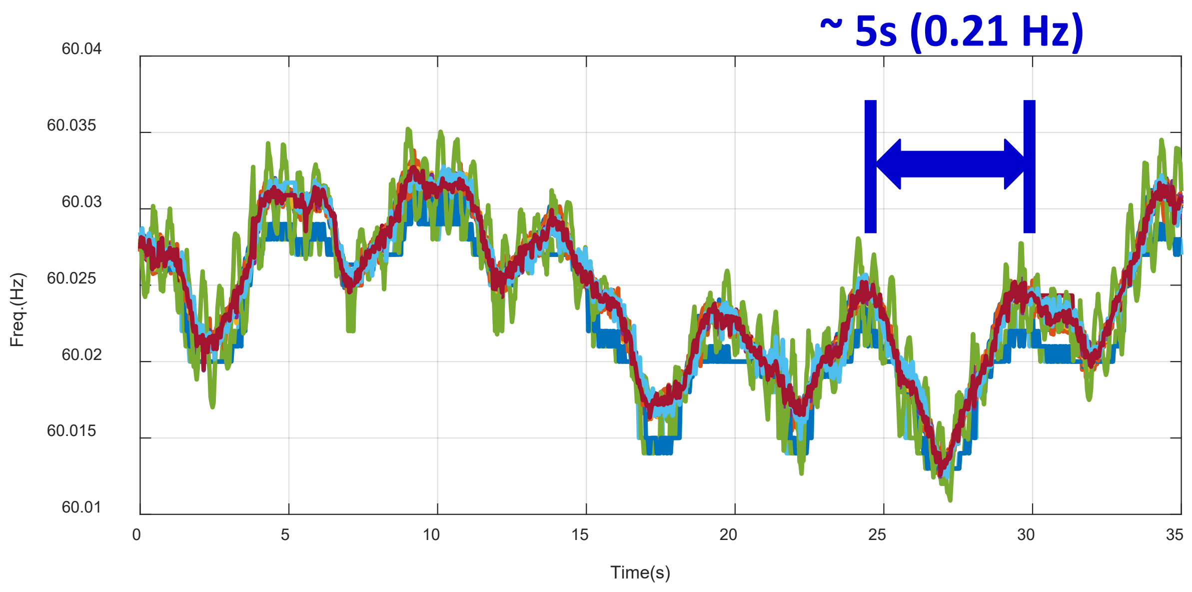
	Issue	Handling
1	No voltage angle (SRP did not download them)	Estimated voltage angle using frequency measurement
2	Missing data	Replaced with the value of previous data point
3	Channels with no data or constant values (e.g., 60 Hz)	This channel was ignored
4	V and f of 09/20/2023 event are in different data files	Matched V and f of the same PMU via name mapping
5	Data format	Converted into FOLT compatible format for V, δ, f, and GPS coordinates

Analysis Results of 09/20/2023 Oscillation Event

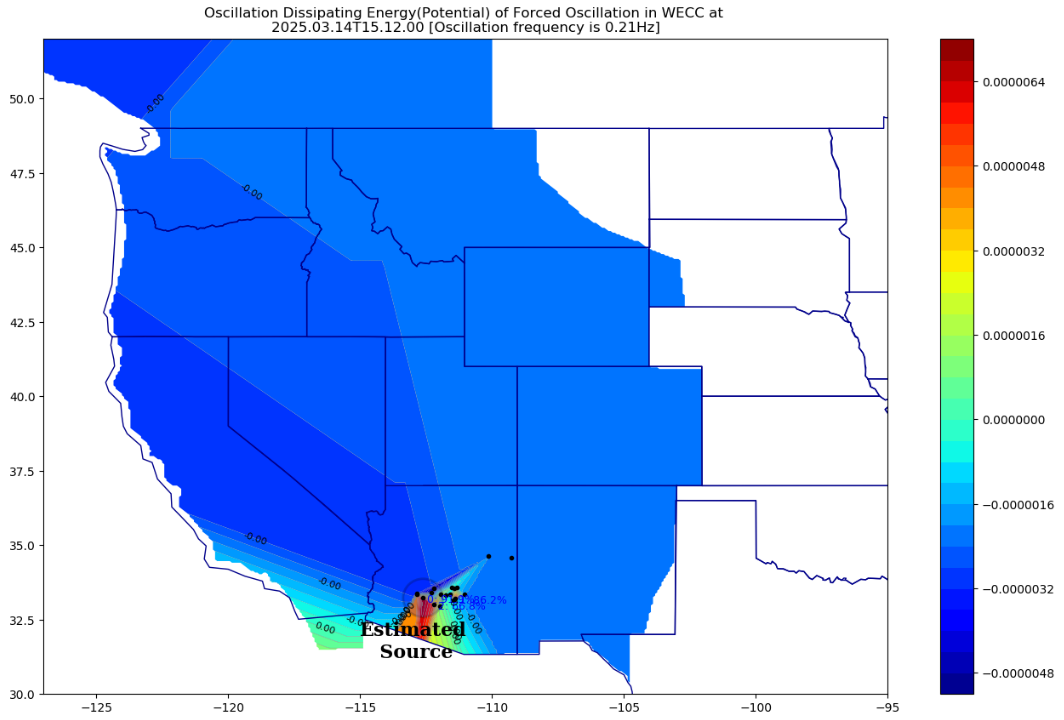
- Analysis results:
  - Oscillation frequency: 0.21 Hz
  - Source location: PV plant with BESS at Location 1
  - Source type: Active power issue
- Analysis results are correct and accurate

Location ID	Confidence Index
1	91.9%
14	86.2%
22	66.1%

Actual source location



Frequency measurements

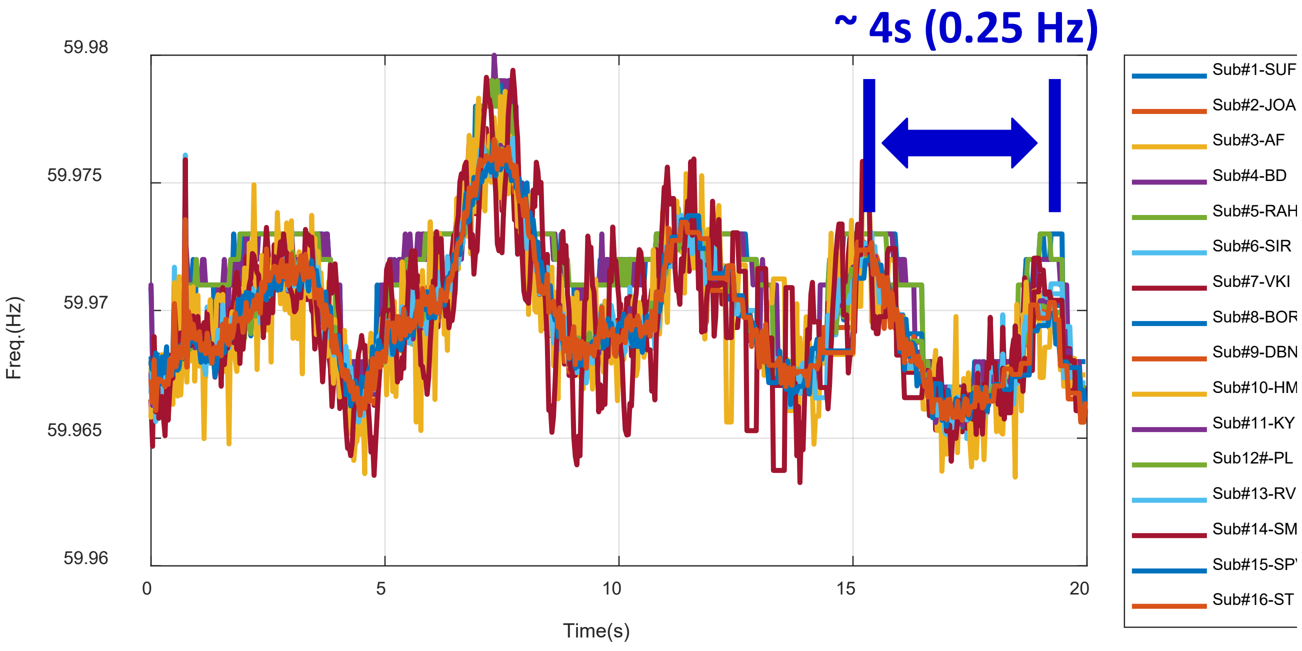


Analysis Results of 11/03/2023 Oscillation Event

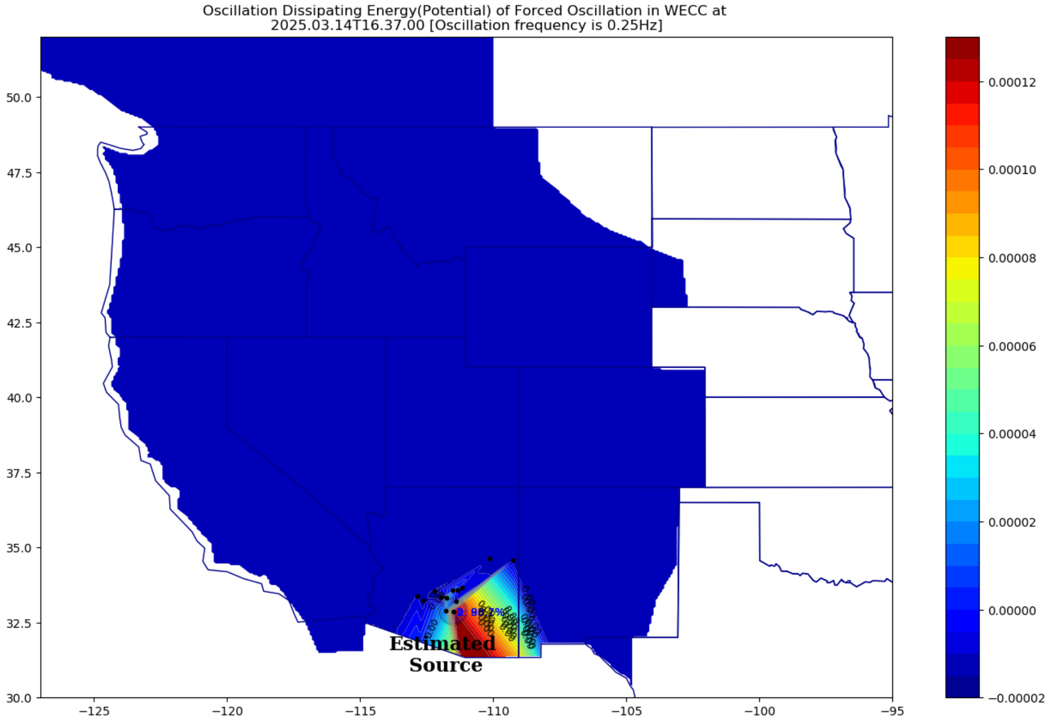
- Analysis Results:
  - Oscillation frequency: 0.25 Hz
  - Source location: PV plant with BESS
  - Source type: Active Power issue
- Analysis results are correct and accurate

Location ID	Confidence Index
15	93.1%
16	91.5%
17	90.2%

- Actual source location
- Different buses in the same plant



Frequency measurements



Summary and Next Steps

- Forced Oscillation Localization Tool
  - Wide-band frequency oscillation (< 0.1 Hz to 15 Hz)
  - Source location, source type, inside/outside identification
  - Does not rely on system topology
- Case study with SRP's actual PMU data
  - Data processing was performed, e.g., Angle estimation, missing data handling
  - Accurately estimated oscillation frequency, source location, and source type of both events
- Next steps
  - Use synchronized waveform data as input to detect and analyze high-frequency oscillations (Due to synchrophasor's limitations)
  - Field deployment of FOLT online tool

FOLT Online v1.0

- **Forced oscillation detection**
- **Source location estimation**
- **Source type estimation**
- **Inside/Outside identification**

Streaming synchrophasor data

openPDC

FOLT Online: Implemented as an openPDC adaptor + GUI

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