Interconnection-Wide Forced Oscillation Source Location: Method, Tool Development, and Actual Event Analysis

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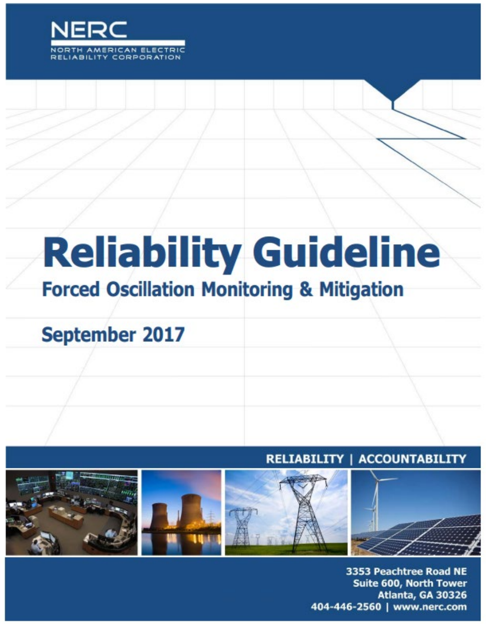
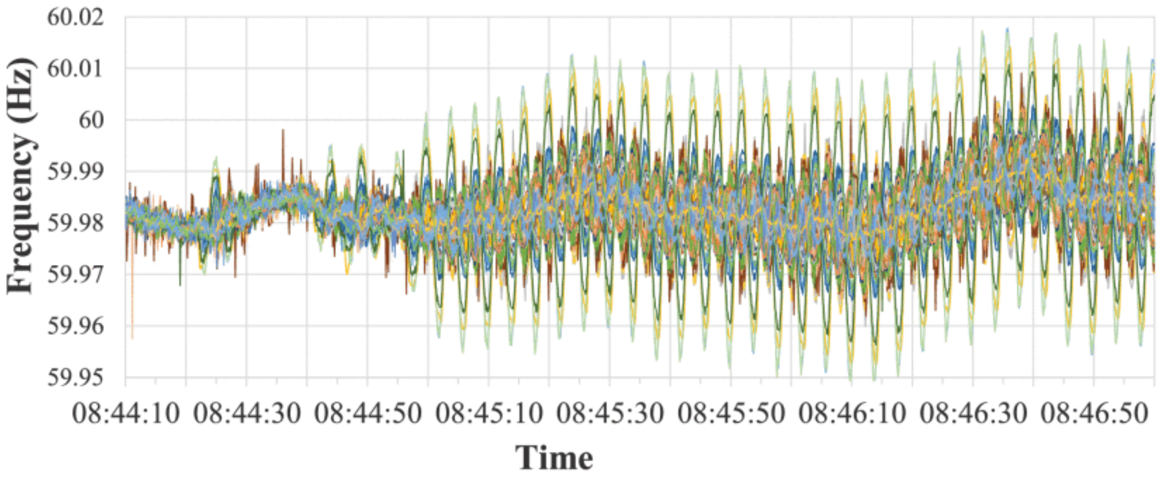
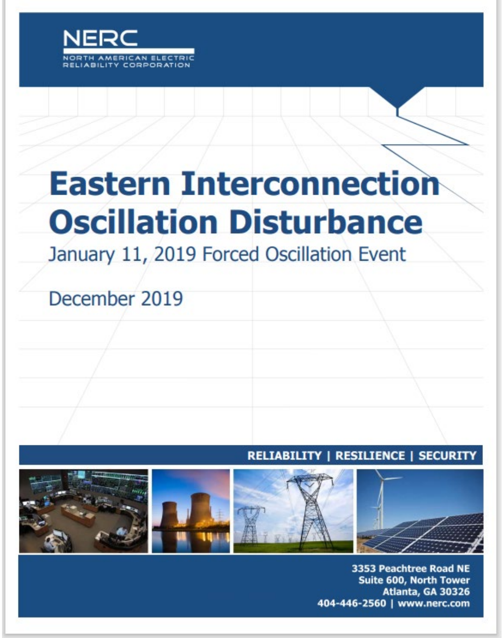
Forced Oscillation - Background

- Sustained oscillations due to equipment failure, inadequate control designs, and abnormal generator operating conditions.
- PMUs 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 Sep. 2017
- More recent oscillation events:
  - WECC, 01/27-28/2022: 0.25Hz, battery energy storage in Southern CA
  - EI, 01/11/2019: 0.25 Hz, generator in Florida

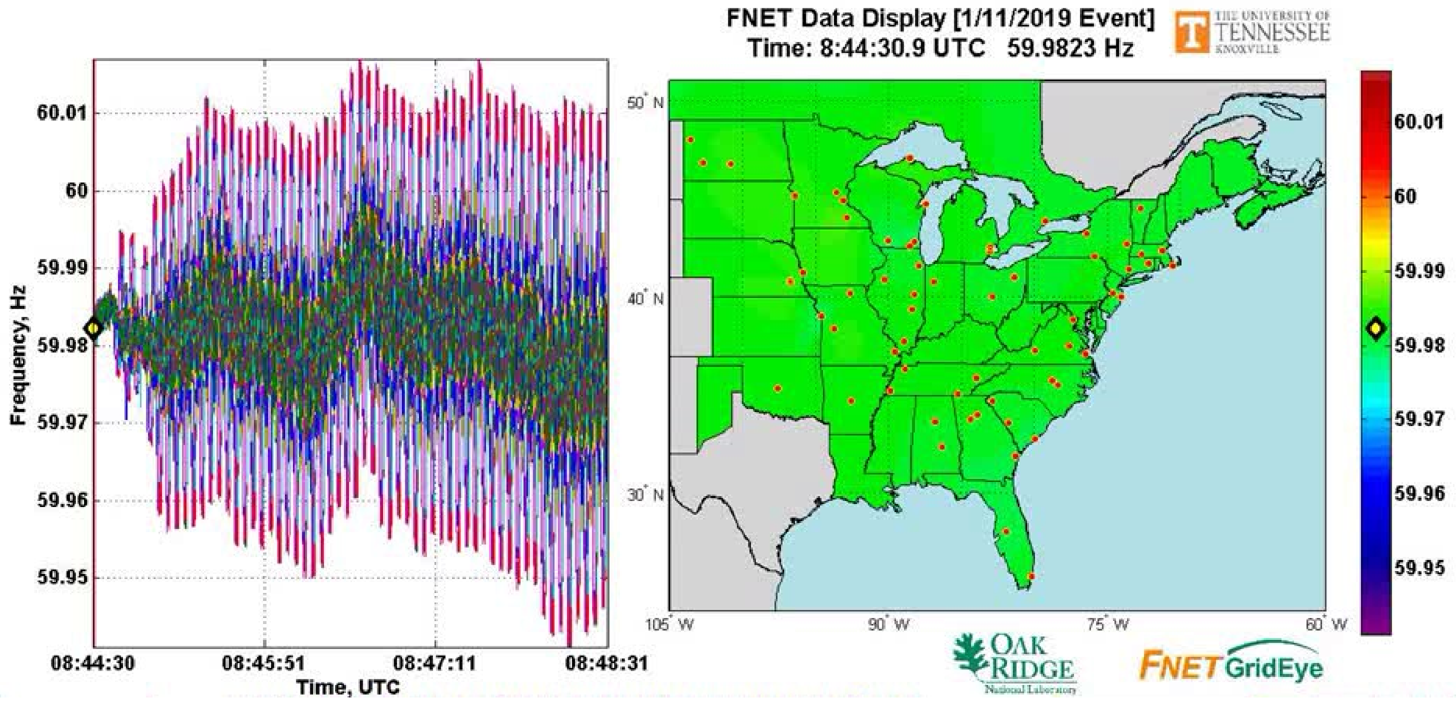


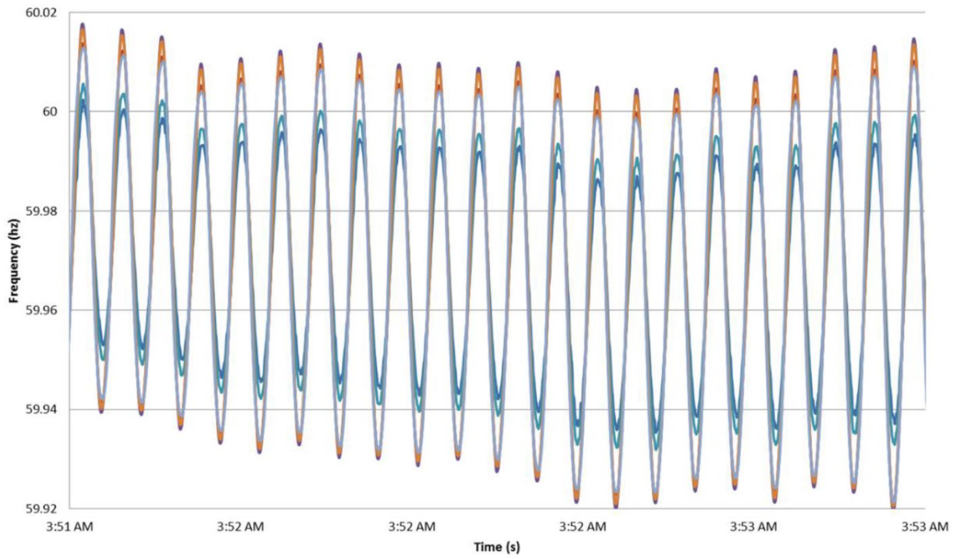




Jan. 11, 2019 Forced Oscillation Event

- 0.25 Hz oscillation observed across entire EI
- Duration > 18 minutes
- The source unit experienced oscillations of around 200 MW peak-to-peak; Power swings were observed as far as the New England area of about 50 MW

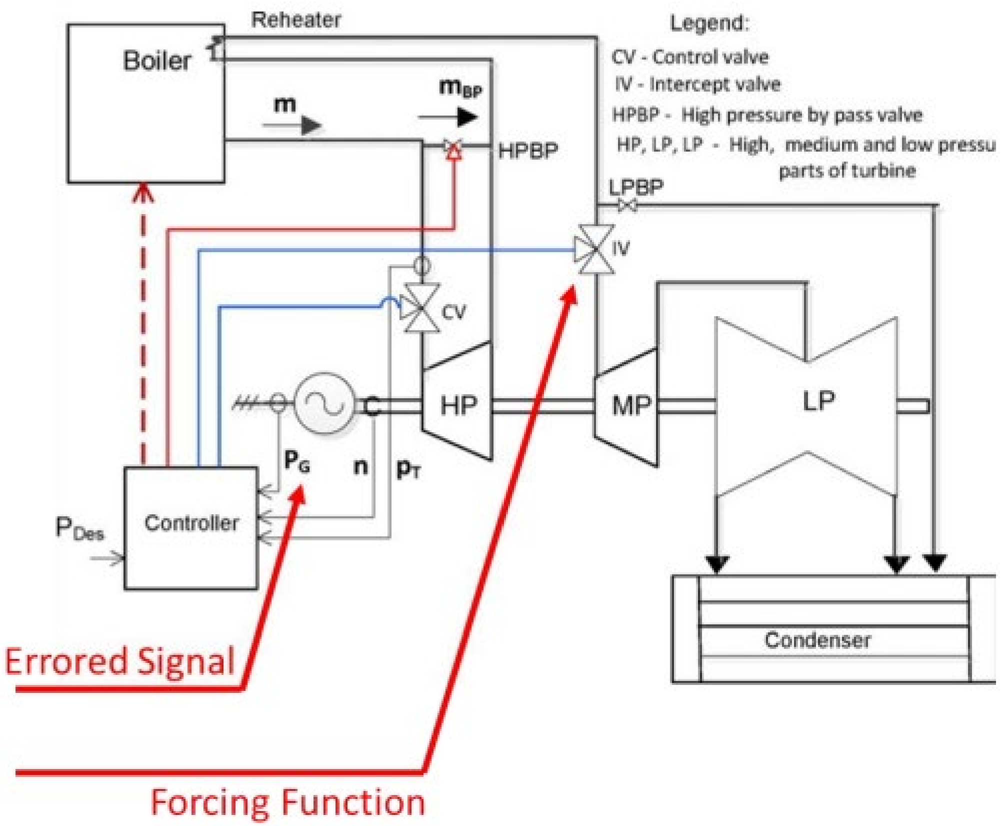




Frequencies in FPL Footprint

Jan. 11, 2019 Forced Oscillation Event

- Errored voltage measurement due to a failed PT connection
- Power load imbalance (PLI) turbine controls closed and opened the intercept valves about every four seconds, causing oscillation of a steam turbine at a combined-cycle power plant
- Interaction with EI 0.25Hz natural oscillation mode among ISO-NE, MISO, and FRCC

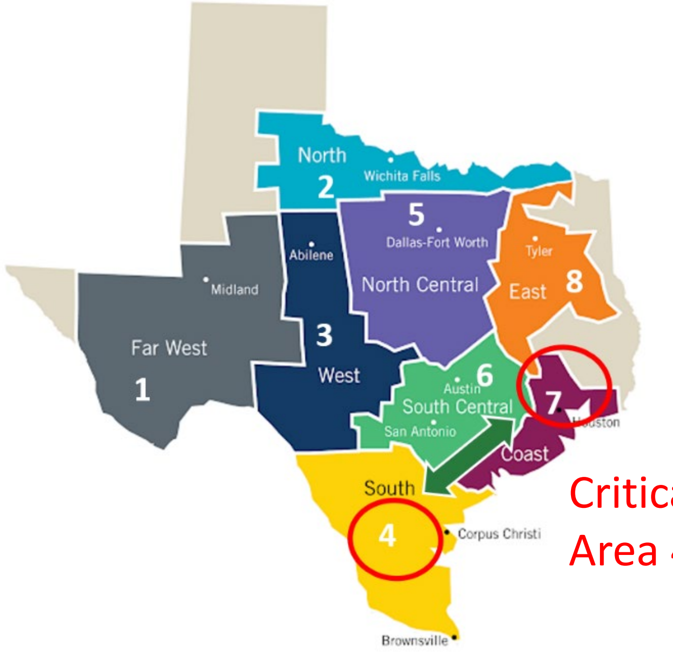


Source: NERC, Eastern Interconnection Oscillation Disturbance January 11, 2019 Forced Oscillation Event. December 2019.

A Comprehensive Method to Mitigate Forced Oscillations

Planning

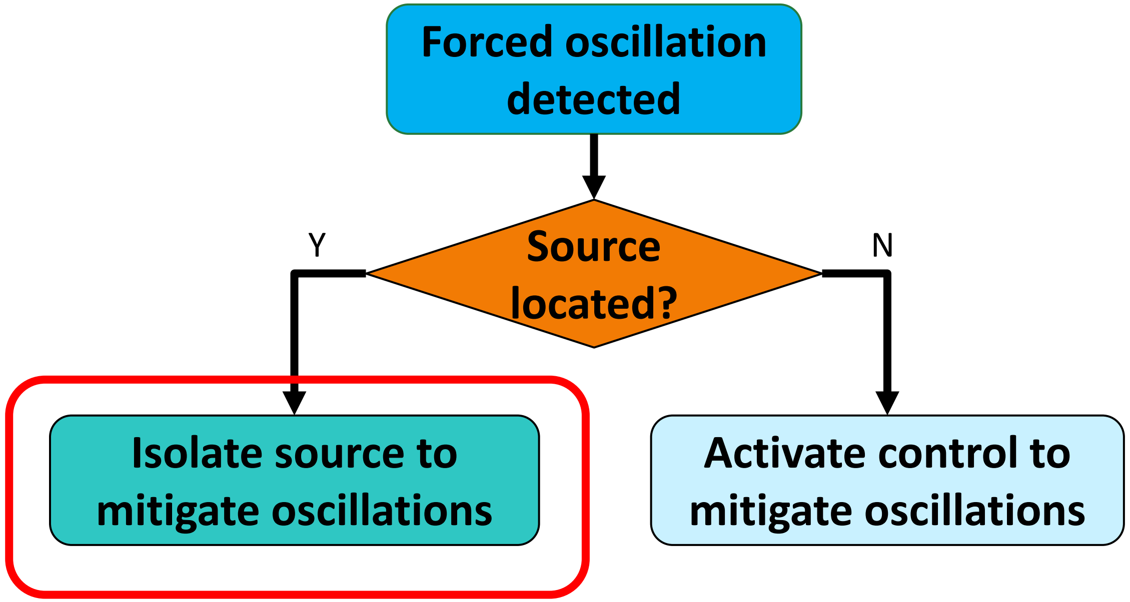
- Better understanding of potential forced oscillations by offline simulations
  - Identify potential resonance
  - Identify areas prone to forced oscillation
  - Identify critical location for controller



Critical area:
Area 4, Zone 21

Operation

- <u>**Forced oscillation source location**</u>
- Use of Inverter-Based Resources (e.g., Battery Energy Storage Systems) to suppress magnitude of forced oscillations



Forced Oscillation Localization Tool (FOLT)

- Three different methods for source location
- Source location estimation with confidence index
- Source type estimation: Governor or Exciter
- Does not rely on system topology

Configuration:
- Method selection and weight
- Data reporting rate
- Data window selection, etc.

Input:
- Voltage mag.
- Voltage angle
- Frequency (optional)
- PMU location: GPS coordinates/zip code/county name

Forced Oscillation Localization Tool

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

Dissipating Potential-Based Source Location Method

- Dissipating Potential (DP) method
  - Estimate Dissipating Energy (DE) flow between PMU locations with frequency and angle.
  - Dissipating energy flows from high DP area to low DP area. Estimate DP based on the estimated dissipating energy flow.
  - Source identified in bus with highest relative potential

$$DE_{ij} \approx \sum (\Delta A_i - \Delta A_j)\Delta f_i$$

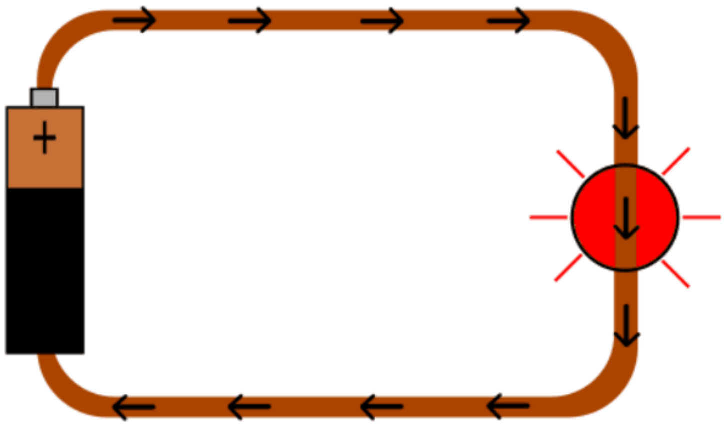
Estimated DE flow from PMU i to j

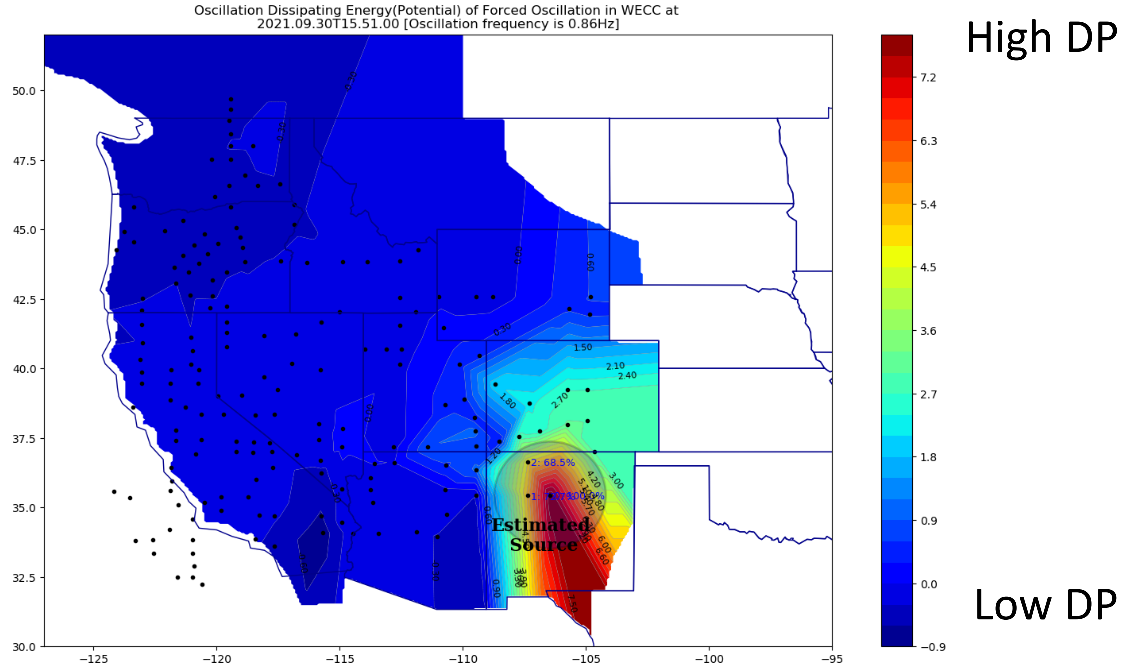
Volt. Angle of PMU i and j

Frequency of PMU i

$$P_i - P_j \approx DE_{ij}$$

Estimated DP at PMU i and j





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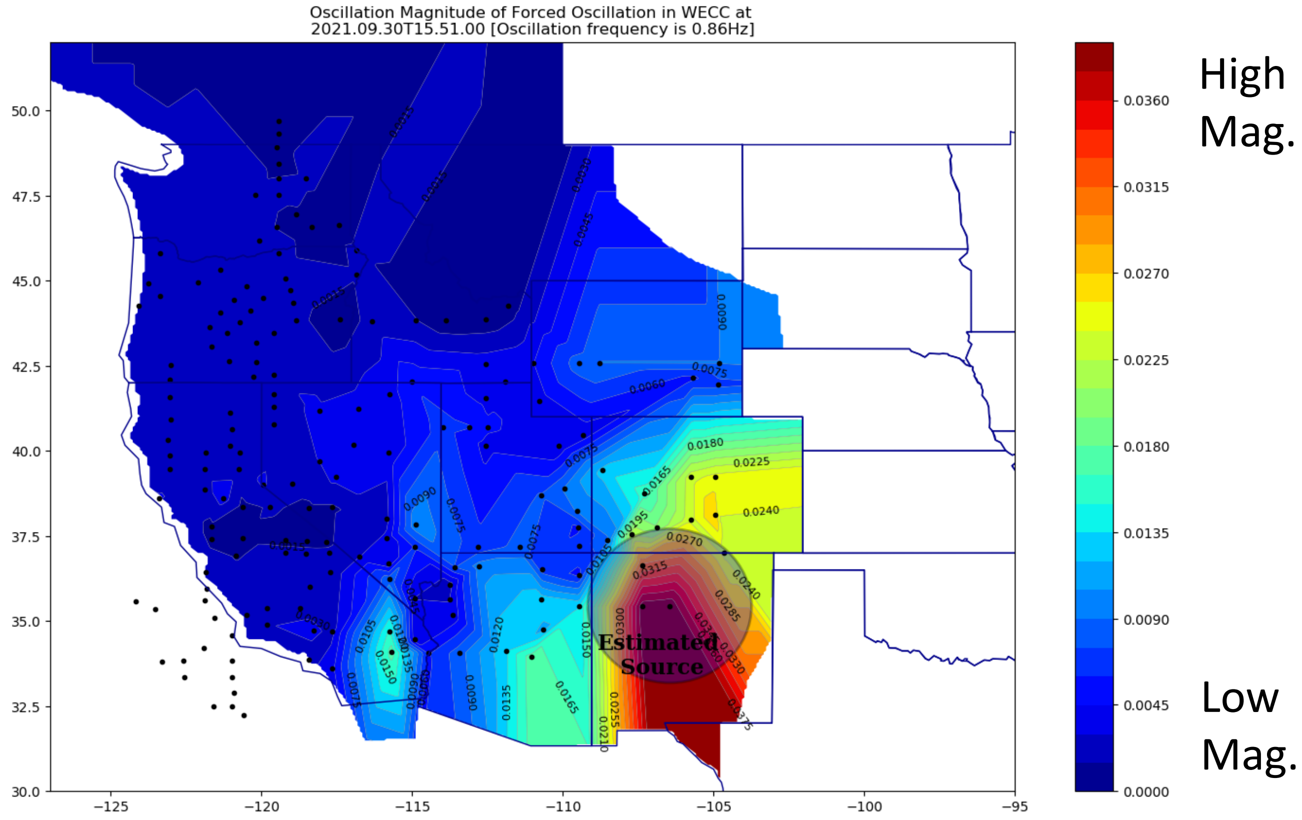
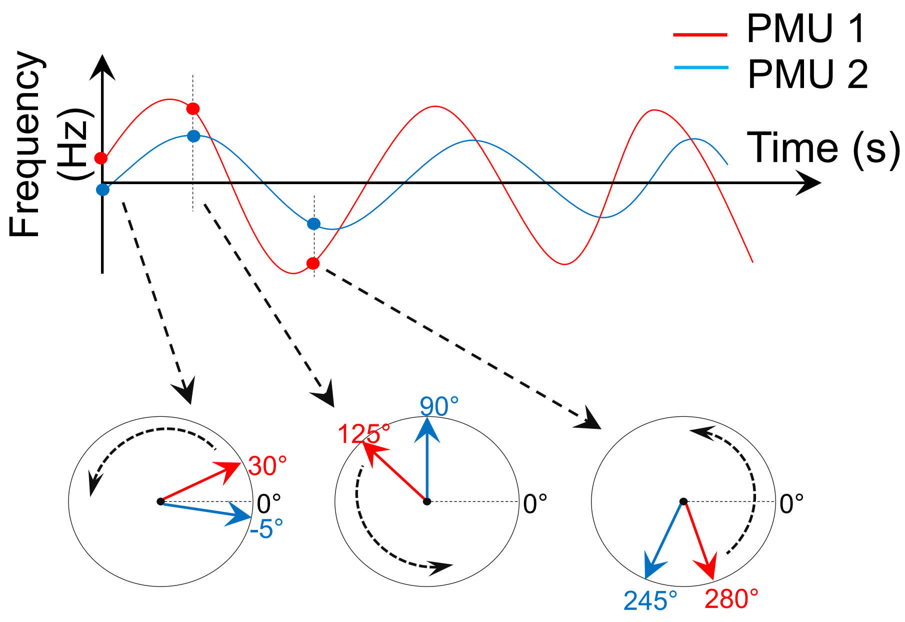
Oscillation Magnitude-Based Source Location Method

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

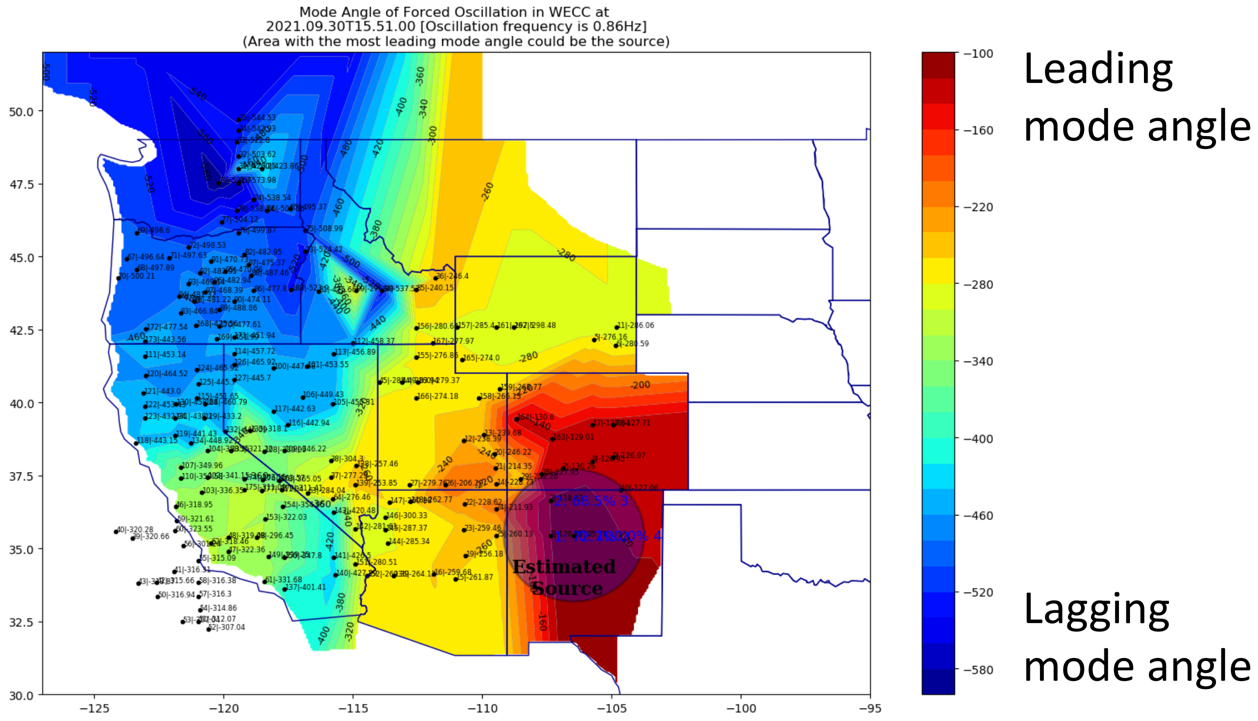


Oscillation Mode Angle-Based Source Location Method

- 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°)



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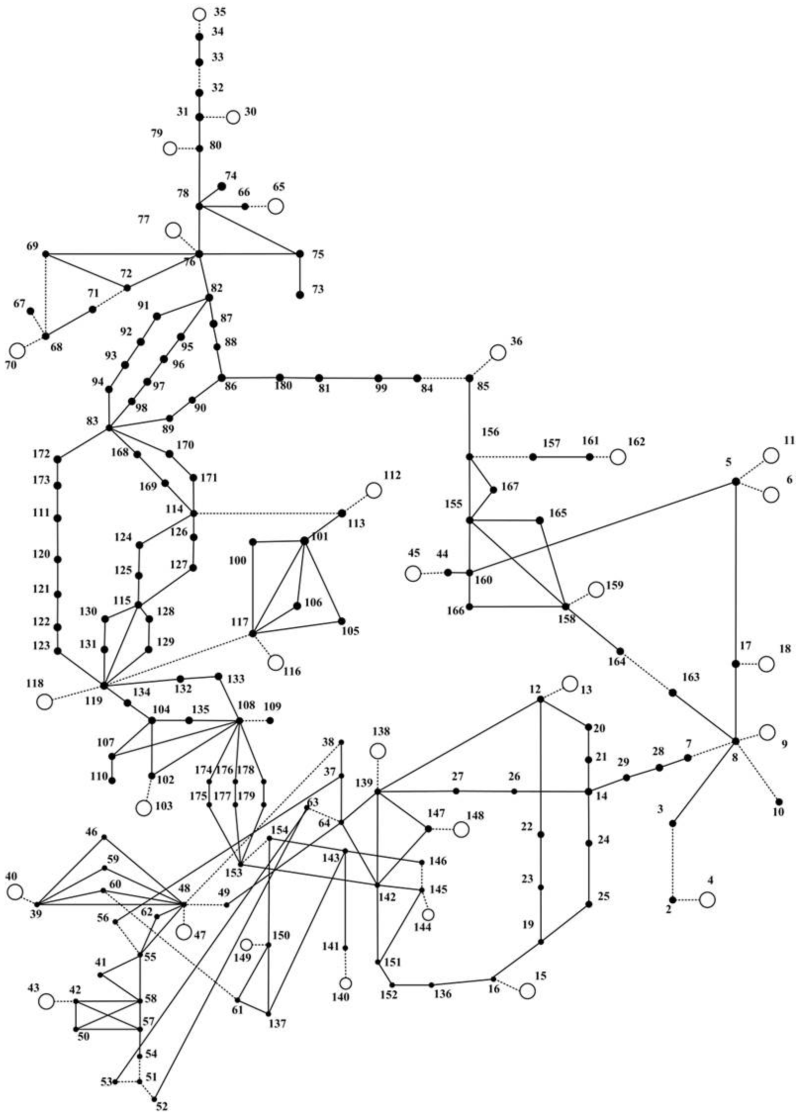
IEEE Test Cases Library of Power System Sustained Oscillations

- Test cases
  - Based on reduced 179-bus WECC model
  - Full observability
- Provided data
  - Bus voltage magnitude (179)
  - Bus voltage angle (179)
  - Line/Transformer current magnitude (526)
  - Line/Transformer current angle (526)
  - Rotor speed (29)
  - Rotor angle (29)
- Bus voltage angle & magnitude and PMU GPS coordinates are used only

Source: https://web.eecs.utk.edu/~kaisun/Oscillation/index.html



Reduced 179-bus WECC model

FOLT Test Results: Summary

* Cases F_7_1, FM_7_1, F_7_2: Two sources. Currently, FOLT cannot handle two sources.

Case #	Type of injected signal	Disturbance Controller	Oscillation Freq. (Hz)	Source Location	FOLT Estimation Results	Correct?
F_1	Sinusoidal	Exciter	0.86	4	4 (Exciter)	✓
F_2	Sinusoidal	Exciter	0.86	79	79 (Exciter)	✓
F_3	Sinusoidal	Exciter	0.37	77	77 (Exciter)	✓
F_4_1	Sinusoidal	Exciter	0.81	79	79 (Exciter)	✓
F_4_2	Sinusoidal	Exciter	0.85	79	79 (Exciter)	✓
F_4_3	Sinusoidal	Exciter	0.89	79	79 (Exciter)	✓
F_5_1	Sinusoidal	Exciter	0.42	79	79 (Exciter)	✓
F_5_2	Sinusoidal	Exciter	0.46	79	79 (Exciter)	✓
F_5_3	Sinusoidal	Exciter	0.50	79	79 (Exciter)	✓
F_6_1	Periodic, rectangular	Exciter	0.1	79	79 (Exciter)	✓
F_6_2	Periodic, rectangular	Exciter	0.2	79	79 (Exciter)	✓
F_6_3	Periodic, rectangular	Exciter	0.4	79	79 (Exciter)	✓
F_7_1	Sinusoidal	Exciter	0.65 & 0.43	79 & 118	Incorrect (multiple modes)	×
F_7_2	Sinusoidal	Exciter	0.43	70 & 118	Incorrect (multiple locations)	×
FM_1	Sinusoidal	Governor	0.86	4	4 (Governor)	✓
FM_3	Sinusoidal	Governor	0.37	77	77 (Governor)	✓
FM_6_2	Periodic, rectangular	Governor	0.2	79	79 (Governor)	✓
FM_7_1	Sinusoidal	Governor	0.65 & 0.43	79 &118	Incorrect (multiple modes)	×

Results of Test Case F_1

- Test case F_1
  - **Exciter**, sinusoidal, one source
  - 0.86 Hz at Bus 4
- Estimation results of FOLT:
  - 0.86 Hz at Bus 4 with 100% confidence index
  - Source type: Exciter

Forced Oscillation Analysis Result

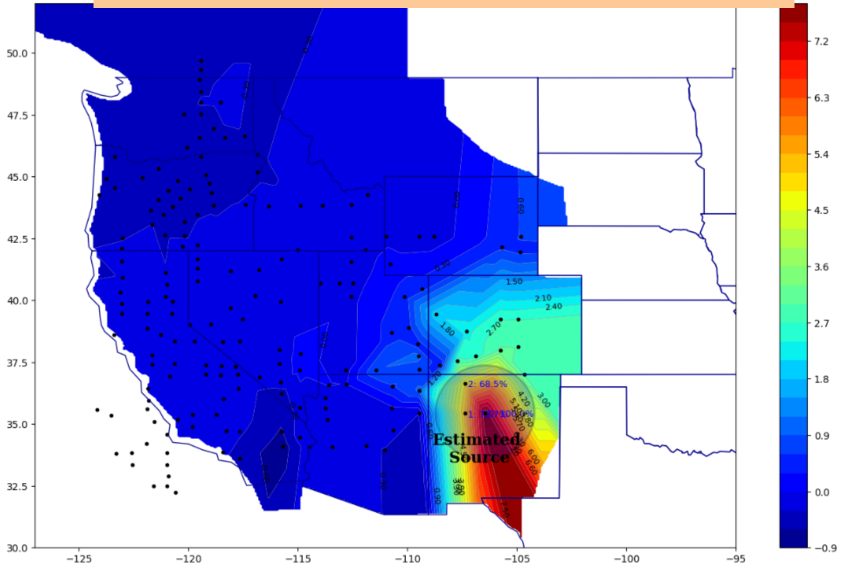
Dominant Frequency: 0.860 Hz.

#1 Most Likely Source: ID = 4, Score = 100.0%.
->Confidence Index of Dissipating Potential: 100.0%;
->Confidence Index of Oscillation Magnitude: 100.0%;
->Confidence Index of Oscillation Mode Angle: 100.0%
#2 Most Likely Source: ID = 2, Score = 72.7%.
->Confidence Index of Dissipating Potential: 67.4%;
->Confidence Index of Oscillation Magnitude: 99.1%;
->Confidence Index of Oscillation Mode Angle: 93.6%
#3 Most Likely Source: ID = 3, Score = 68.5%.
->Confidence Index of Dissipating Potential: 62.4%;
->Confidence Index of Oscillation Magnitude: 76.2%;
->Confidence Index of Oscillation Mode Angle: 94.3%

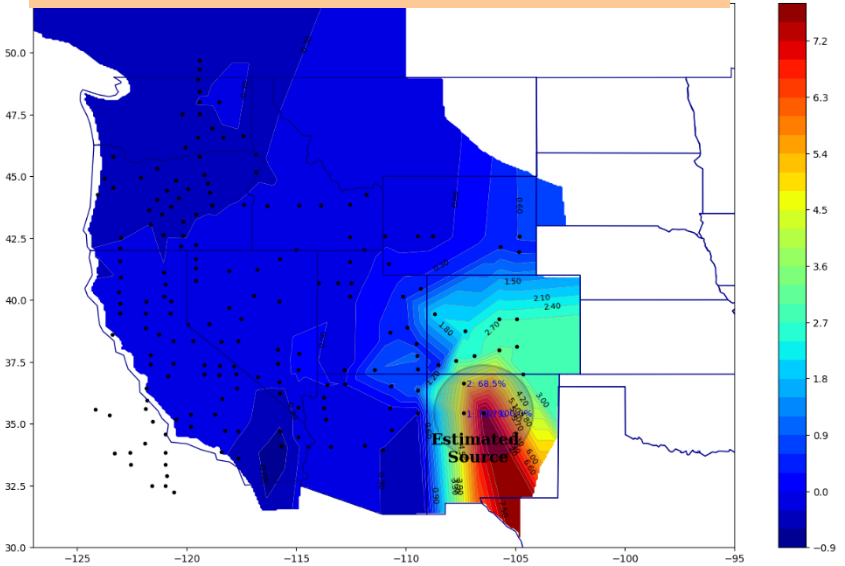
Source Type Estimation Result:

The estimated type of the oscillation source is: << EXCITER >>
->Frequency oscillation magnitude = 0.04100 Hz, phase = -153.5°;
->Voltage oscillation magnitude = 0.04316 p.u., phase = 48.5°.

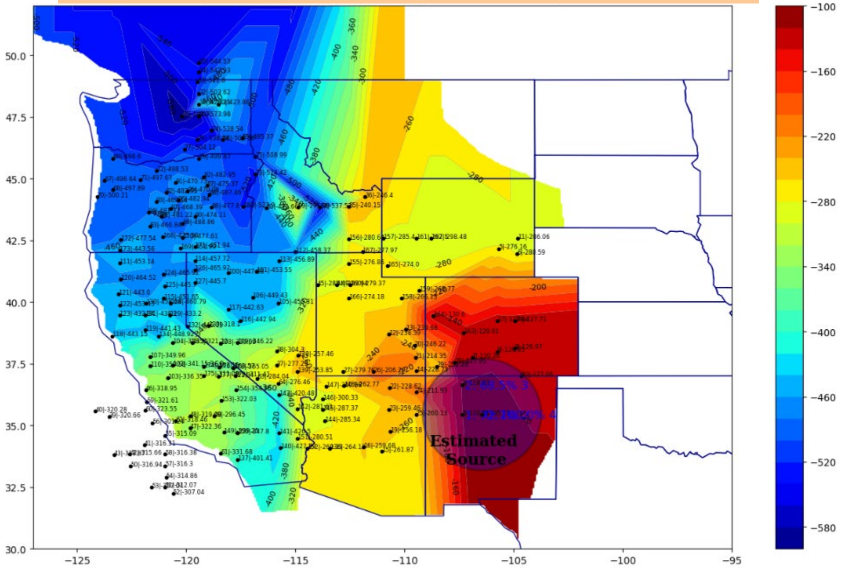
Dissipating Potential-Based



Oscillation Magnitude-Based



Oscillation Mode Angle-Based



Results of Test Case FM_3

- Test case FM_3
  - **Governor**, sinusoidal, one source
  - 0.37 Hz at Bus 77
- Estimation results of FOLT:
  - 0.37 Hz at Bus 77 with 93.9% confidence index
  - Source type: Governor

Forced Oscillation Source Location Result:

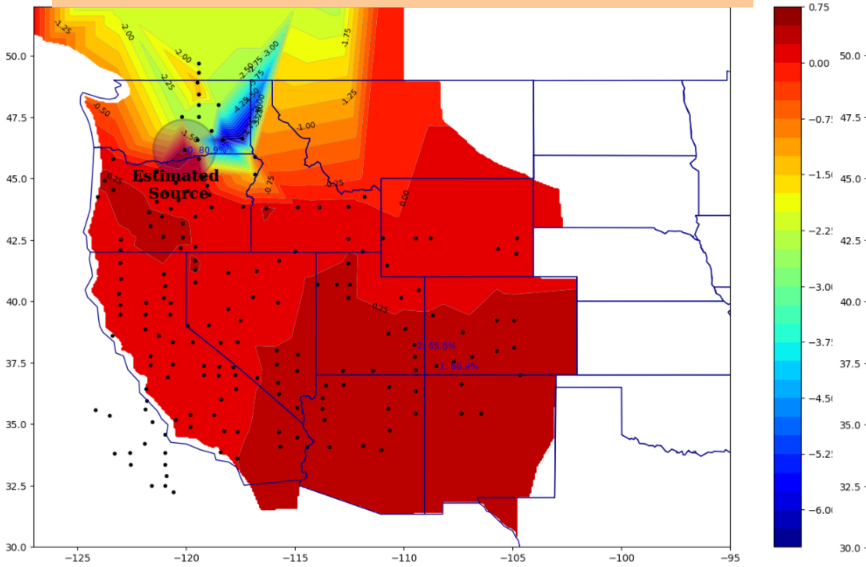
Dominant Frequency: 0.370 Hz.

#1 Most Likely Source: ID = 77, Score = 93.9%.
->Confidence Index of Dissipating Potential: 100.0%;
->Confidence Index of Oscillation Magnitude: 20.6%;
->Confidence Index of Oscillation Mode Angle: 43.7%
#2 Most Likely Source: ID = 76, Score = 62.9%.
->Confidence Index of Dissipating Potential: 66.0%;
->Confidence Index of Oscillation Magnitude: 11.5%;
->Confidence Index of Oscillation Mode Angle: 40.7%
#3 Most Likely Source: ID = 72, Score = 57.8%.
->Confidence Index of Dissipating Potential: 60.3%;
->Confidence Index of Oscillation Magnitude: 11.5%;
->Confidence Index of Oscillation Mode Angle: 40.8%

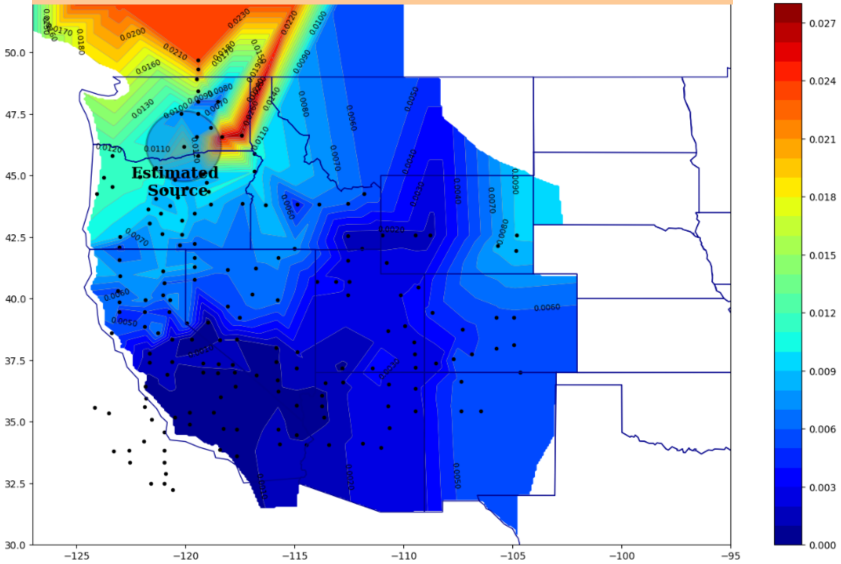
Source Type Estimation Result:

The estimated type of the oscillation source is: << GOVERNOR >>
->Frequency oscillation magnitude = 0.01214 Hz, phase = -60.2°;
->Voltage oscillation magnitude = 0.00171 p.u., phase = -8.6°.

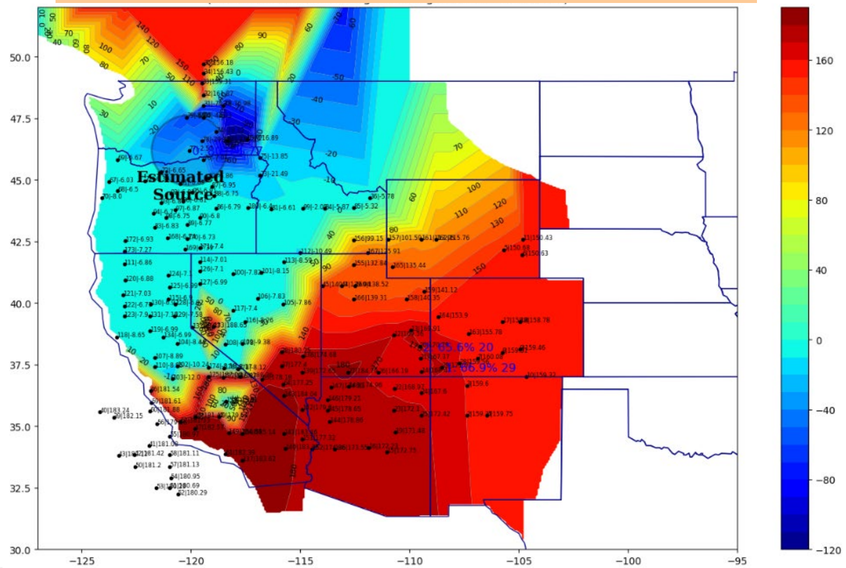
Dissipating Potential-Based



Oscillation Magnitude-Based



Oscillation Mode Angle-Based



EI 01/11/2019 Forced Oscillation Event

- Actual measurements collected during the oscillation event
- Actual source location: Florida
- FOLT suggested source location: Florida
- FOLT suggested source type: Governor

Forced Oscillation Source Location Result:

Dominant Frequency: 0.250 Hz.

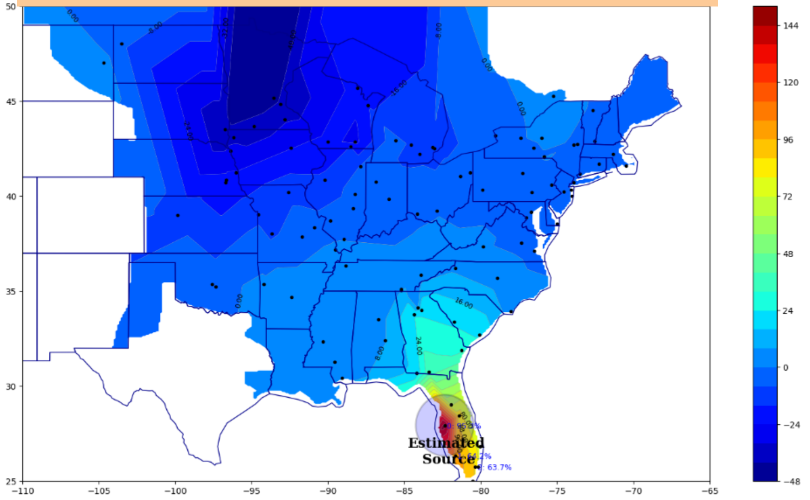
#1 Most Likely Source: ID = 623, Score = 99.9%.
->Confidence Index of Dissipating Potential: 100.0%;
->Confidence Index of Oscillation Magnitude: 96.6%;
->Confidence Index of Oscillation Mode Angle: 100.0%
#2 Most Likely Source: ID = 899, Score = 85.5%.
->Confidence Index of Dissipating Potential: 84.2%;
->Confidence Index of Oscillation Magnitude: 99.2%;
->Confidence Index of Oscillation Mode Angle: 96.1%
#3 Most Likely Source: ID = 1427, Score = 43.4%.
->Confidence Index of Dissipating Potential: 41.3%;
->Confidence Index of Oscillation Magnitude: 0.0%;
->Confidence Index of Oscillation Mode Angle: 77.7%

Source Type Estimation Result:

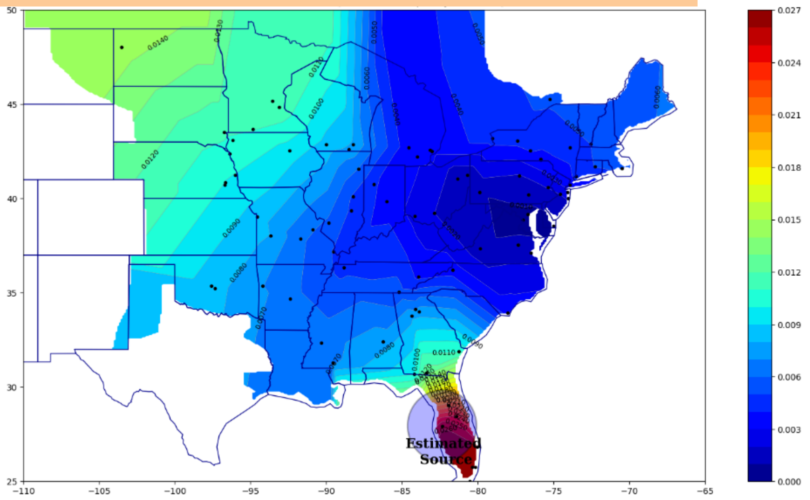
**** Warning: The estimated / specified source bus is NOT a generator bus. ****

The estimated type of the oscillation source is: << GOVERNOR >>
->Frequency oscillation magnitude = 0.03304 Hz, phase = 38.5°;
->Voltage oscillation magnitude = 0.21361 p.u., phase = 74.3°.

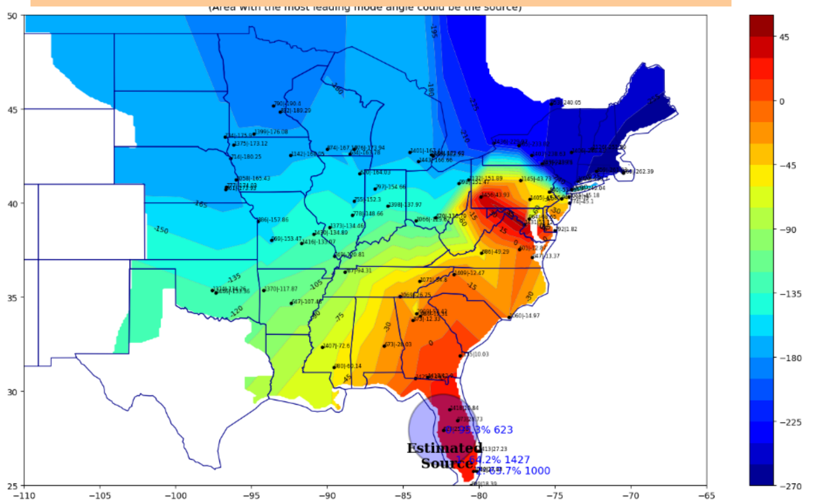
Dissipating Potential-Based



Oscillation Magnitude-Based



Oscillation Mode Angle-Based



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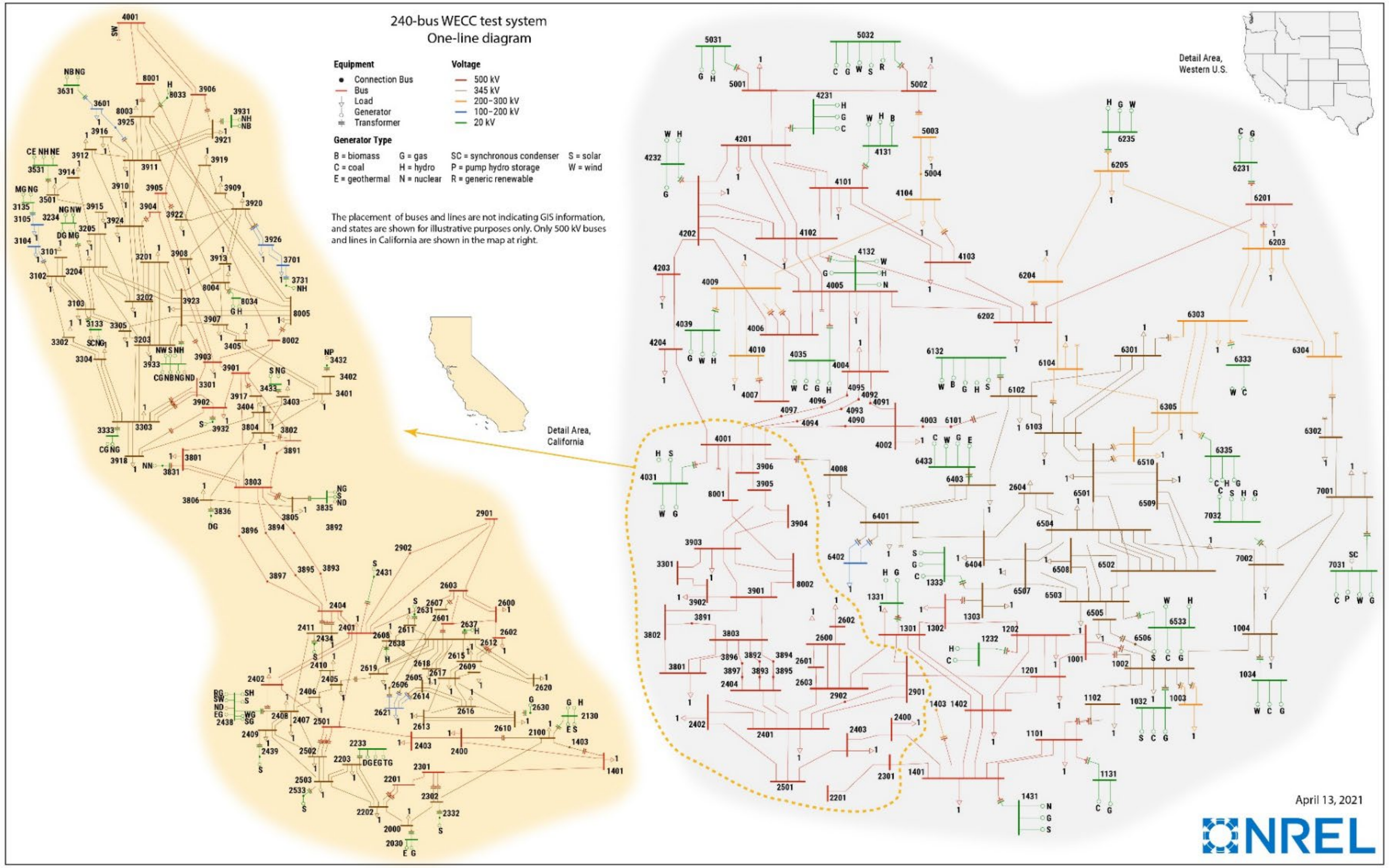
Summary and Future Work

- Developed a tool to identify forced oscillation source location and type
- Implemented three methods: Do not rely on system topology
  - Dissipating potential-based
  - Oscillation magnate-based
  - Oscillation mode angle-based
- Tested with simulated events and actual events
- Future work
  - Collaborating with Dominion on analysis of a local oscillation event
  - More case studies with actual events
  - Online tool

Together…Shaping the Future of Energy™

2021 IEEE-NASPI Oscillation Source Location Contest

- Contest cases
  - Based on 243-bus reduced WECC model
  - Partial PMU observability: 58 bus voltages, 89 transmission line currents
- Provided data
  - Bus voltage angle
  - Bus voltage magnitude
  - Line current angle
  - Line current magnitude



Source: http://web.eecs.utk.edu/~kaisun/Oscillation/2021Contest/

243-bus reduced WECC model

FOLT Results of Contest Test Cases

Source bus is not monitored.
FOLT suggested a nearby bus as the source.

- Data used by FOLT
  - Bus voltage angle & magnitude
  - PMU GPS coordinates
  - Current magnitude & angle are NOT used
- Localization
  - No time-domain simulations or manual analysis involved
  - If the source is not monitored, a nearby bus is identified as the source.
  - Controller type (governor or exciter) identification method is preliminary.

Case	Frequency	Area	Bus	Asset Type	Controller
1	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	NA
3	✓	✓	Close	NA	✓
4	✓	✓	Close	NA	✓
5	✓	✓	Close	✓	×
6	✓	✓	✓	✓	✓
7	✓	×	×	NA	NA
8	✓	✓	✓	✓	×
9*	✓	✓	Close	✓	✓
	✓	NA	NA	NA	NA
10*	✓	✓	✓	✓	×
	✓	NA	NA	NA	NA
11	✓	✓	Close	NA	NA
12	✓	✓	✓	✓	NA
13	✓	✓	✓	NA	NA

✓Correct Answer

× **Incorrect Answer**

NA: No Answer

* Case 9 and 10 have multiple sources. Only one source was identified.