Planning for Large Load Oscillations:

Evaluating System Risks and Measurement Limitations

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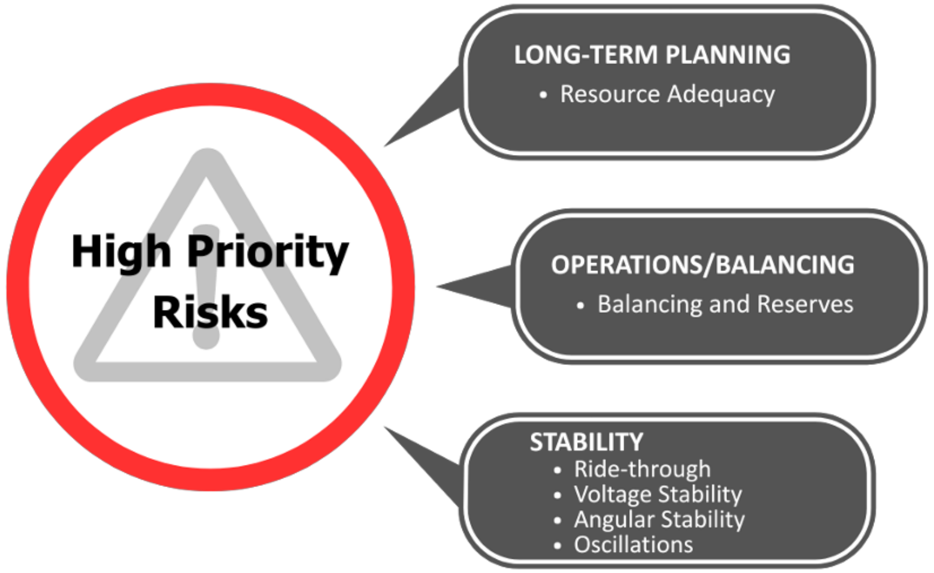
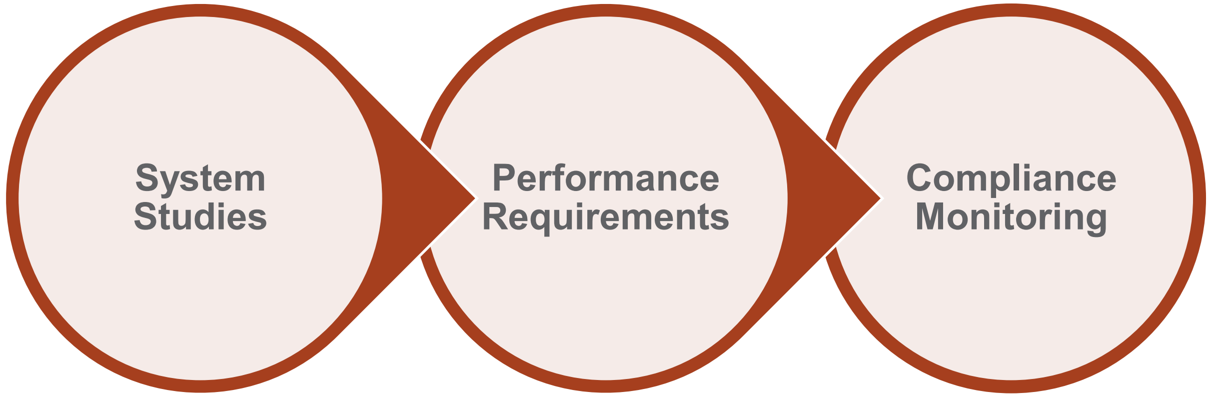
PNNL-SA-219397

The Challenge





- Data center loads can fluctuate periodically, introducing forced oscillations in the grid.
- If these oscillation frequencies are near system modes (inter-area or local), wide-area propagation and/or oscillation amplification is possible. Risks vary with where the oscillation source is located.
- How to evaluate oscillation susceptibility at the planning stage?
- What are permissible oscillation limits that will not lead to protection/control misoperations?

NERC, “Characteristics and Risks of Emerging Large Loads: Large Loads Task Force White Paper”, July 2025.
Biswas S., A. Varghese, K. Chatterjee, S. Nekkalapu, B.A. Ross, and J.D. Follum. 2025. "Evaluating the Risk to Bulk Power System Reliability from Large Load Induced Oscillations." PNNL-SA-214877.

Why do we Care?

- Large power/voltage swings can cause protection mis-operations leading to cascading failures.
- Oscillations in the 0.1-1.5 Hz frequency range tend to spread across large areas (**inter-area**).

Frequency	Characteristics	Problems
0.1-1.5 Hz	May spread across large areas	Resonance with inter-area modes may cause amplification in distant locations
>1.5 Hz	Tend to be localized	Flicker, power quality problems, equipment fatigue
>10 Hz	Tend to be localized	Resonance with torsional modes, mechanical vibrations

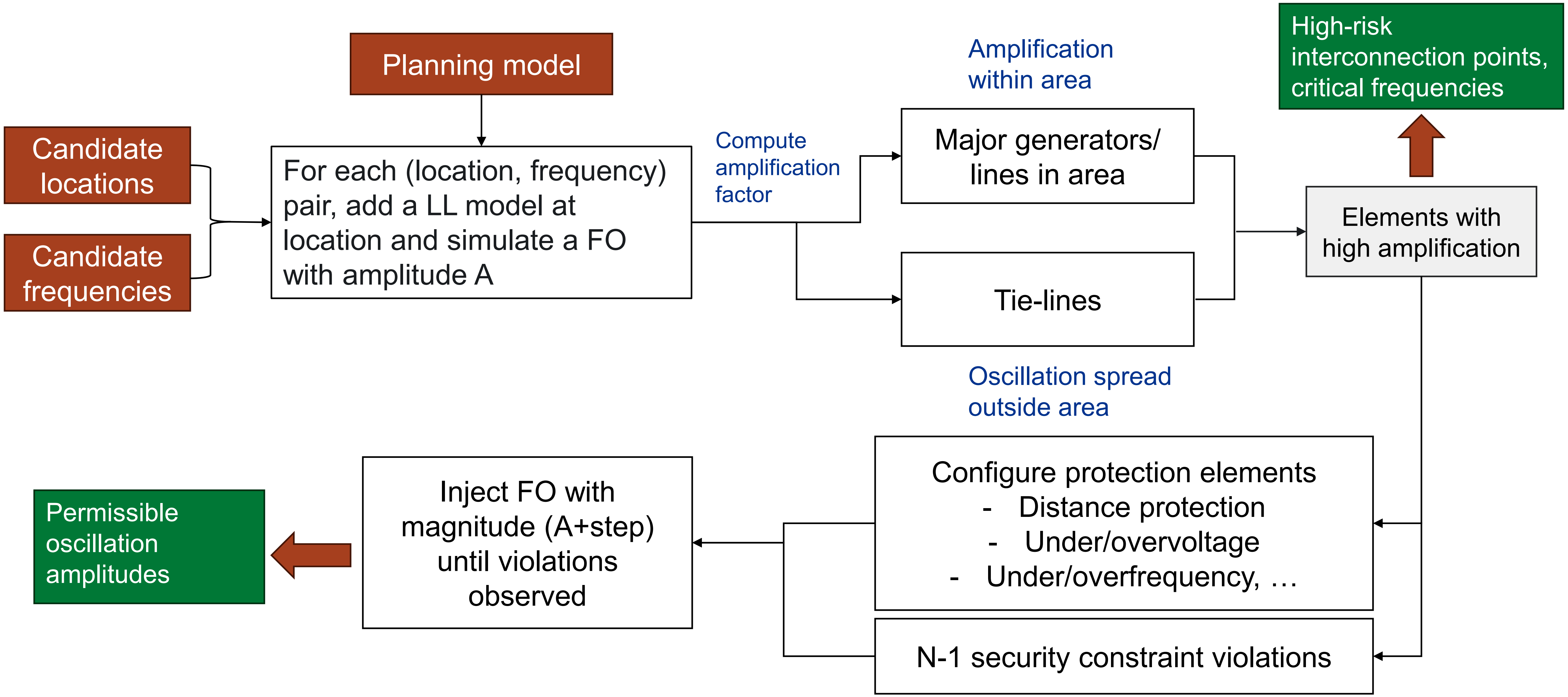
Can be studied with positive sequence models (0.1-1.5 Hz)

EMT models needed (>1.5 Hz, >10 Hz)

Proposed Approach

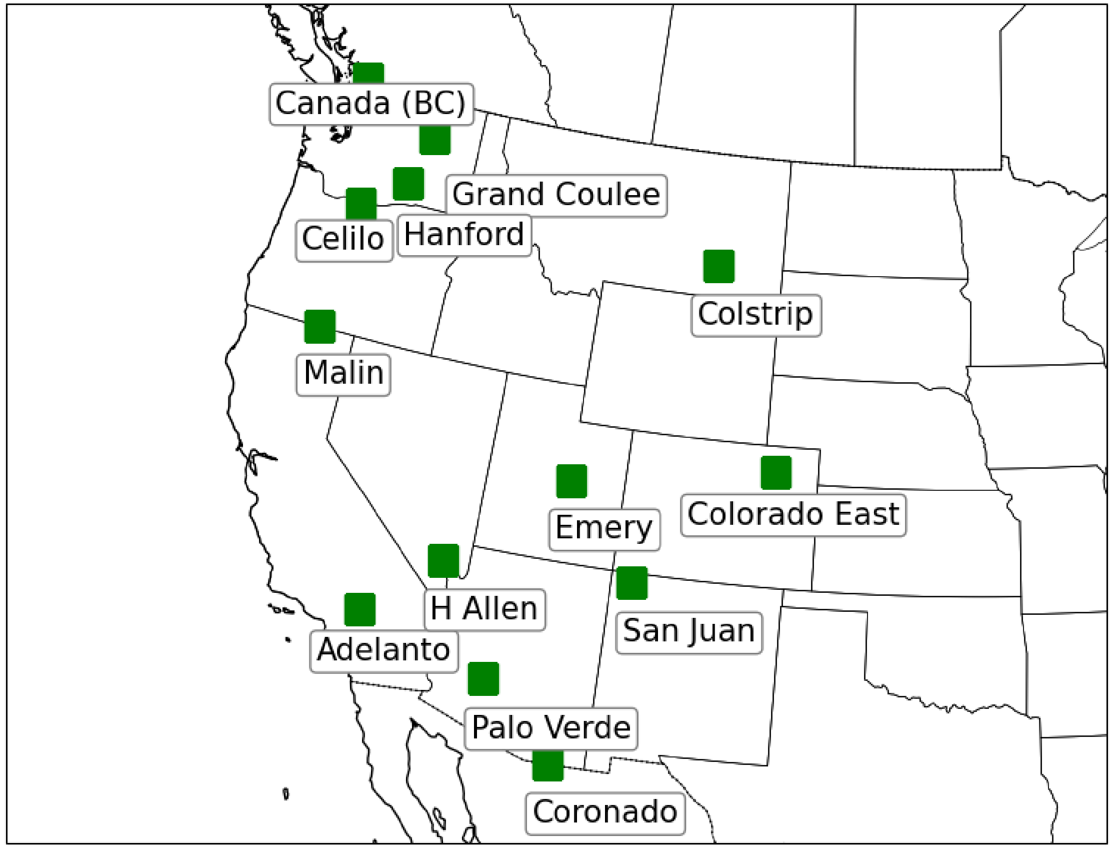
[pnnl/LL-risk-assessment: A suite of scripts that helps evaluate and visualize the grid reliability risk due to events introduced by large dynamic digital loads (LDDLs) at the planning stage.]

Readily automatable framework to evaluate oscillation-induced reliability risk during planning studies.

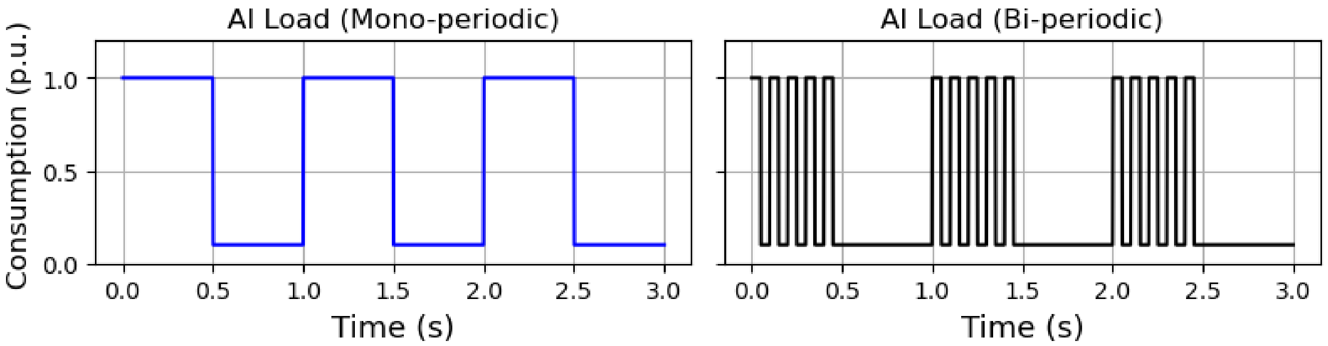


Some Results

- Simulation methodology developed and illustrated with the 240-bus reduced WECC model. High-risk large load interconnection points and critical oscillation frequencies can be identified.
- Also tested with the South Carolina 500-bus and Texas 2000-bus synthetic networks from the TAMU synthetic cases repository.



Two types of load oscillatory behavior modeled.

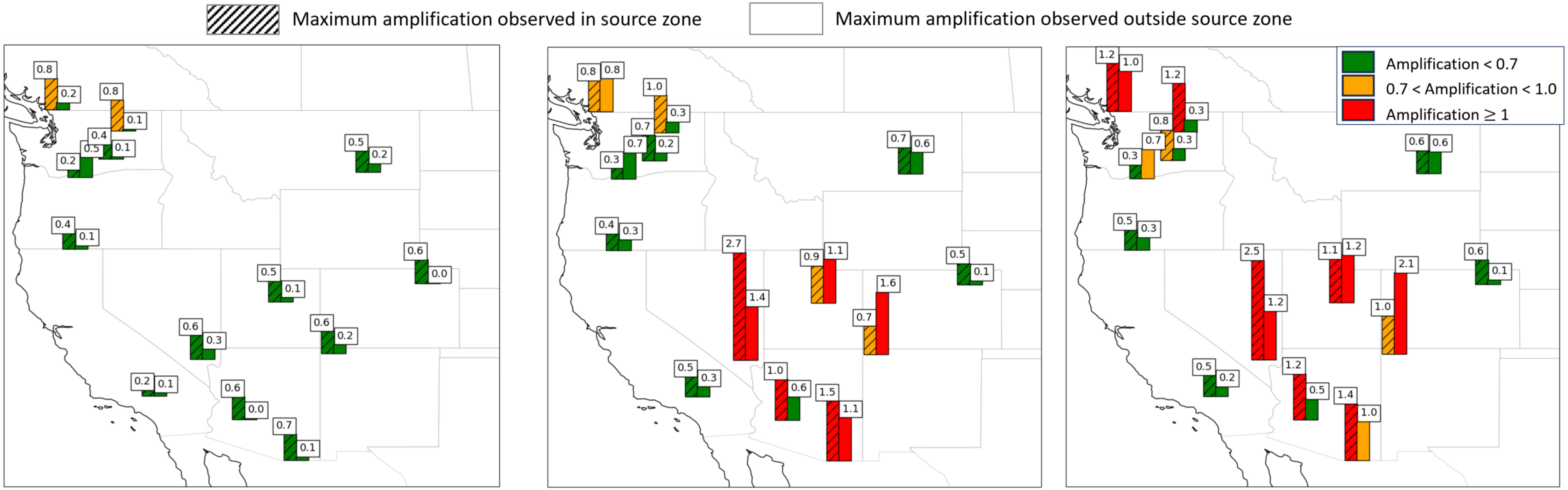


Disclaimer: Results from the reduced WECC model cannot be directly extrapolated to the Western Interconnection.

H. Yuan, R. S. Biswas, J. Tan and Y. Zhang, "Developing a Reduced 240-Bus WECC Dynamic Model for Frequency Response Study of High Renewable Integration," *2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Chicago, IL, USA, 2020, pp. 1-5, doi: 10.1109/TD39804.2020.9299666.

Some Results

The risk of oscillation propagation and amplification is a function of the source location and oscillation frequency.



(a) Oscillation frequency = 0.5 Hz
(Forcing function is a square wave)

(b) Oscillation frequency = 1 Hz
(Forcing function is a square wave)

(c) Oscillation frequency = 0.1 Hz, 1 Hz
(Forcing function is bi-periodic)

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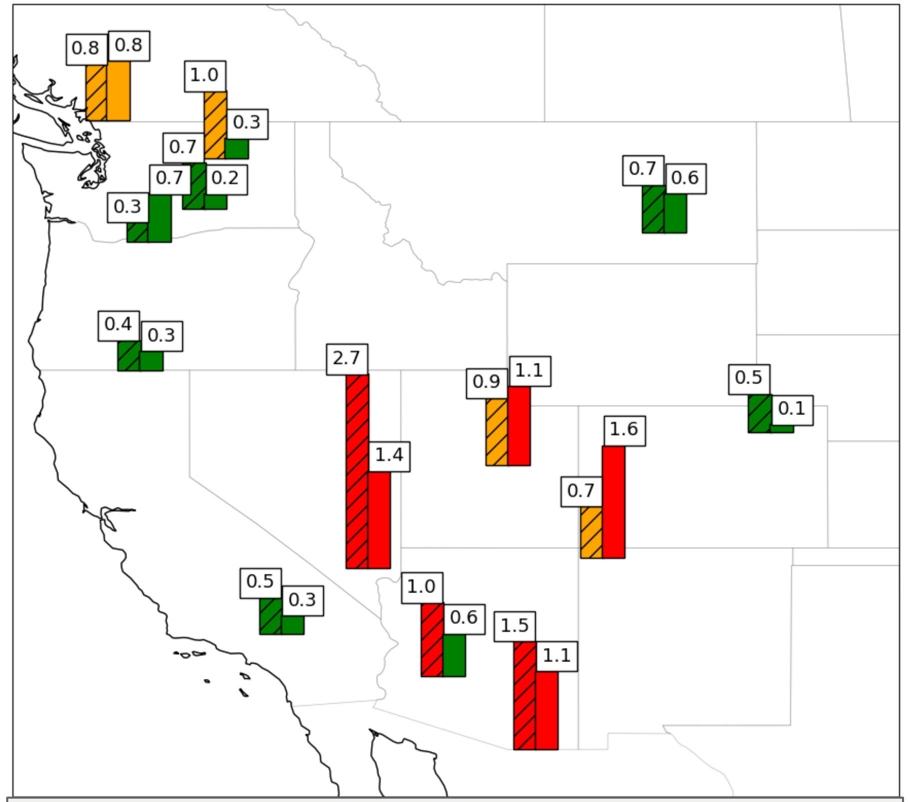
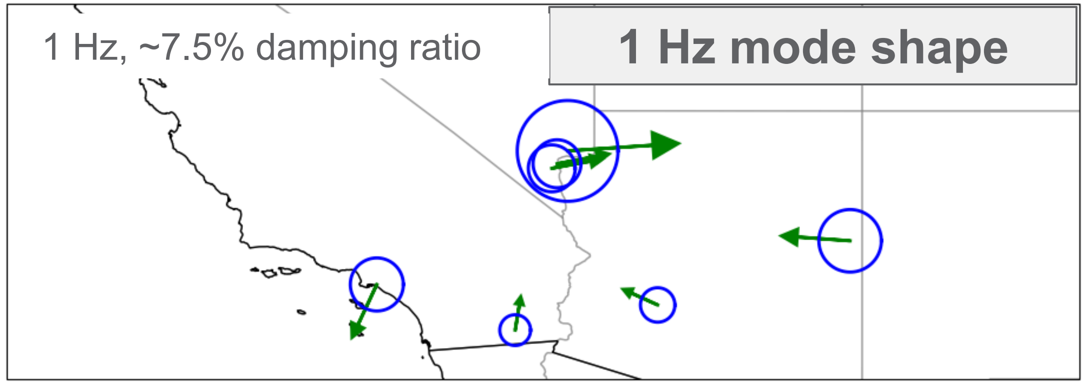
Closer Look at the 1 Hz Mode

Highest amplification in 1 Hz oscillations observed when the source is located in the Southwestern region.

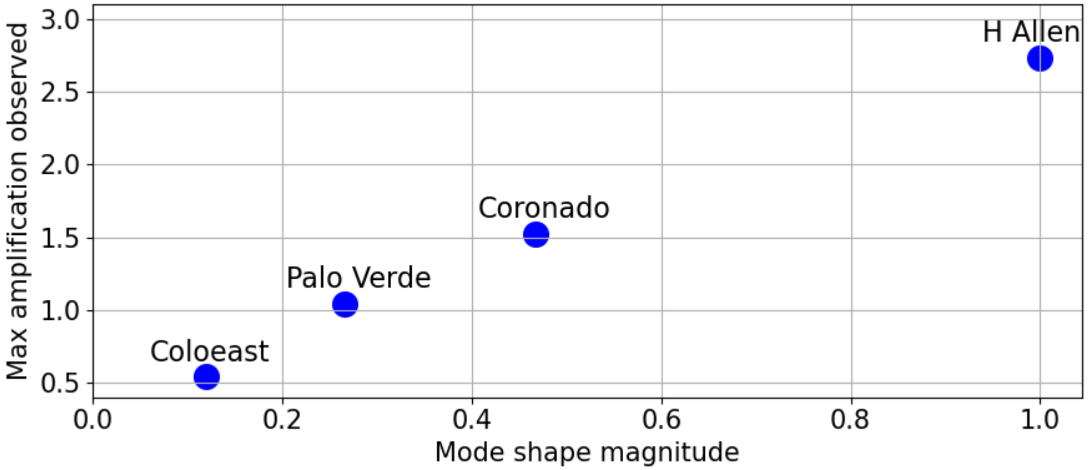
Insight: Reliability risk high if oscillatory LL is located close to generators with high participation in a system mode. Mitigation measures may be necessary.



Amplification when 1 Hz oscillations introduced from different locations



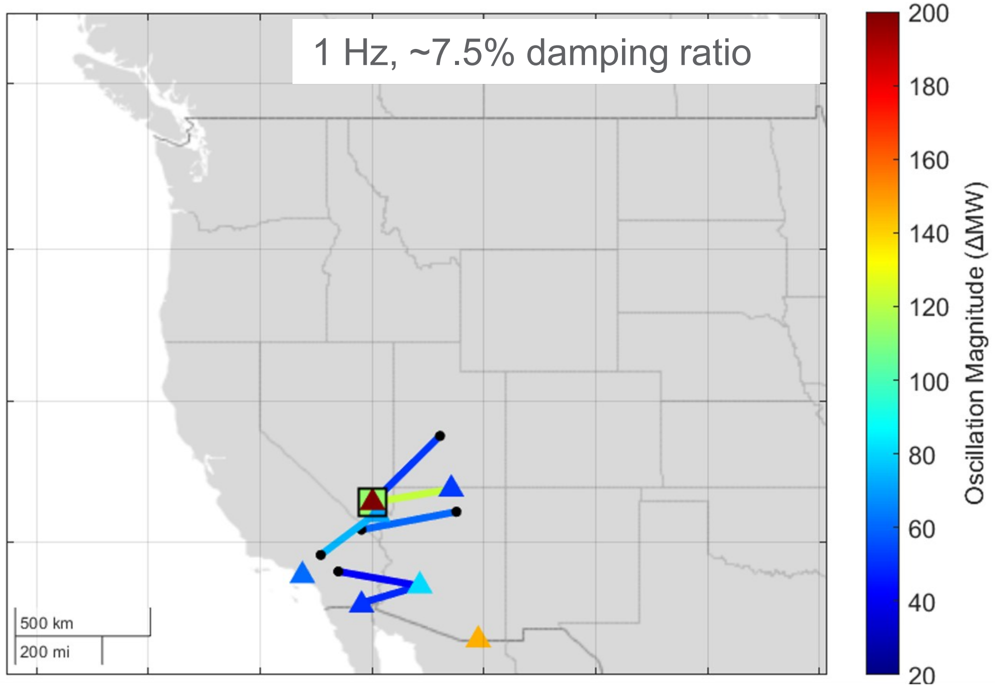
1 Hz mode shape



Some Results

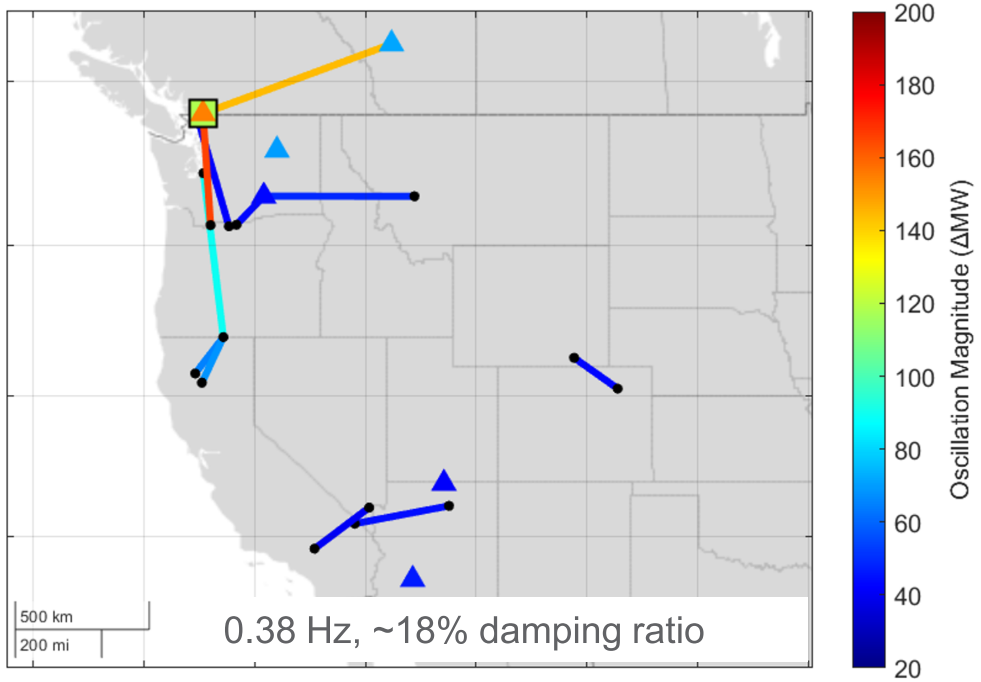
- Planning studies can identify locations where oscillation amplification factors are high.

Source location: H Allen, Nevada



1 Hz, 100 MW square wave load perturbation

Source location: British Columbia



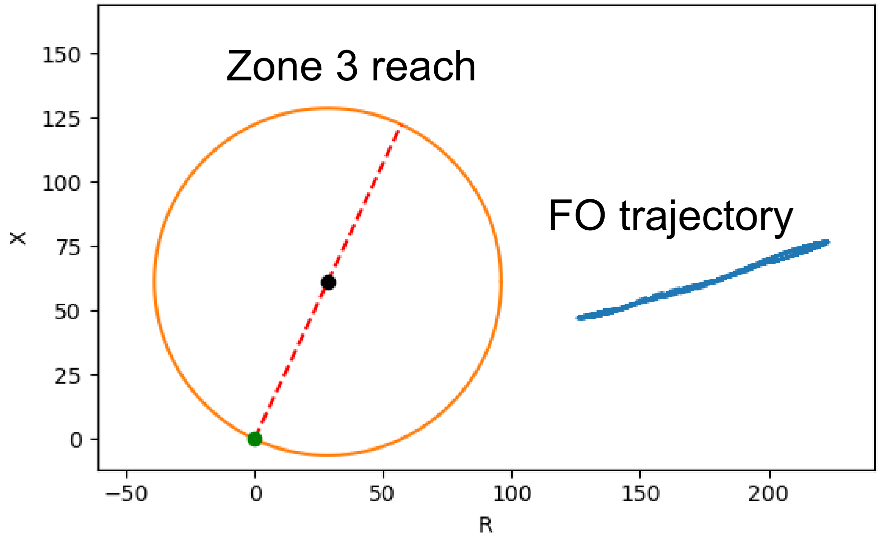
0.38 Hz, 100 MW square wave load perturbation

Takeaways

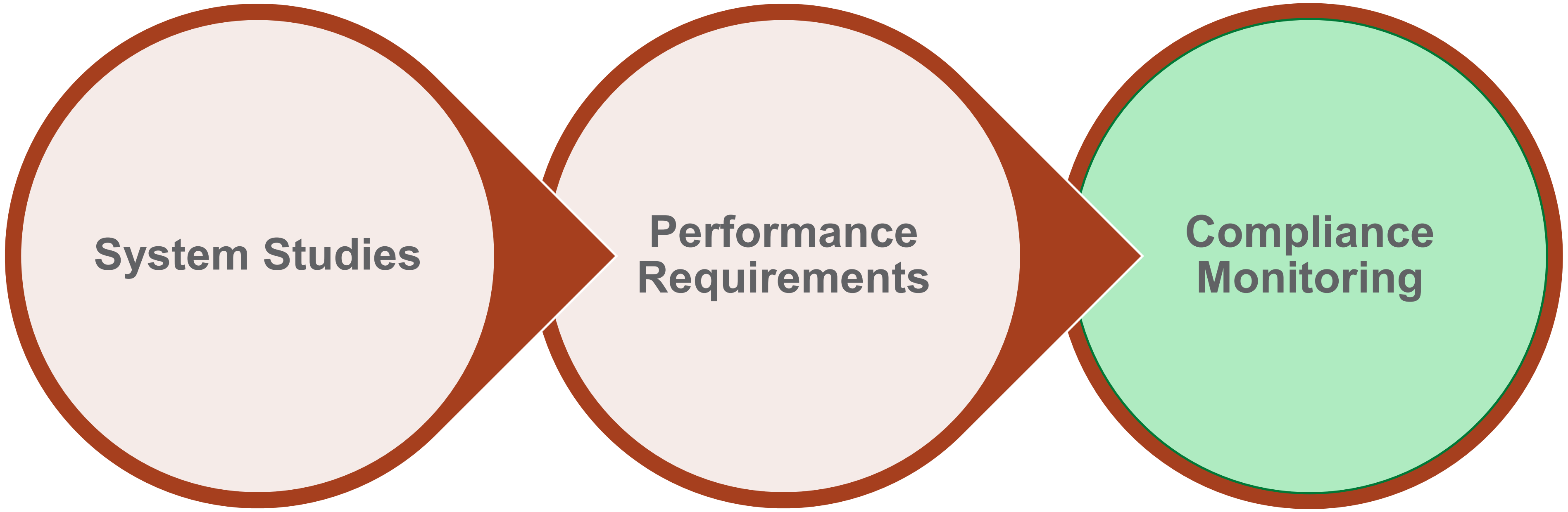
- A framework developed to identify high-risk locations where FO–natural mode resonance and wide-area propagation of induced oscillations are likely.
- Open-source scripts (PSSE+Python) publicly available: https://github.com/pnnl/LL-risk-assessment
- Looking for feedback.

Work in progress:

- Configuring protection elements to determine permissible oscillation magnitudes.
- Extending the framework to identify risks associated with load steps/ramps, synchronized behavior of multiple LLs.
- Illustration with full interconnection models.



Preprint available: http://dx.doi.org/10.13140/RG.2.2.32970.43206


System Studies
Performance Requirements
Compliance Monitoring

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Proposed LDDL-Oscillation Limits

- Multiple system operators are proposing operational limits on LDDL-induced FOs to maintain grid reliability
  - Notable examples: AESO, ATC, ERCOT
    - ✓ Limits defined on peak-to-peak oscillation amplitude in each frequency band, periodic load variability, etc.
    - ✓ Enforces FOs not to be too close to poorly-damped natural modes, including torsional modes of nearby generators

AESO Connection Requirements for Transmission-Connected Data Centres

6.5 Load-Induced Forced Oscillation

- The TCDC must be designed to prevent the emergence of forced oscillations that may arise from internal load dynamics, such as repetitive control actions, cycling behaviour, fast ramping or abrupt power demands
- To limit the risk of power oscillations, the TCDC's net load variability must be limited to less than 16 kW per 100 milliseconds
- Forced power oscillation amplitude within sub-synchronous frequency band must be limited to less than ± 160 KW
- These indicative values may be refined based on system-specific electromagnet transient (EMT) studies, accounting for local grid strength, connection configuration, and facility control behaviour

AESO Connection Requirements for Transmission-Connected Data Centers. https://aesoengage.aeso.ca/connection-requirements-for-transmission-connected-data-centres

ATC	Criteria	Department:	System Planning
		Document No:	PLG-CR-0001-V25
Title: Transmission System Planning Criteria		Issue Date:	August 28, 2025
		Previous Date:	February 4, 2025

Table 9.1-1: Active Power Oscillation Criteria Limits

Constant	Limit	Unit
ΔP2	25	MW
T1	5	seconds
P3	50	MW
R2	0.5	MW/second (MW/s)

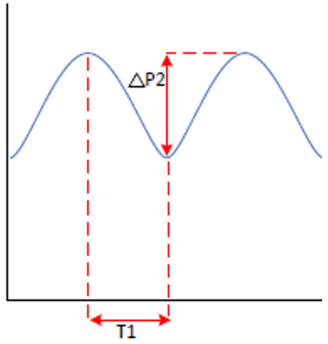
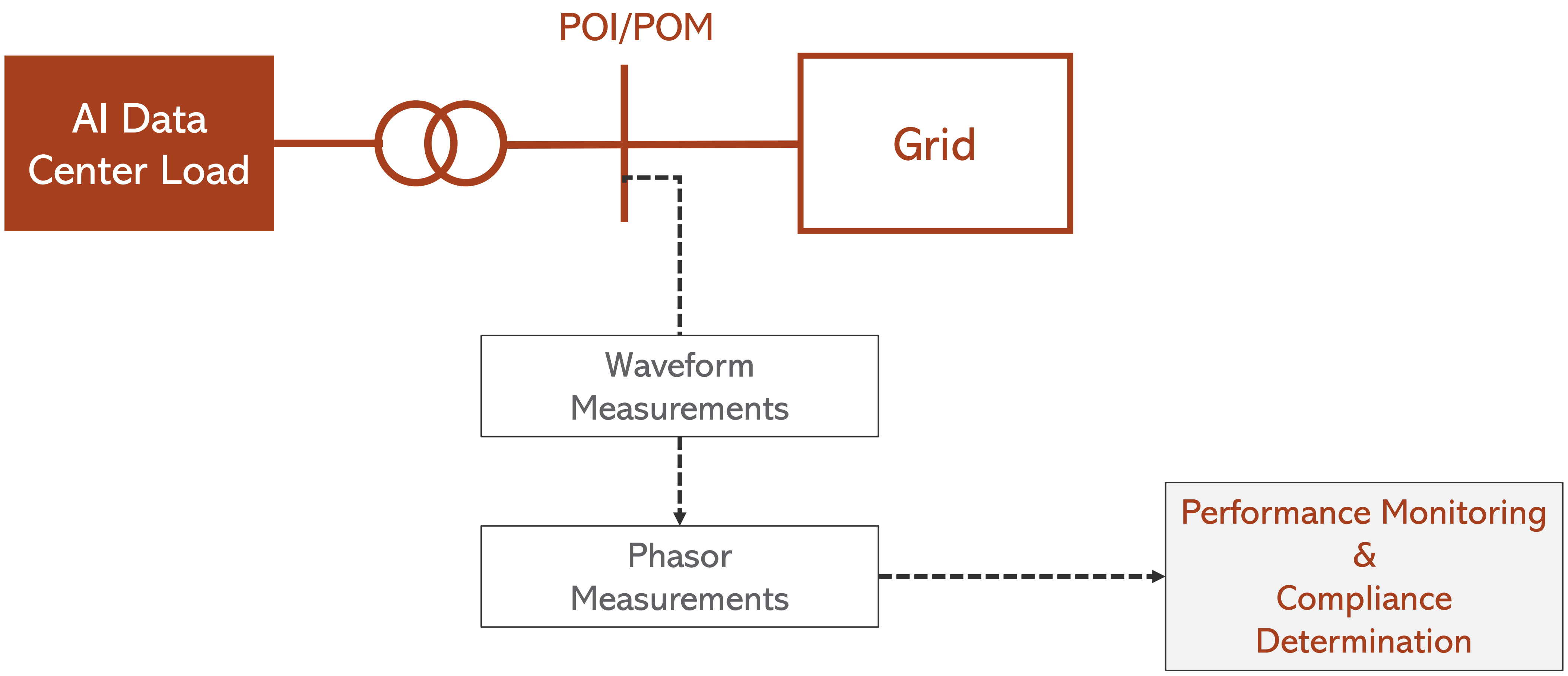


Figure 9.1-2: Active Power Criterion for ΔP2 and T1, Example 2

ATC system Planning Criteria. https://cdn.misoenergy.org/ATC%20TO%20Planning%20Criteria108210.pdf

Measurement Systems for Monitoring LDDLs

- Compliance with the proposed requirements will require measurement systems capable of capturing LDDL dynamics, including high-frequency oscillations
  - Understanding the limitations of existing measurement systems, particularly PMUs, crucial



Limitations of PMUs in Monitoring High-Frequency LDDL Oscillations

- PMUs monitoring high-frequency oscillations face two major limitations:

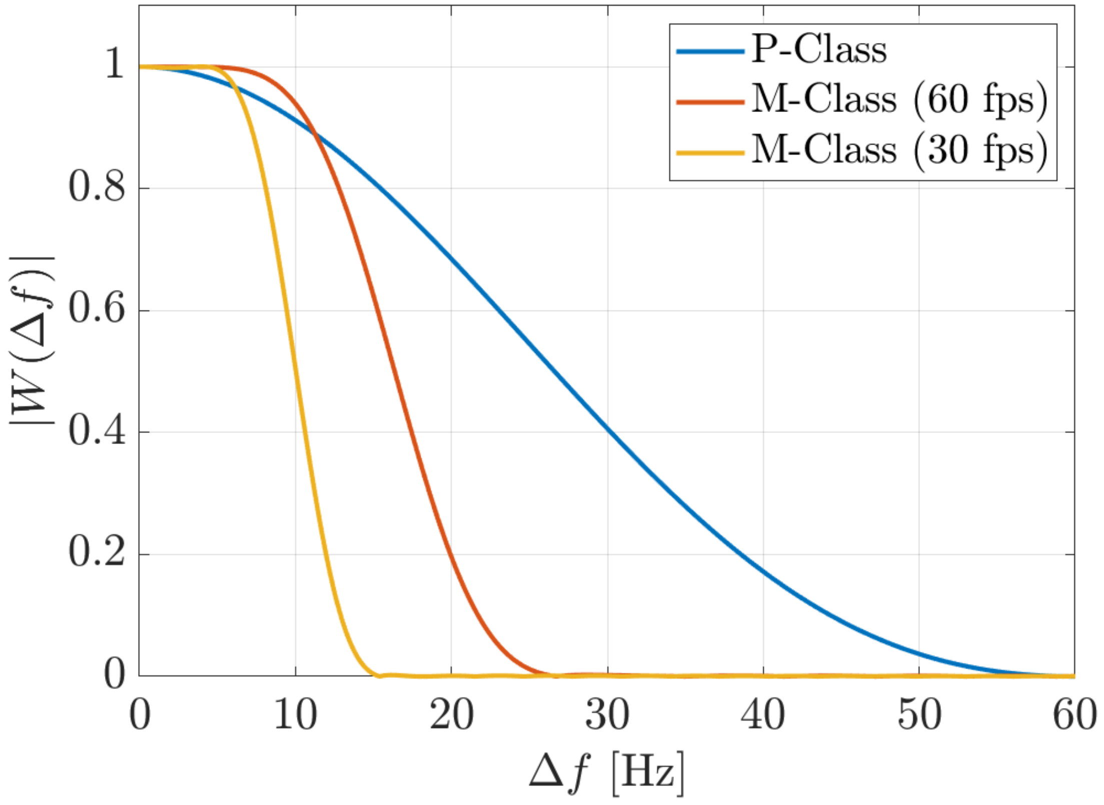
1. Due to reporting rate (RR)
   - ✓ Oscillations with frequency above Nyquist rate (corresponding to the RR) will be aliased
     - Eg: A PMU reporting at 30 fps cannot capture oscillations above 15 Hz -- PMU with higher RR will be needed
     - However, increasing the RR alone will not solve the problem

2. Due to low-pass filtering
   - ✓ Filters in phasor estimators are typically designed to be highly selective with a narrow passband around the fundamental
     - Significantly attenuate phasor oscillations greater than 5 Hz
   - ✓ IEEE standards define dynamic performance requirements only up to 5 Hz for M-class and up to 2 Hz for P-class PMUs
     - Commercial PMUs are not required to meet any accuracy requirements outside these frequency ranges

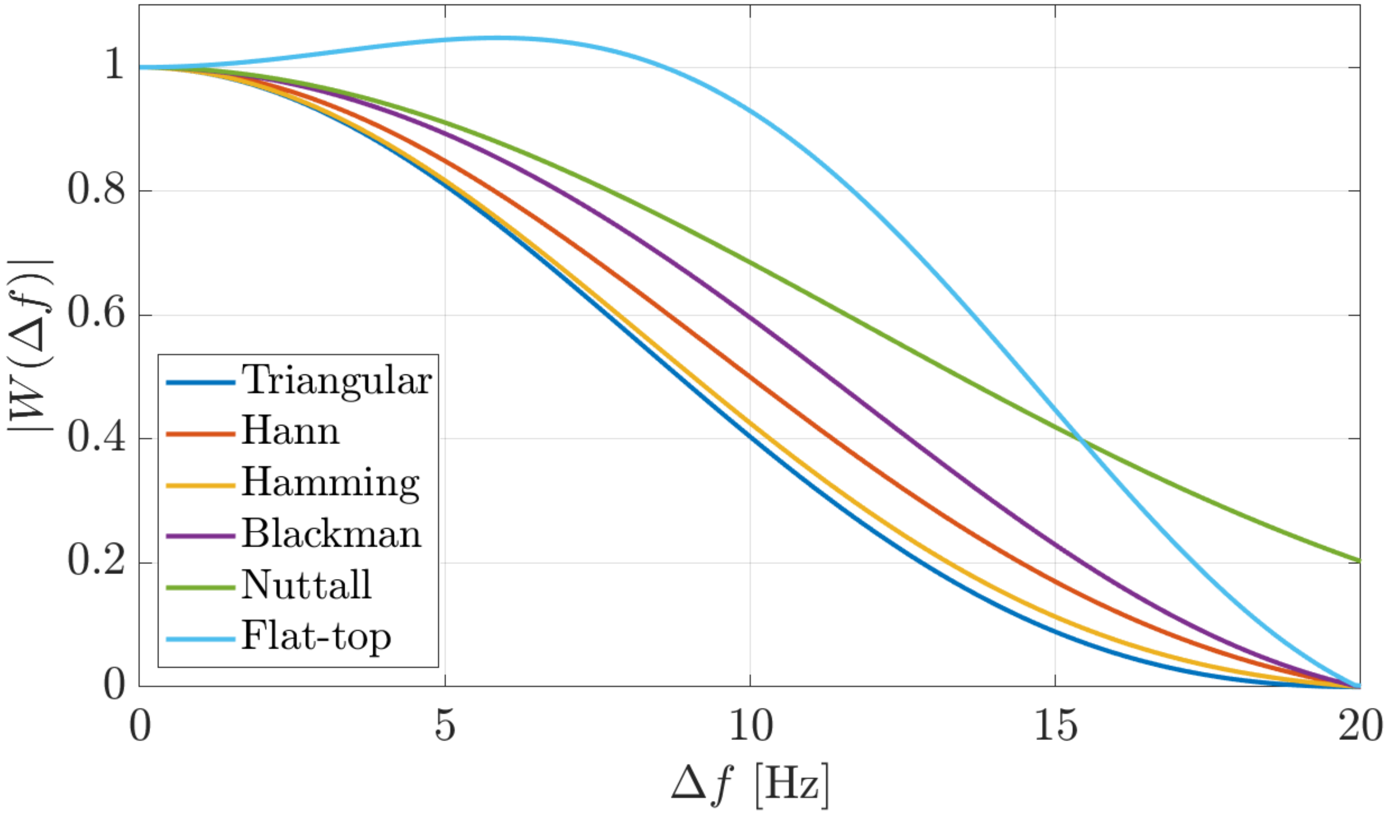
Filter-Related Oscillation Attenuation in Phasor Estimates

- Attenuation behavior of some commonly used filters in PMUs

P- and M-Class reference filters from the IEEE Std.



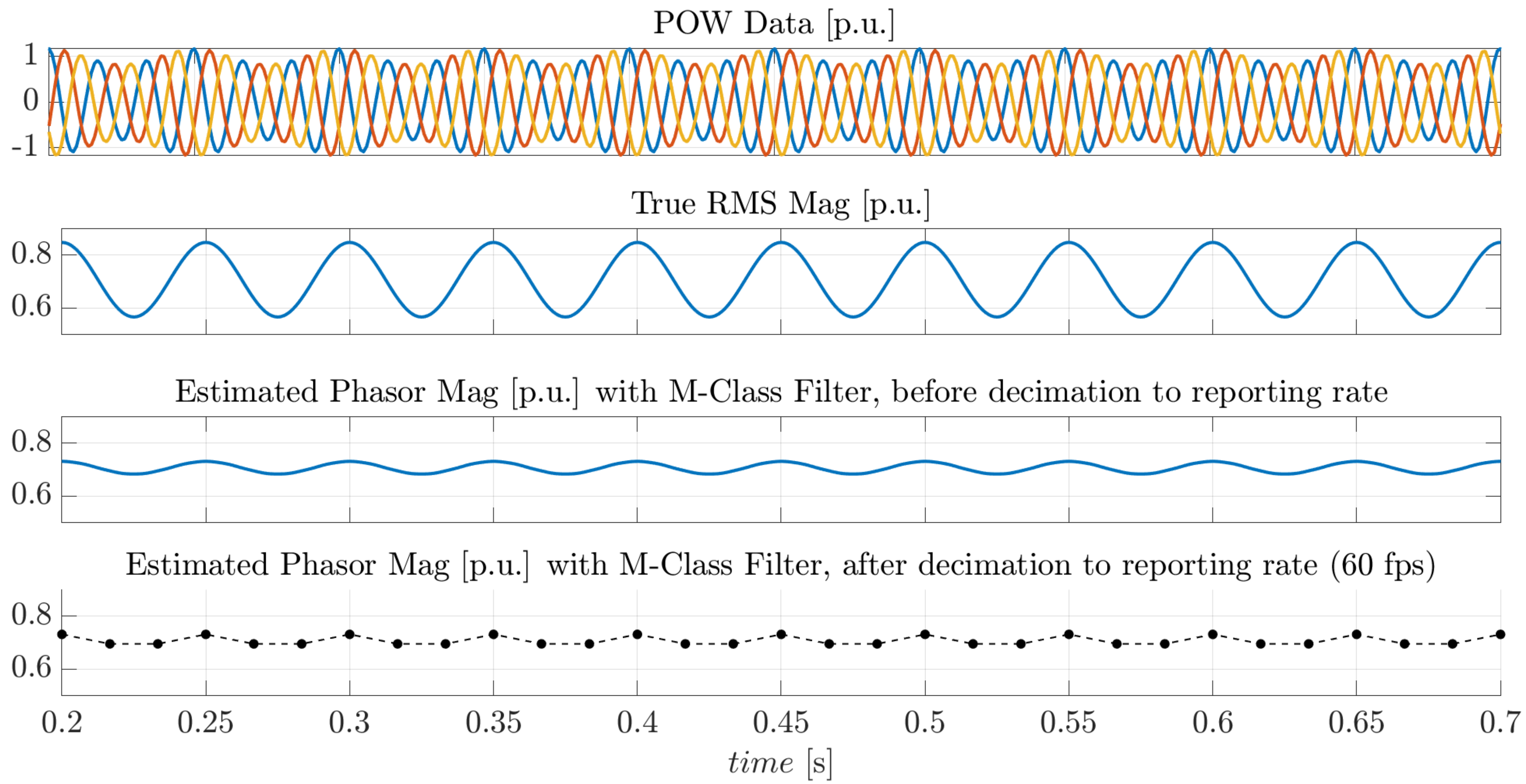
Few other commonly used filters in commercial PMUs



Attenuated oscillation estimates can lead to optimistic compliance assessments and inaccurate reliability evaluations

An Example of Filter-Related Attenuation

- **Synthetic data:** Three phase waveforms with 20 Hz oscillations in signal magnitudes with 0.25 p.u. peak-to-peak (p-p) amplitude
- **Phasor estimation** using reference M-Class filter from IEEE Std.
  - 60-fps M-class filter attenuates 0.25 p.u. p-p oscillation to 0.05 p.u. p-p



- Summary: At 60 fps PMU reporting, although the oscillation frequency preserved, the oscillation amplitude significantly attenuated

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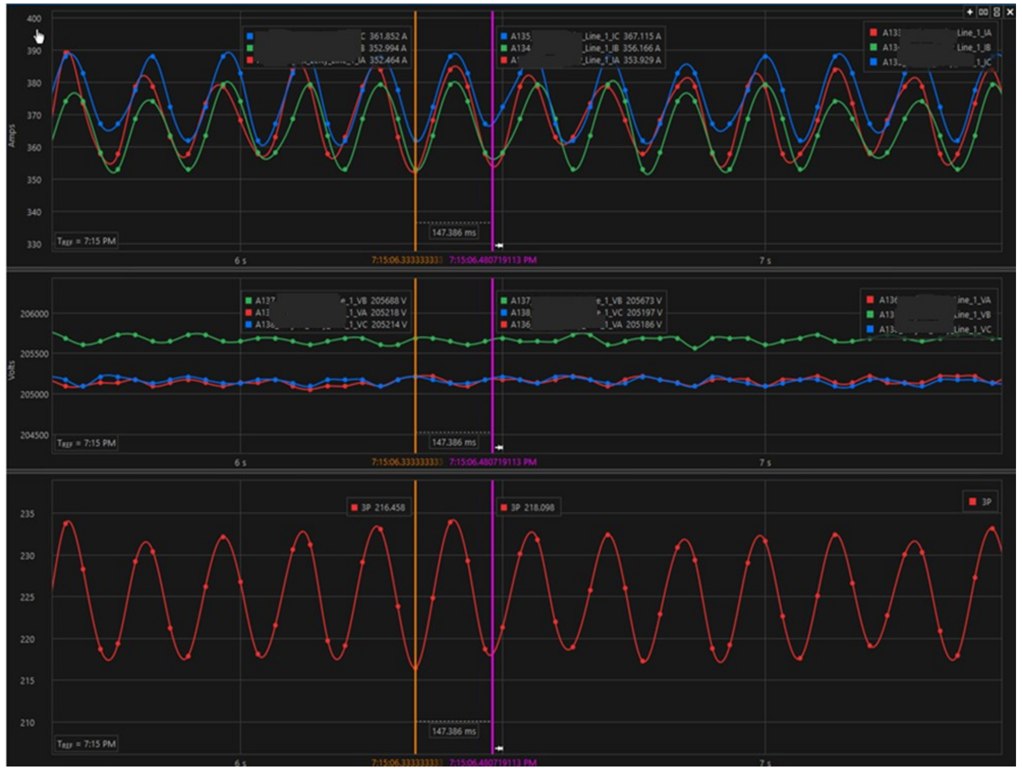
Another Example from a Real-World Incident

- ERCOT reported a similar observation when monitoring LDDL during an oscillation event
  - 30-fps PMU data at a POM showed 15-20 MW p-p oscillation at 7.5 Hz – this was later identified to be aliased and heavily attenuated
  - 20 samples/cycle DFR data from the same POM, corrected this observation to be 50 MW p-p oscillation at 23 Hz

PMU Data

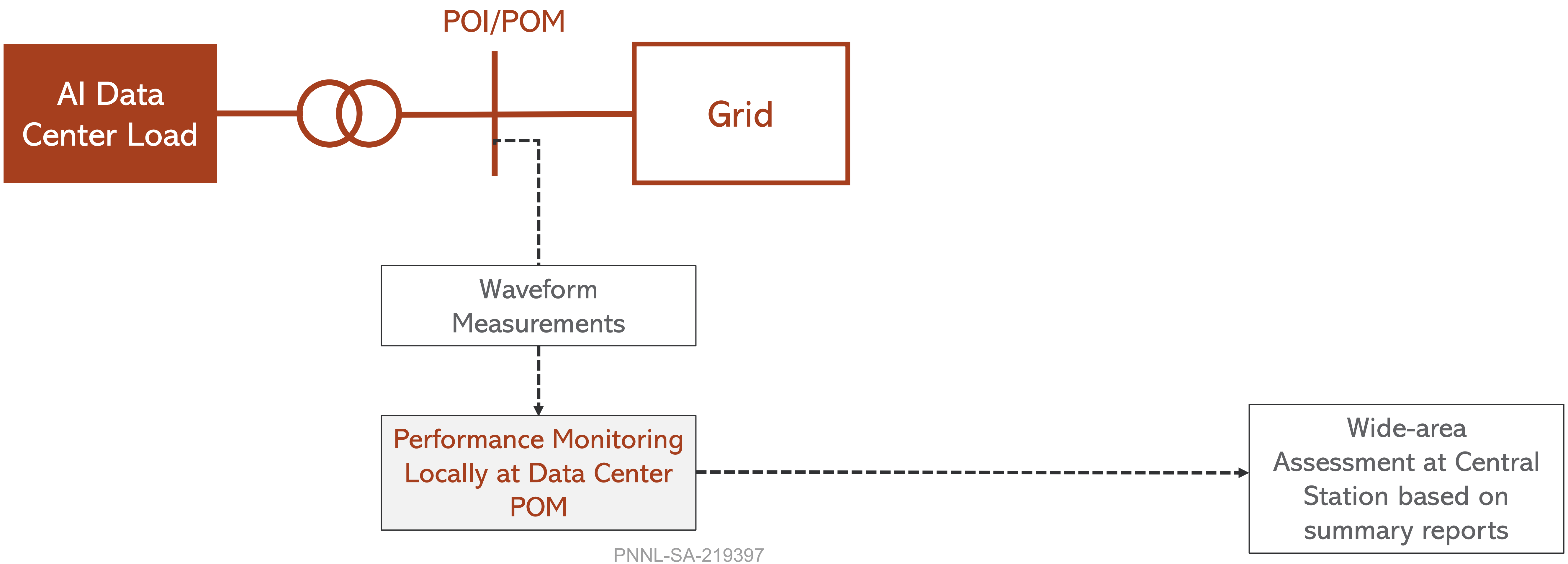


DFR Data (waveform)

Courtesy/Source: P. Gravois, ERCOT Large Load Event. https://www.ercot.com/calendar/03042025-LFLTF-Meeting

Point-on-Wave (POW) Measurements for Monitoring LDDL

- High-resolution POW data best suited for monitoring high-frequency oscillations
- However, existing communication infrastructure not equipped to stream large volumes of POW data
- Exploring distributed architectures to facilitate hybrid analysis
  - performance monitoring locally at LDDL and results communicated to control station for wide-area analysis



Thank you