Pacific Northwest
NATIONAL LABORATORY

Measurement Adequacy for Monitoring Data Center Oscillations

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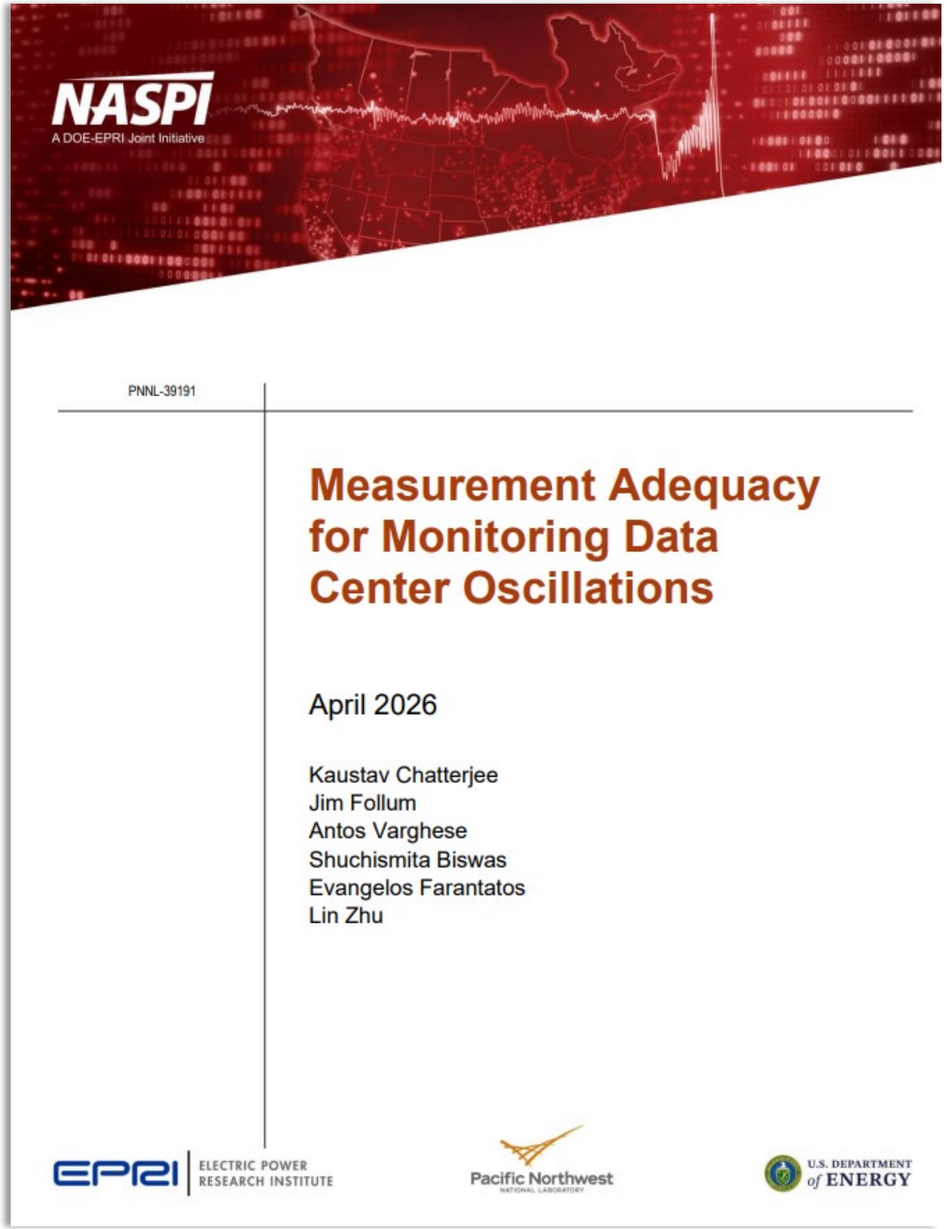
NASPI Technical Report

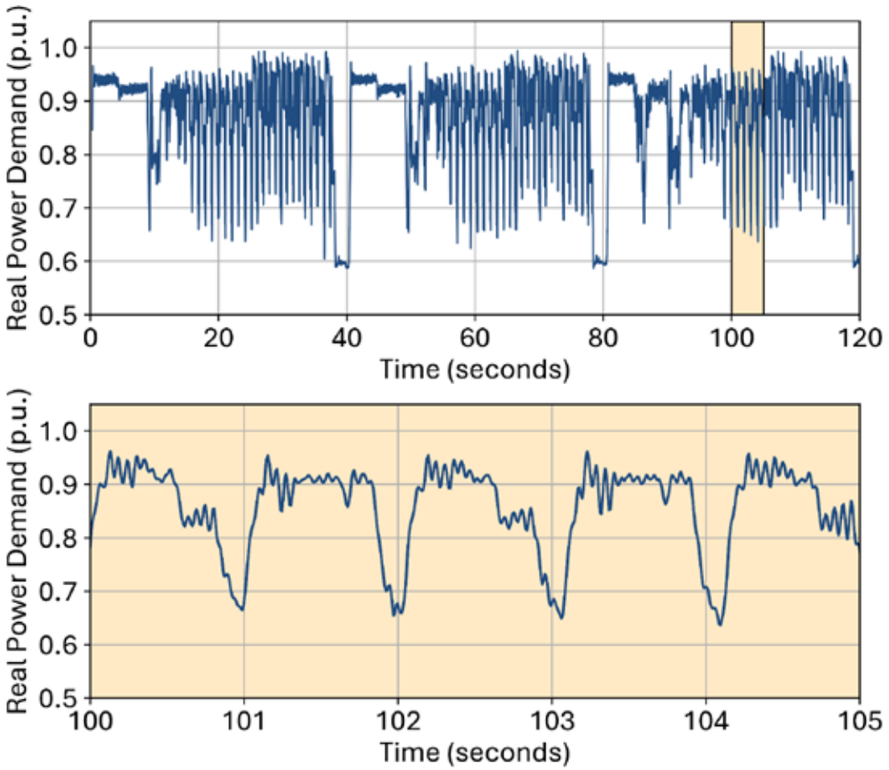
- Newly released NASPI report on measurement adequacy for monitoring data center oscillations
  - Comprehensive assessment of capabilities and limitations of PMU and POW measurement systems for monitoring oscillations
  - Based on DOE-OE funded research at the Pacific Northwest National Laboratory
  - Includes collaborative contributions from Electric Power Research Institute

https://www.naspi.org/documents/measurement-adequacy-monitoring-data-center-oscillations



Data Center-Related Oscillations

- Grid operators are seeing an unprecedented growth in hyper-scale AI data center loads
  - This has introduced new operational challenges
- AI training workloads have periodic demand profile that may induce forced oscillations in power system
  - Demand alternates between a high-power compute phase and a low-power data transfer and synchronization phase
- Induced oscillations can span a broad frequency range
  - Low frequencies: 0.1-1 Hz
  - Sub-synchronous frequencies: 5-59 Hz
- Forced oscillations (FOs) can pose reliability risks
  - May adversely interact with systems' natural oscillation modes



Source: NERC LLTF White Paper
www.nerc.com/globalassets/who-we-are/standing-committees/rstc/3_doc_white-paper-characteristics-and-risks-of-emerging-large-loads.pdf

Emerging Large Load Oscillation Limits

- Multiple system operators in North America are proposing operational limits on large load-induced oscillations to maintain grid reliability
- Notable examples: AESO, ATC, ERCOT, PSEG (LIPA)
  - Limits defined on peak-to-peak oscillation amplitude in frequency bands, periodic load variability, etc.
  - Restricts oscillations from being too close to poorly-damped natural modes, including torsional modes of nearby generators

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Frequency Band	Limit	Rolling Window (w) for Calculation
High Subsynchronous (5.0 – 55.0 Hz)	The $P_{0\text{-}pk,avg}$ for the sum of any two adjacent frequency bins shall not exceed 3.5 $MW_{0\text{-}pk,avg}$	10 second rolling window
Low Subsynchronous (0.1 – 5.0 Hz)	The $P_{0\text{-}pk,avg}$ for the sum of any two adjacent frequency bins shall not exceed 10.0 $MW_{0\text{-}pk,avg}$	60 second rolling window
Low Subsynchronous (0.1 – 5.0 Hz)	The $P_{0\text{-}pk,avg}$ for the sum of all bins shall not exceed 20.0 $MW_{0\text{-}pk,avg}$	60 second rolling window

LIPA Performance Requirements. https://www.psegliny.com/aboutpseglongisland/legalandregulatory

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)

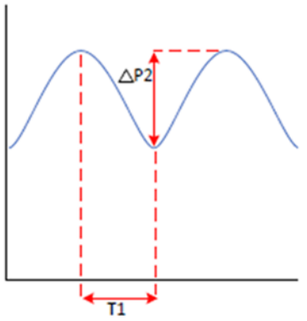


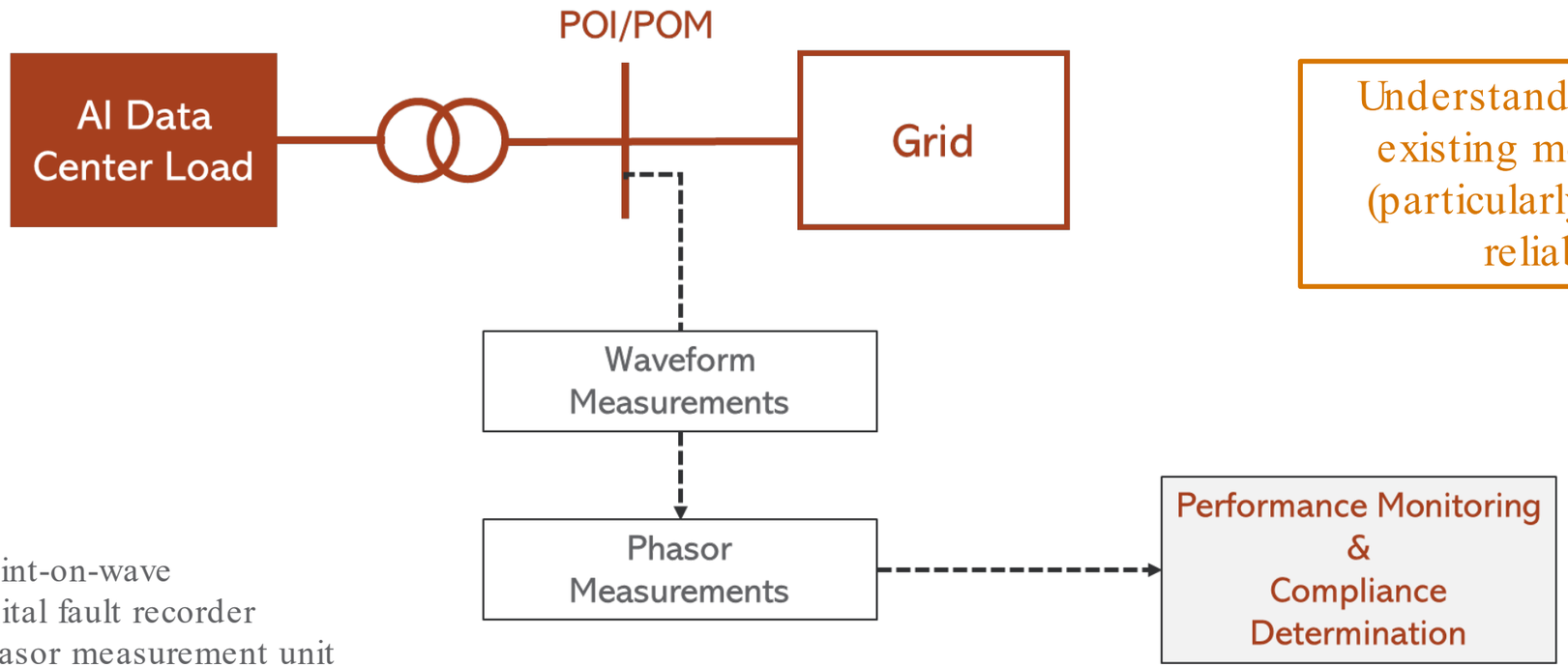
Figure 9.1-2: Active Power Criterion for ΔP2 and T1, Example 2

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

Measurement Systems for Performance Monitoring

- Performance monitoring against proposed limits will require advanced measurement systems capable of capturing emergent load dynamics, including high-frequency oscillations

- High-speed measurement systems include:
  - Direct waveform measurements as sampled POW data (at kHz resolution) – DFRs, PQ meters
  - Derived phasor measurements (at 30/60/120 fps reporting rate) -- PMUs



Understanding the limitations of existing measurement systems (particularly PMUs) is crucial for reliable monitoring

POW: point-on-wave
DFR: digital fault recorder
PMU: phasor measurement unit

Performance Limits of PMUs

- IEC/IEEE 60255-118-1 standard specifies the performance requirements for PMUs
  - Specifies dynamic measurement bandwidth (i.e., Δf) up to which certified PMUs are required to maintain performance guarantees (i.e., TVE < 3%)

- Performance requirement to maintain TVE < 3% up to
  - $\Delta f = 2$ Hz for P-class PMUs
  - $\Delta f = 5$ Hz for M-class PMUs

- Some vendors have products with extended bandwidth
  - Not a requirement in PMU standard

Table 4 – Synchrophasor measurement bandwidth requirements using modulated test signals

Modulation level	Reference condition	Minimum range of influence quantity over which PMU shall be within given TVE limit			
		P class		M class	
		Range	Max. TVE	Range	Max. TVE
k_x = 0,1, k_a = 0	100 % rated signal magnitude, $f_{nominal}$	Modulation frequency 0,1 to lesser of F_s/10 or 2 Hz	3 %	Modulation frequency 0,1 to lesser of F_s/5 or 5 Hz	3 %
k_x = 0, k_a = 0,1	100 % rated signal magnitude, $f_{nominal}$		3 %		3 %

Source: PMU Std: https://ieeexplore.ieee.org/document/6111219

Vendors may have different phasor estimation algorithms, but if compliant with the IEC/IEC Std., their dynamic performance is only guaranteed within the performance-class bandwidth

TVE: total vector error

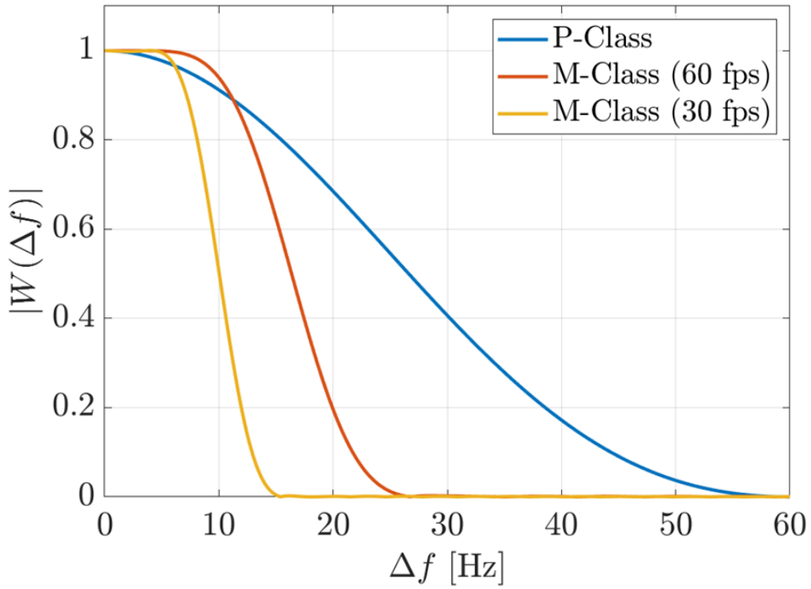
Challenges of Monitoring Higher-Frequency Oscillations with PMUs

- PMU performance boundaries in the IEC/IEEE Std. point to the following:
  - PMUs are well-suited for capturing low-frequency oscillations (< 5 Hz) but may face challenges in accurately representing higher-frequency oscillations

- Two primary factors determine effective performance limits of the PMUs

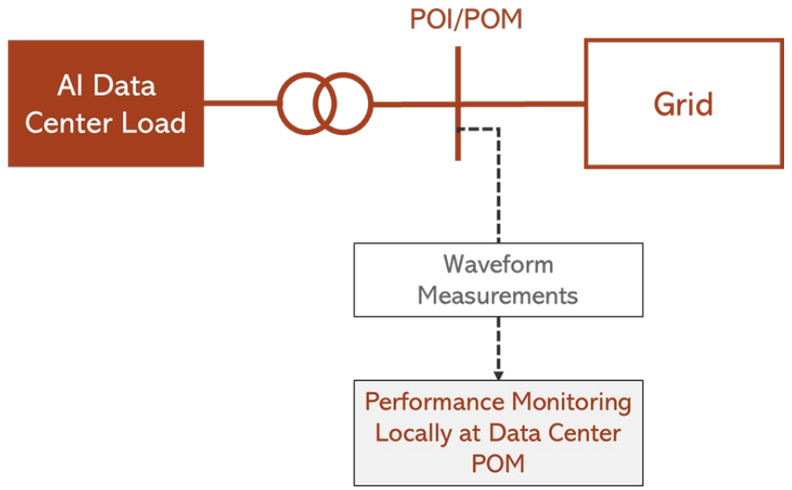
  - Reporting rate of the PMUs (e.g., 30/60/120 fps)
    - Determines the theoretical limit on the observable frequencies
    - Oscillations with frequency above Nyquist limit aliased and/or removed

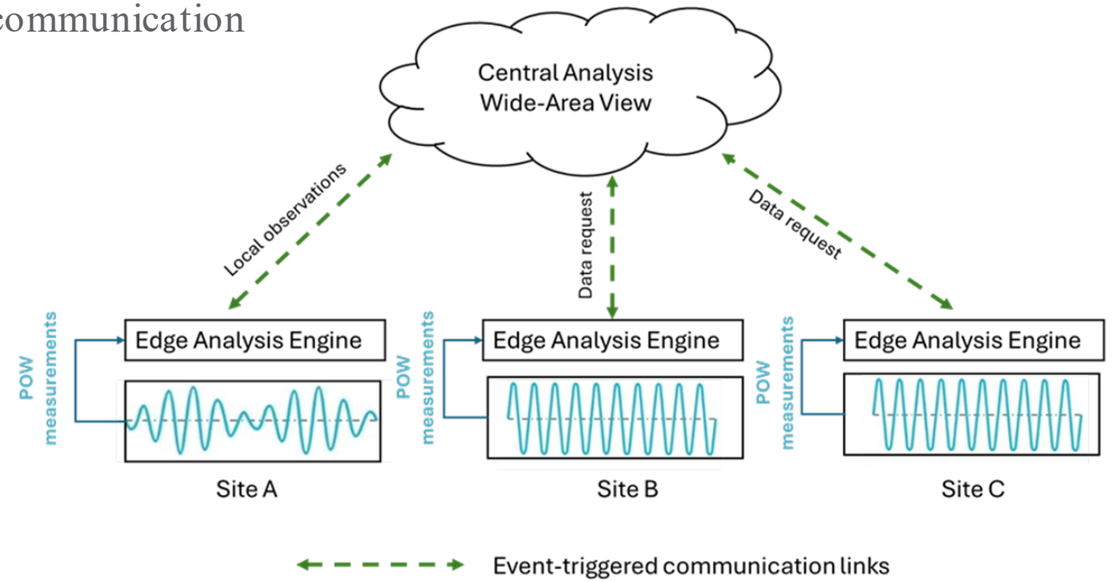
  - Low pass filtering in the phasor estimation
    - Attenuates amplitudes of oscillations outside filter passband
    - Most PMUs have narrow passband
    - Attenuated amplitude may result in optimistic assessment of compliance



Monitoring Based on POW Data

- POW measurements offer significantly higher temporal resolution and do not suffer from estimation-related attenuation
  - Addresses most limitations of PMUs, particularly for monitoring high-frequency oscillations
- Presents other challenges related to data acquisition, continuous streaming, and storage
- Emerging solutions for using POW data in oscillation monitoring
  - Local analysis at POM
  - Cloud-based services for centralized analysis
  - Hybrid solutions – distributed computing with limited communication





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Thank you

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