Localizing Cyclic Industrial Load-Induced Forced Oscillations at the Entergy Grid Using Synchrophasor Measurements

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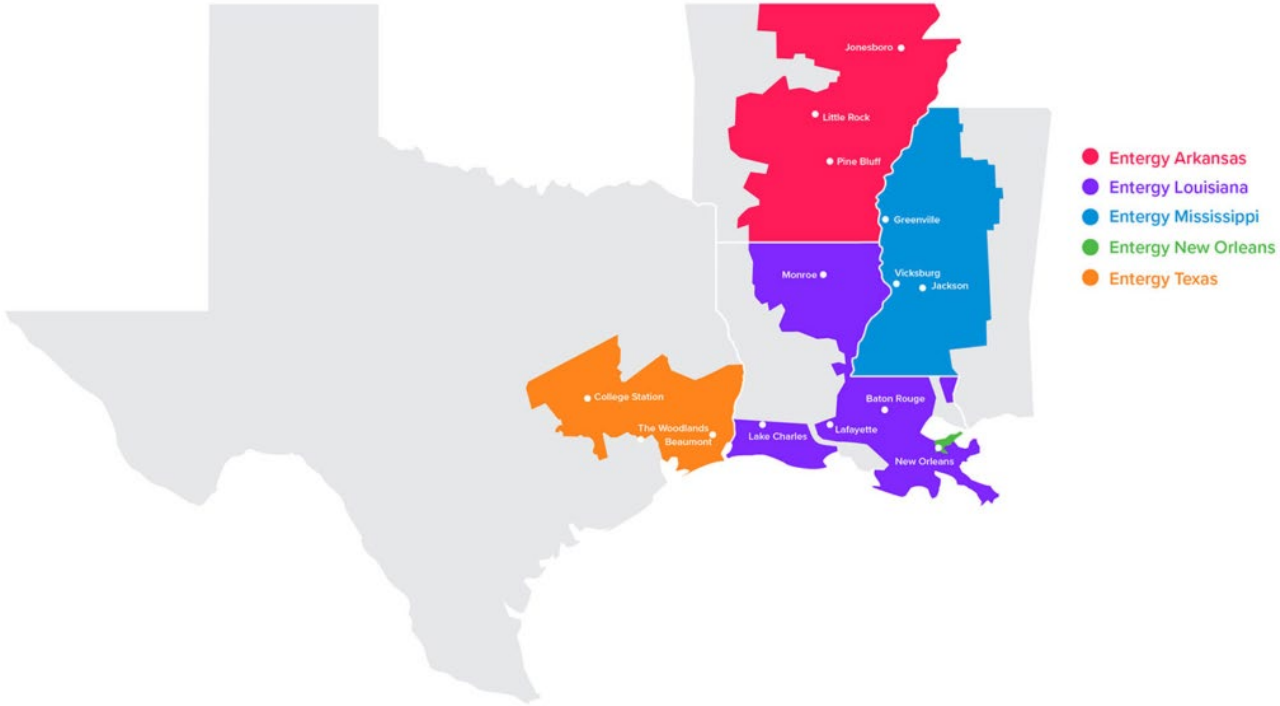
Entergy by The Numbers

- Operate across four-state service area: Portions of Arkansas, Mississippi, Texas and Louisiana, including the city of New Orleans



110+ years of service

3 million electric customers

12,000 employees

24,000 megawatts of power generation capacity

107,000 circuit miles of distribution lines

16,100 circuit miles of high-voltage transmission lines

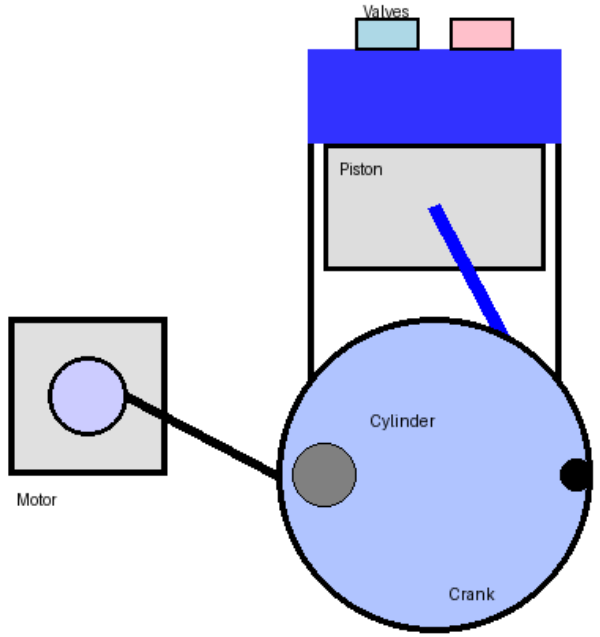
Fortune 500 company

$100+ million in value delivered to our communities each year

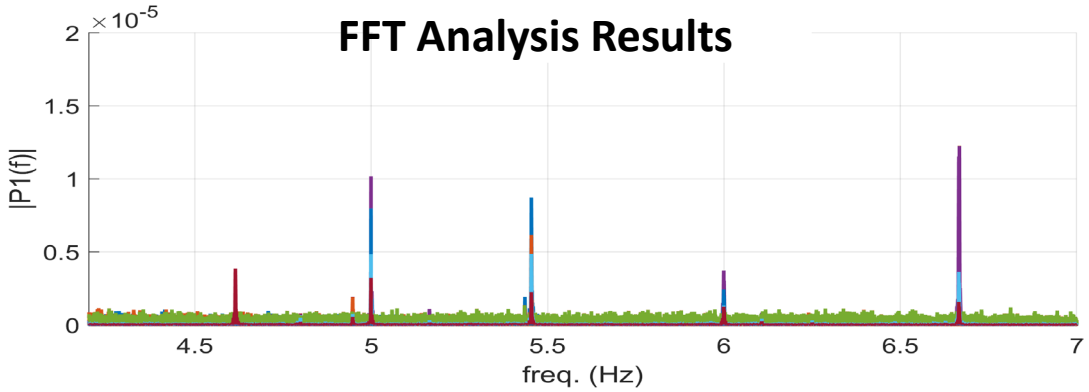
Source: Energy, https://www.entergy.com/about

Background and Motivation

- Multiple oscillation modes between 3-7 Hz are being consistently observed by PMU measurements
- **Challenge:** Risk of resonance with torsional turbine-governor mode of a large synchronous generator that could damage the plant
- **Objective:** Identify source of oscillations and mitigation measures
  - Synchronous motors driving reciprocating compressors

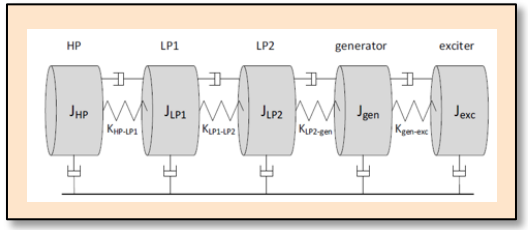


Synchronous motor driving reciprocating compressor Created by Copilot



Power Grid 3-7 Hz Oscillations

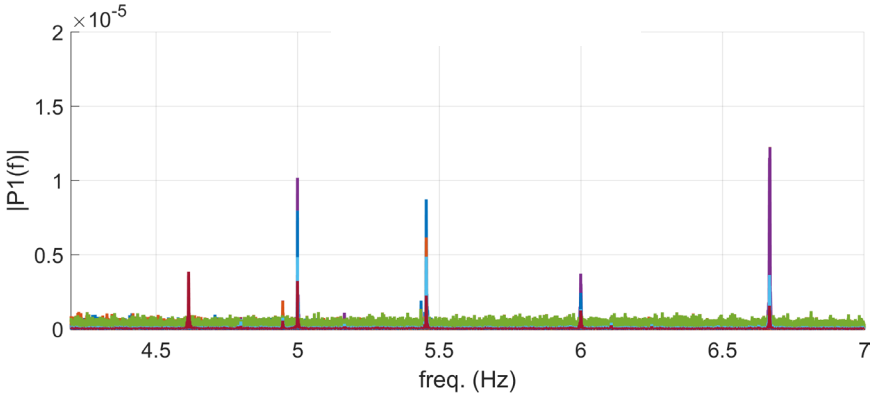
Potential Dangerous Resonance



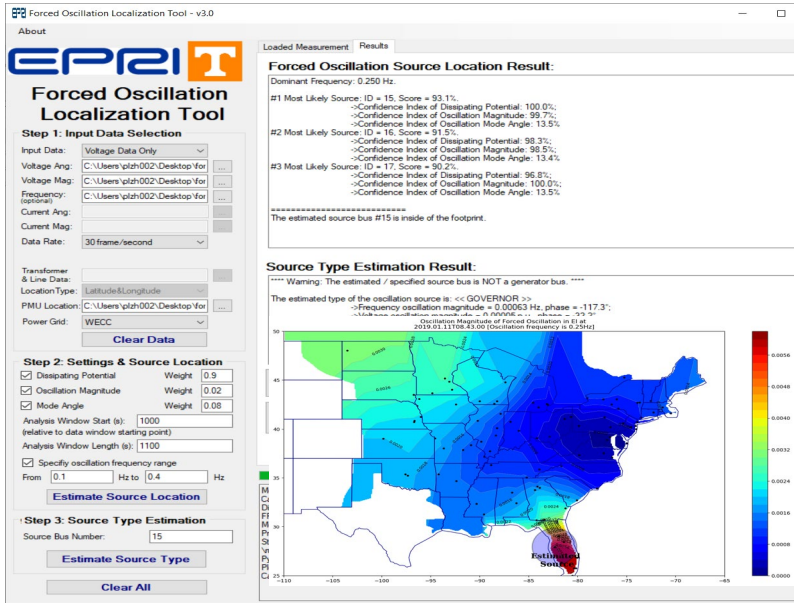
Torsional Modes of Turbine Generator

Data, Tools and Procedure

- Data: Recorded synchrophasor measurements from PMUs/DFRs and temporary sensors within Entergy territory (82 substations)
- Tools:
  - **FFT analysis:** Confirm whether the modes exist and estimate mode magnitude/energy
  - **EPRI's Forced Oscillation Localization Tool (FOLT):** Estimate source location and source type
- Procedure
  - Nearby synchronous generators/renewables?
  - Nearby loads?
  - Deploy temporary sensors to suspected substations to locate the exact source(s)



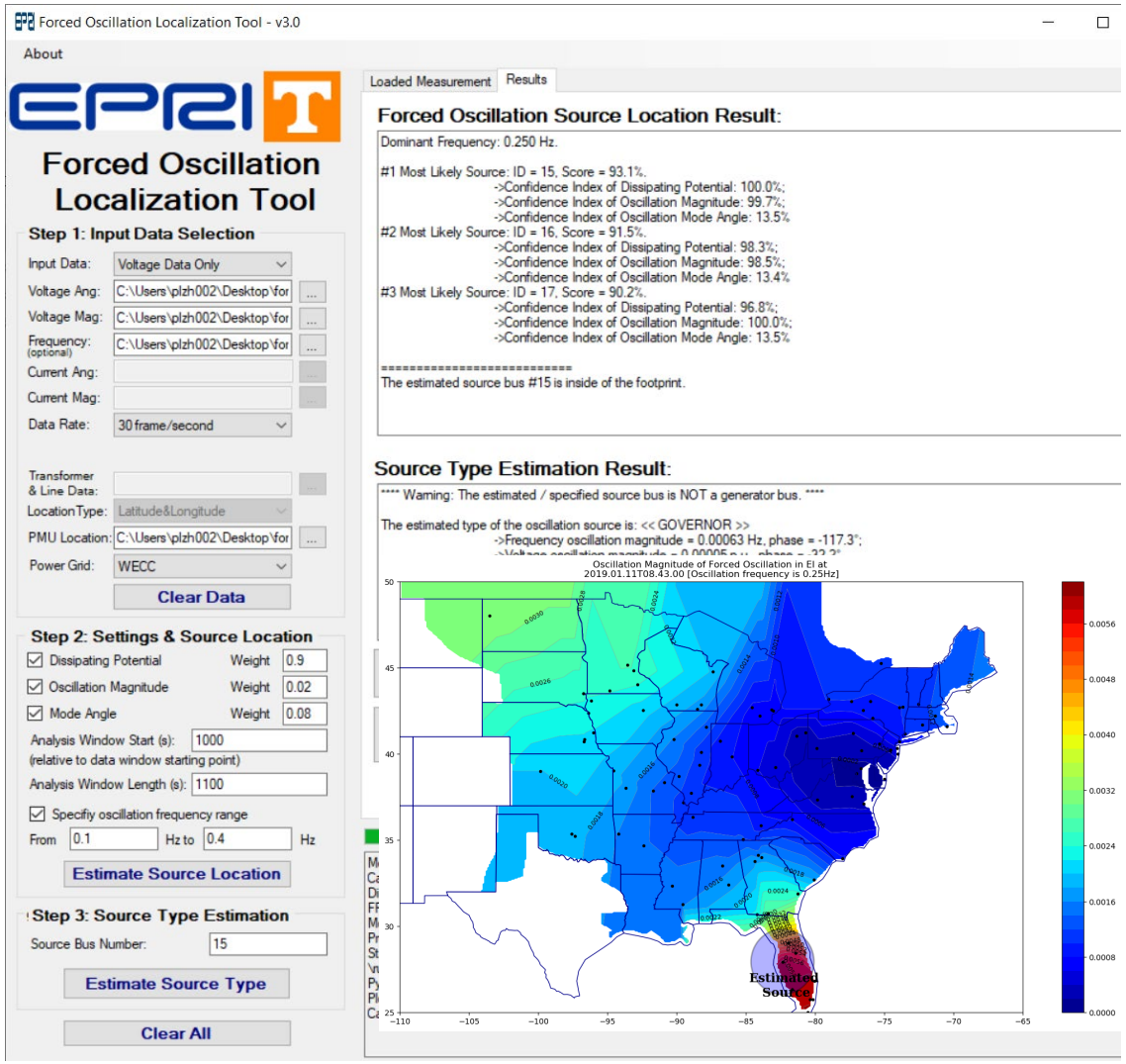
FFT Analysis



EPRI's FOLT

Forced Oscillation Localization Tool (FOLT) Offline v2025

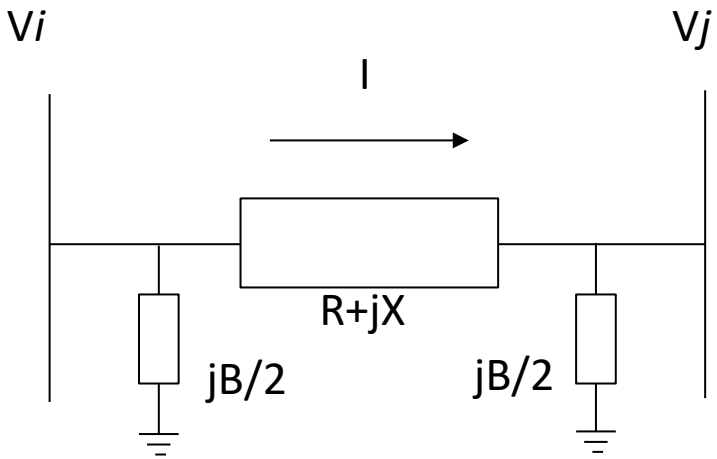
- Wide-band frequency oscillations (< 0.1 Hz to 15 Hz)
- Three different methods for oscillation source location
  - Dissipating Potential method
  - Oscillation Magnitude method
  - Oscillation Mode Angle method
- Source location estimation with confidence index
- Source type estimation: Active or reactive 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



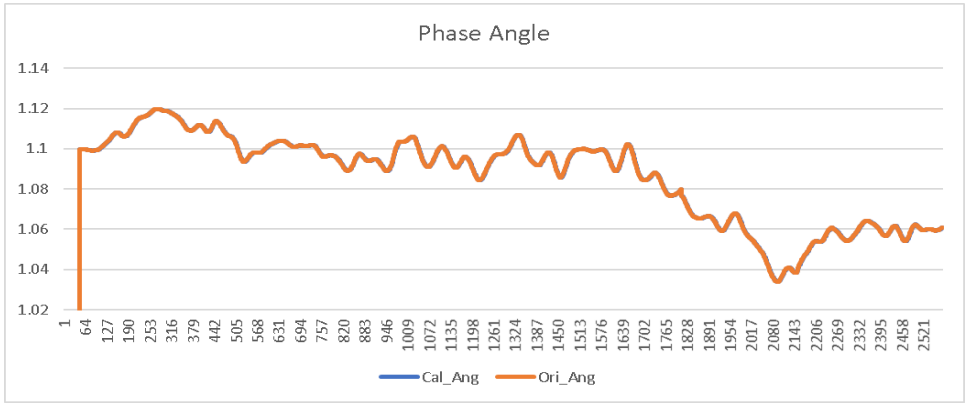
In Collaboration with University of Tennessee for Tool Development

Grid Observability Expansion

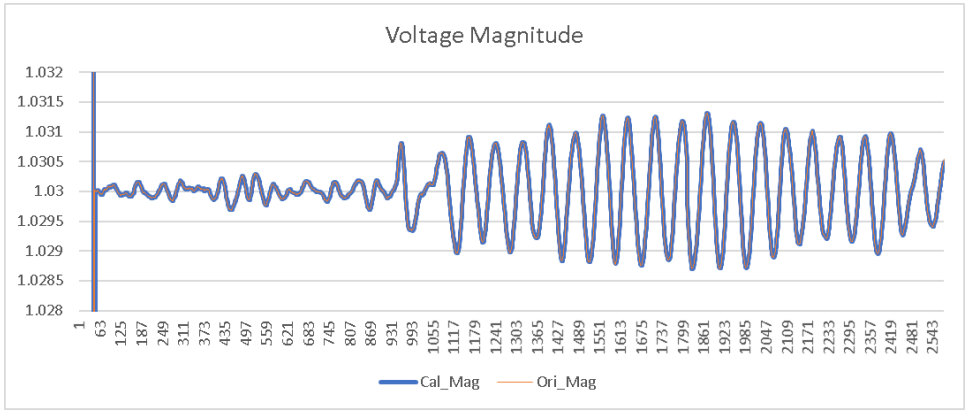
- **Improve grid observability**: Estimate voltage magnitude and angle of unmonitored bus using voltage and current measurements from PMUs
- A function implemented in FOLT tool



- **Known: Vi, I, R, B, X**
- **Unknown: Vj**



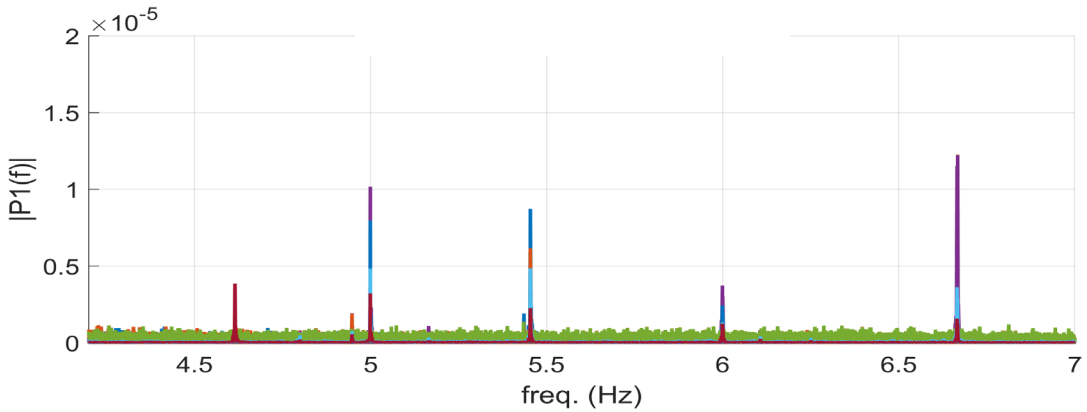
Voltage Angle:
Estimated(blue) vs. Actual(orange)



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

Are Nearby Generators the Sources?

- Performed FFT analysis on frequency measurements when suspected generators were out of service
- All oscillation modes can be observed with high magnitude/energy
- These generators are **NOT** the sources

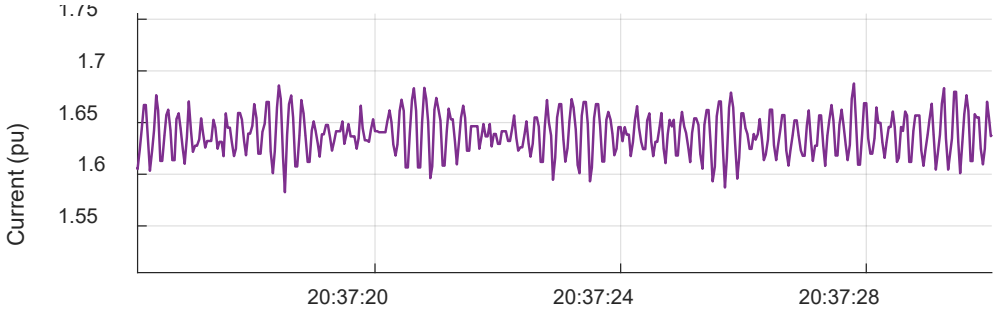


FFT Analysis Results

Plant	Generator	Day 1	Day 2	Day 3	Day 4	Suspected Source?
Plant A	All generators	OFF	N/A	N/A	N/A	NO
Plant B	Generator #1	ON	ON	ON	OFF	NO
Plant B	Generator #2	ON	ON	ON	OFF	NO
Plant B	Generator #3	ON	ON	ON	OFF	NO
Plant B	Generator #4	ON	OFF	ON	OFF	NO
Plant B	Generator #5	OFF	ON	ON	ON	NO
Plant C	Generator #1	ON	OFF	ON	OFF	NO
Plant C	Generator #2	OFF	ON	ON	ON	NO
Plant D	Generator #1	ON	OFF	OFF	ON	NO
Plant D	Generator #2	OFF	OFF	OFF	OFF	NO
Plant D	Generator #3	ON	ON	OFF	ON	NO
Plant D	Generator #4	ON	ON	OFF	ON	NO
Plant D	Generator #5	ON	ON	OFF	ON	NO
Oscillations Observed?		Yes	Yes	Yes	Yes	

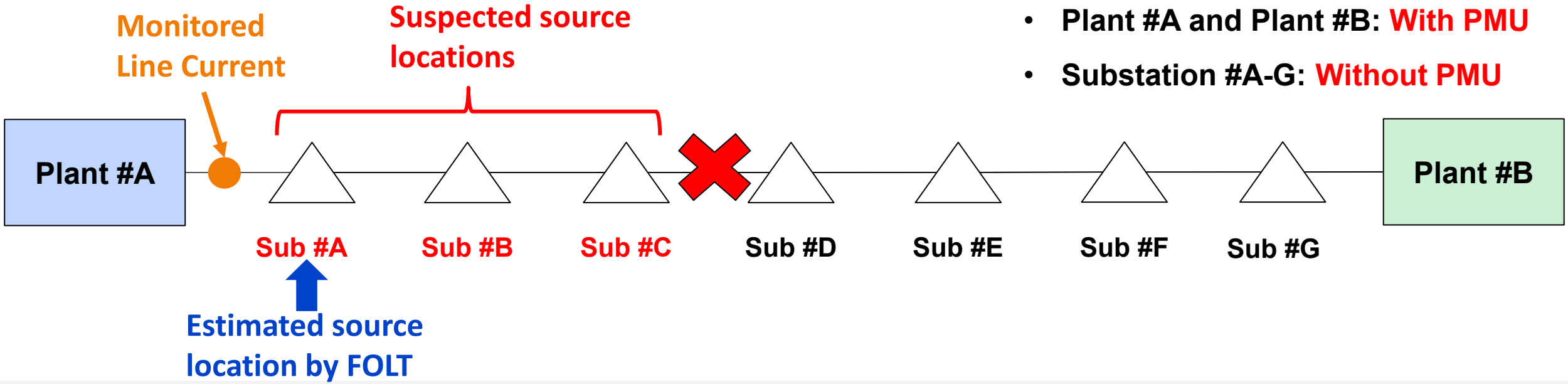
Are Nearby Loads the Sources?

- FOLT suggested source location: Substation #A
- FOLT suggested source type: Active power
- Multiple modes between 3-7 Hz were observed in line current from Plant #A to Substation #A
  - Even under an unplanned outage of line between Substation #C and Substation #D
  - Substations #A, #B, #C are suspected source locations



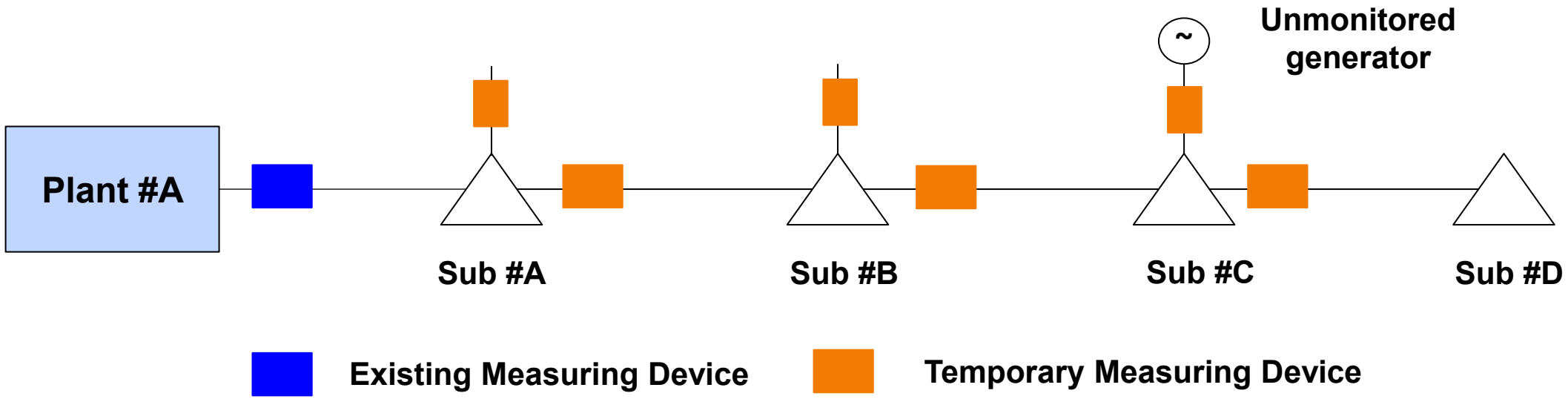
Line Current from Plant #A to Substation #A

- **Plant #A and Plant #B: With PMU**
- **Substation #A-G: Without PMU**



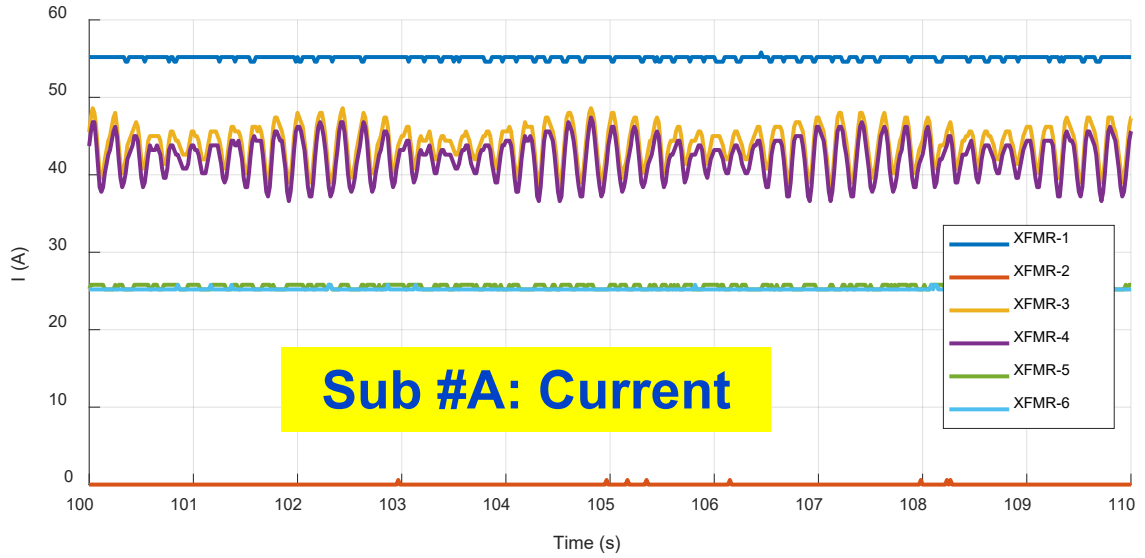
Temporary Sensors Deployment: High-Voltage Buses

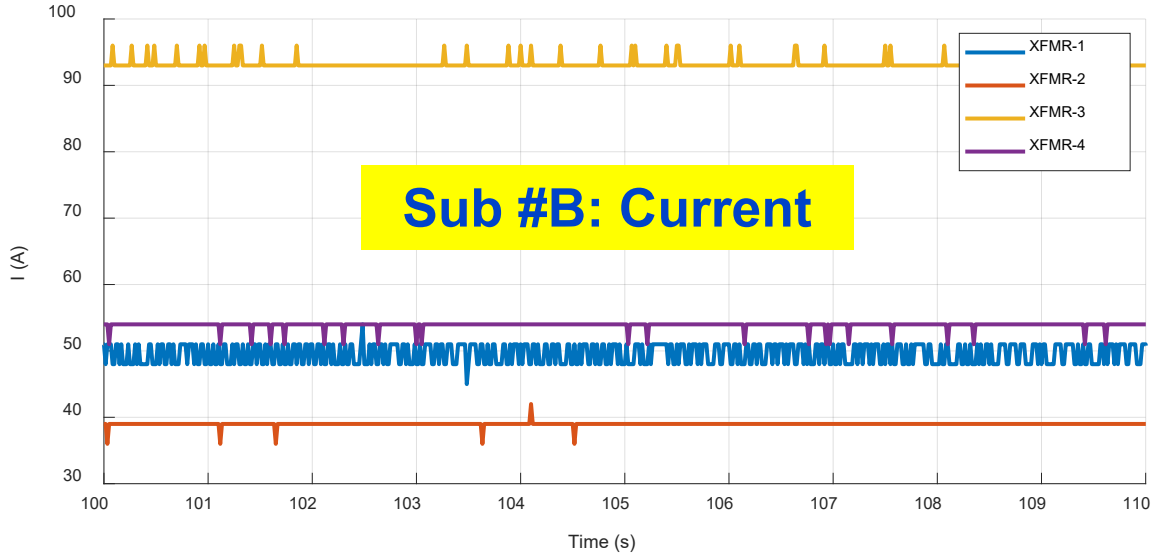
- Temporary sensors were deployed at high-voltage buses of three suspected substations
  - Synchrophasor measurements: f, V, I, etc.
  - Reporting rate: 60 Hz
- Sources of 4.62 Hz, 5.00 Hz, 5.46 Hz, and 6.00 Hz modes were identified

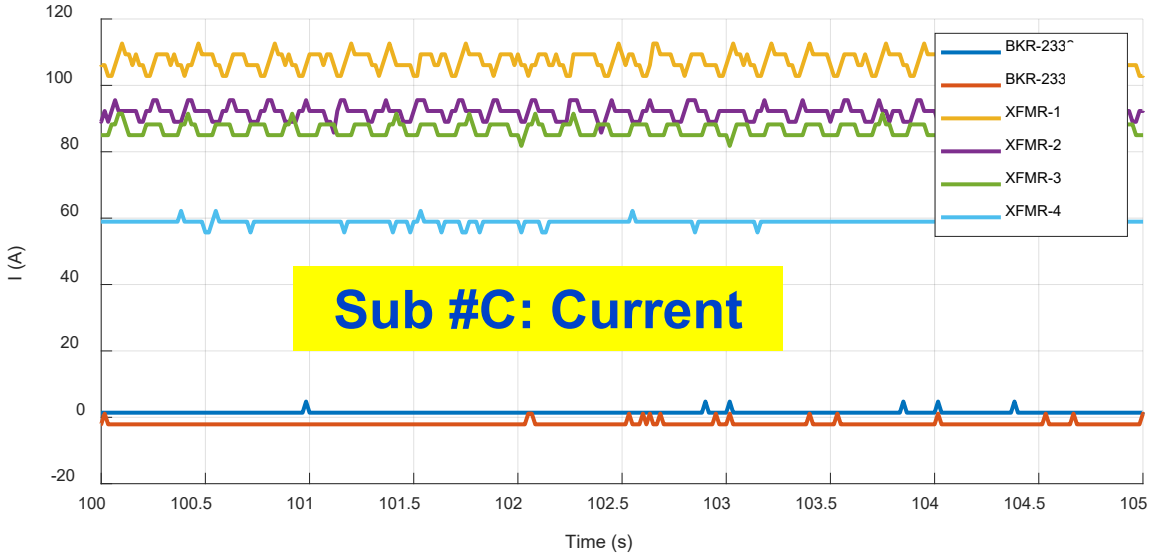


Identified Source Locations

- Substation #A: Transformer #3 and #4 (4.62 Hz + 5.00 Hz)
- Substation #B: No sources were identified
- Substation #C: Transformer #1 and #2 (5.46 Hz), Transformer #3 (6.00 Hz)

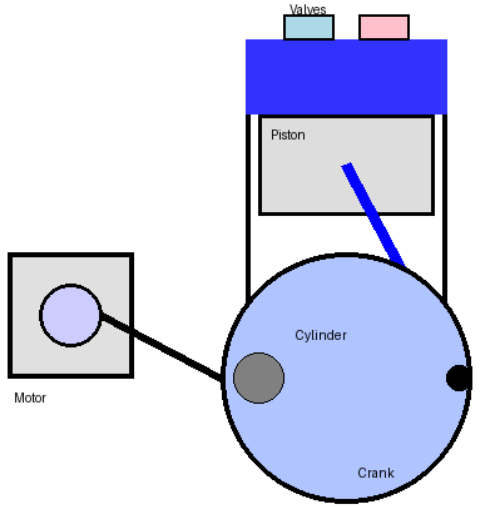






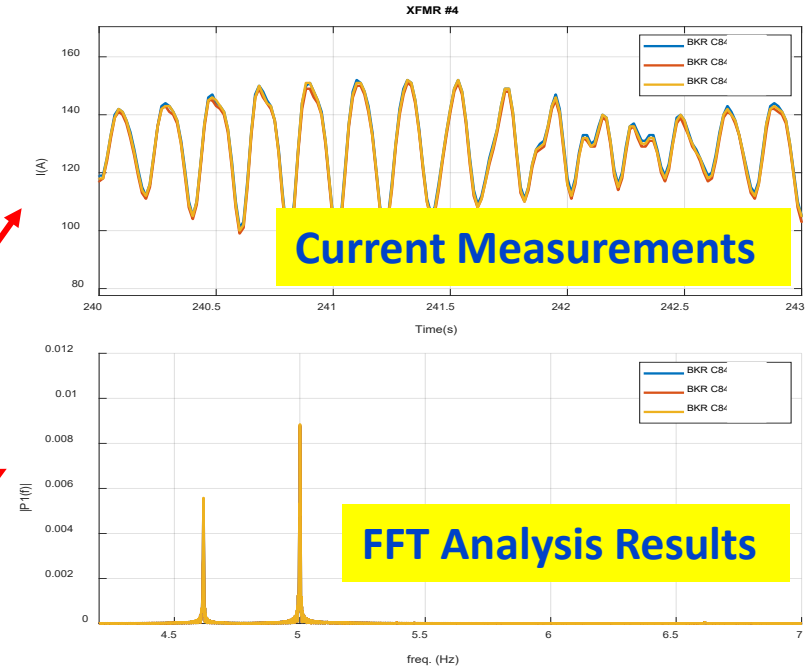
Temporary Sensors Deployment: Low-Voltage Buses

- **Substation #A:** Transformer #3 and #4 (4.62 Hz + 5.00 Hz)
- Sources: Synchronous motors of 4.47 MW/5.37 MW driving reciprocating compressors (cyclic load-induced forced oscillations)
- Oscillation frequency is solely determined by **motor speed**:
  - 277 RPM: 4.62 Hz and 300 RPM: 5.00 Hz



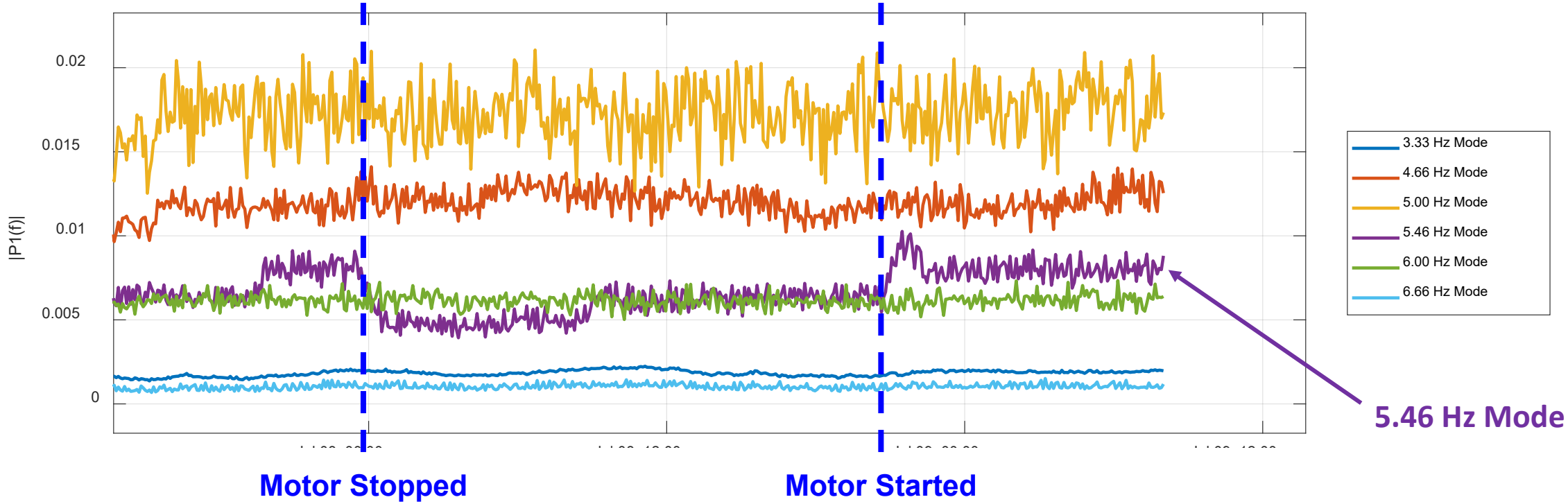
Synchronous motor driving reciprocating compressor Created by Copilot

	Feeder	Identified Sources
Transformer #3	Feeder #1	N/A
	Feeder #2	N/A
	Feeder #3	Synchronous motors: 277 and 300 RPM
	Feeder #4	N/A
Transformer #4	Feeder #1	N/A
	Feeder #2	N/A
	Feeder #3	N/A
	Feeder #4	Synchronous motors: 277 and 300 RPM



Planned Outage of One Sync. Motor in Substation #C

- FFT analysis of line current from Plant #A to Substation #A
  - Variations in the magnitude of the 5.46 Hz oscillation before/after the motor stop and after the motor restart

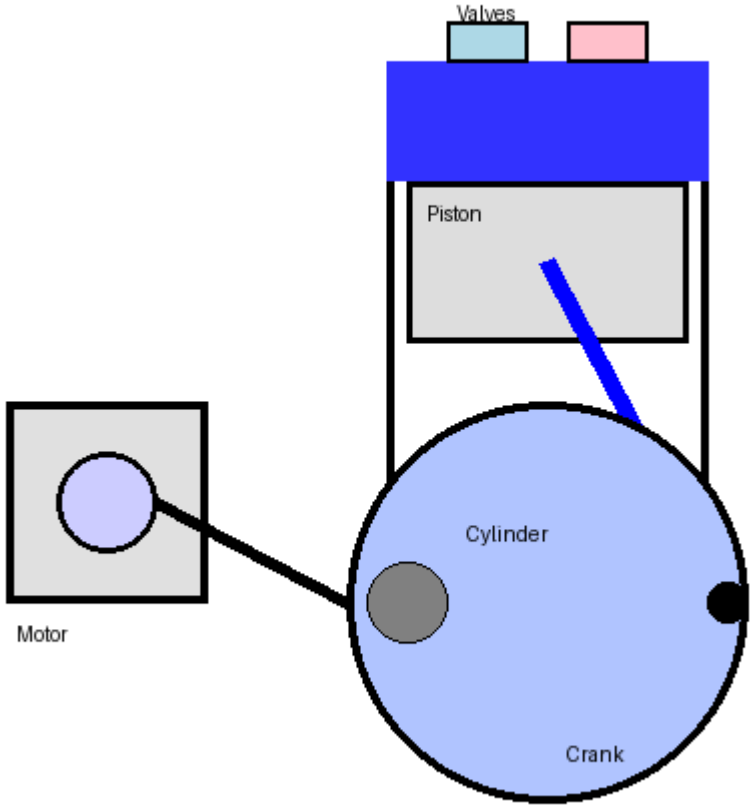


Potential Mitigation Measures Based on Entity

Load/Customer Solution	• Reduction of magnitude of motor current pulsation by proper sizing of motor inertia • Motor connection through Variable Frequency Drive (VFD) to modify oscillations frequency
Transmission/Utility Solution	• Device installation to suppress oscillations magnitude by absorbing oscillations energy, e.g., STATCOM, BESS • Special Protection Scheme (SPS) to trip motor when oscillations magnitude exceeds a predefined threshold
Generation Solution	• Installation of torsional damping controller

Summary

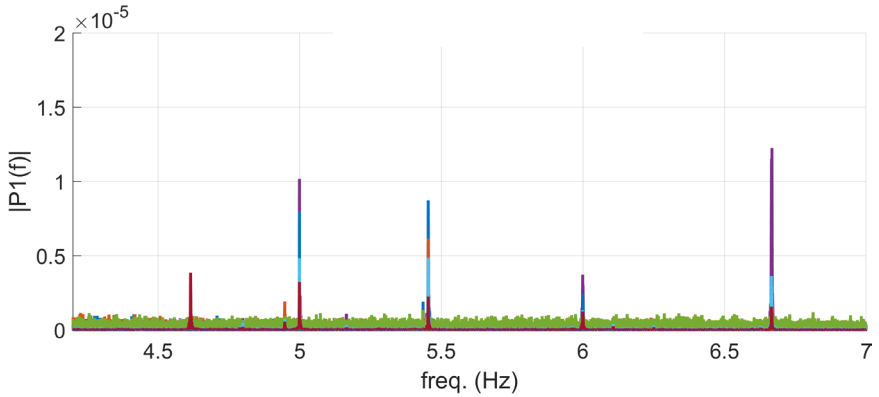
- Multiple forced oscillation modes observed in Entergy territory
- Used synchrophasor measurements from PMUs/DFRs and temporary sensors to locate sources of 3-7 Hz forced oscillations
- The 4.62/5.00/5.46/6.00 Hz oscillations are induced by **synchronous motors driving reciprocating compressors** (cyclic load-induced forced oscillations)
- These forced oscillations pose a significant risk to equipment and grid reliability (Risk of resonance with torsional modes), **despite the small capacity** of the synchronous motors (4.47 MW/5.37 MW)
- The oscillation frequency does not change, and it is solely determined by motor speed
  - 277/300/327/360 RPM: 4.62/5.00/5.46/6.00 Hz



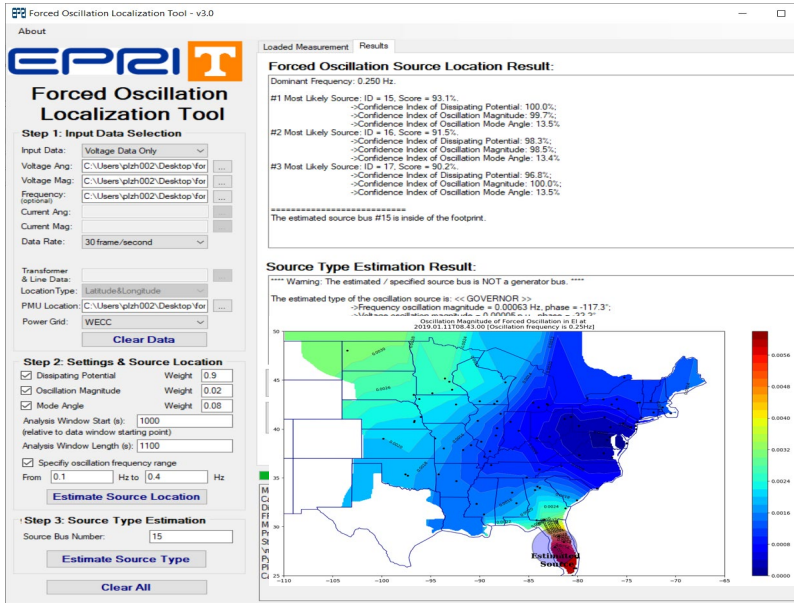
Synchronous motor driving reciprocating compressor: Created by Copilot

Summary, Cont'd

- The developed approach/procedure can be used to pinpoint exact source locations of 3-7 Hz modes in other areas within Entergy
  - Perform FFT analysis on PMU measurements and use EPRI's FOLT tool to locate sources to a few substations
  - Deploy temporary sensors at suspected substations high/low voltage buses to locate the exact source(s)
- High-resolution synchrophasor measurements are critical to pinpoint the source locations
- Potential mitigation measures
  - **Load/Customer:** Shift the forced oscillation frequency to avoid potential resonance with generation unit's torsional mode
  - **Transmission/Utility:** Deploy new devices STATCOM/SVC/BESS to absorb forced oscillation energy, special protection scheme
  - **Generation:** Install additional tortional damping controller at the generation unit to reduce forced oscillation energy



FFT Analysis



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