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Measurement Adequacy for Monitoring Data Center Oscillations

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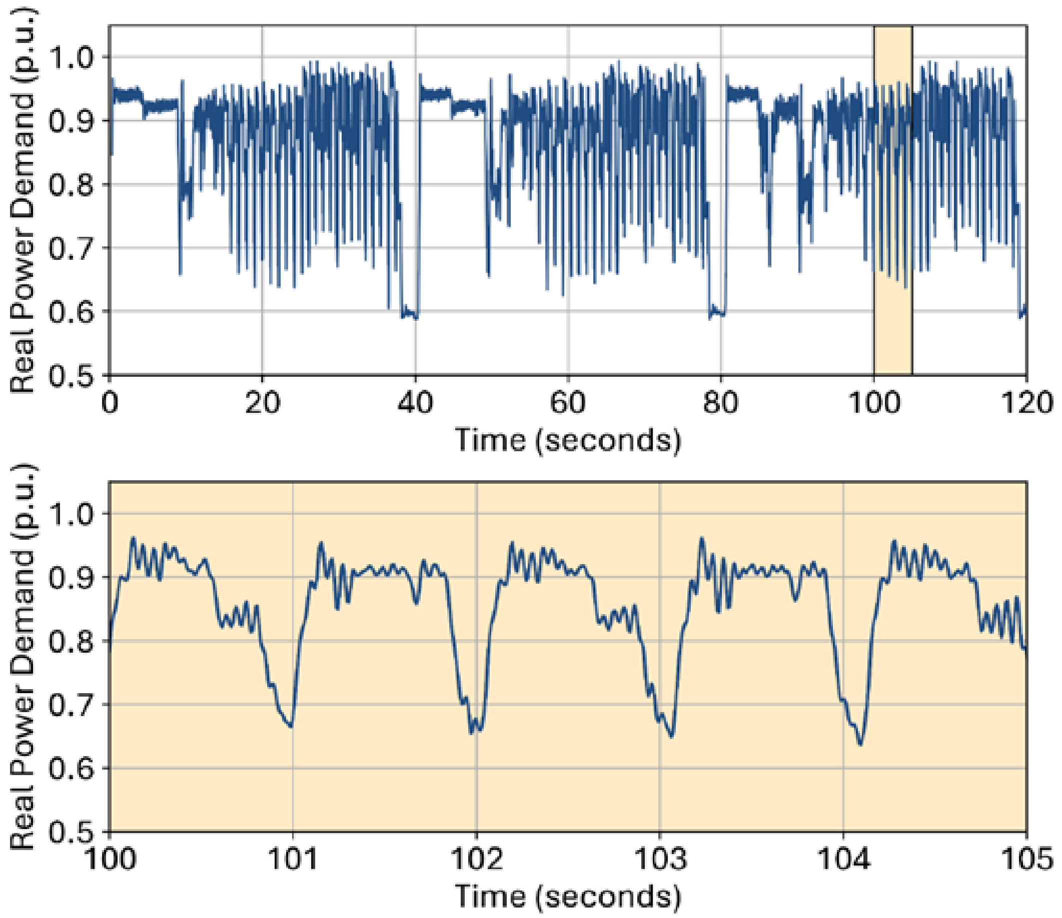
Introduction

- United States is 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)
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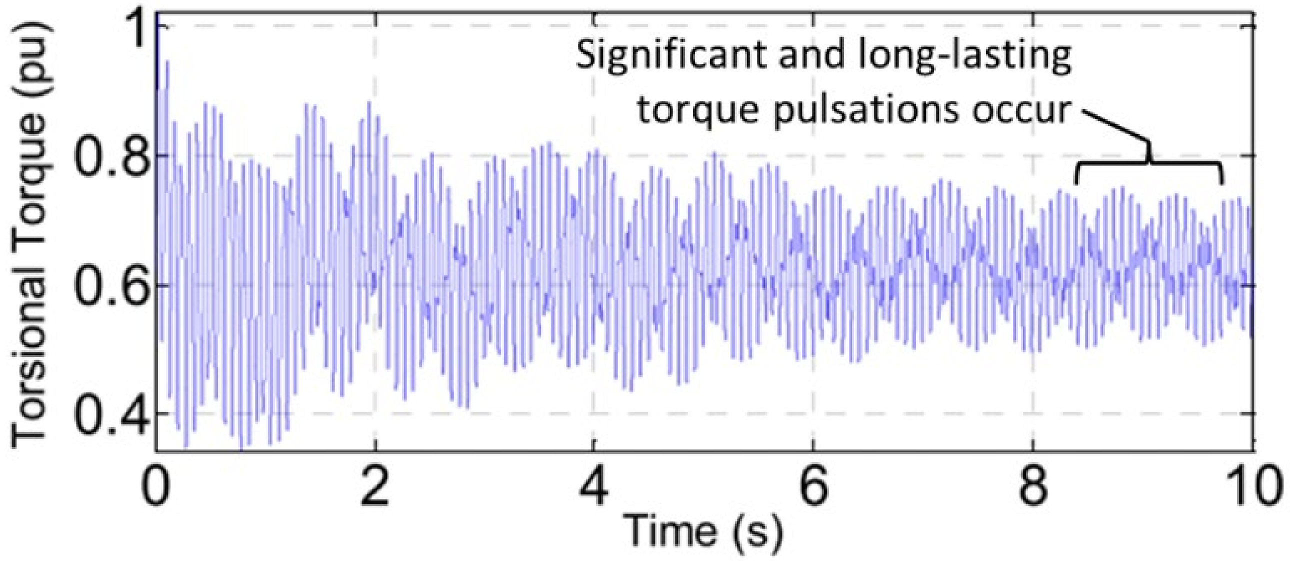
Adverse Impacts of Forced Oscillations

- **Low-frequency FOs** can cause resonance with systems' poorly-damped inter-area modes
  - Can amplify power oscillation in important tie-lines and corridors potentially leading to tripping and/or other protection actions

- **Higher-frequency FOs** in the sub-synchronous range may align with torsional modes of nearby synchronous generators
  - Can amplify mechanical oscillations and torque pulsations in the generator shaft inducing stress and fatigue

Need for defining permissible oscillation limits for AI-training loads and real-time monitoring



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

FO: forced oscillation

Emerging Large Load Oscillation Limits

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- 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.
  - Enforces oscillations not to be 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)

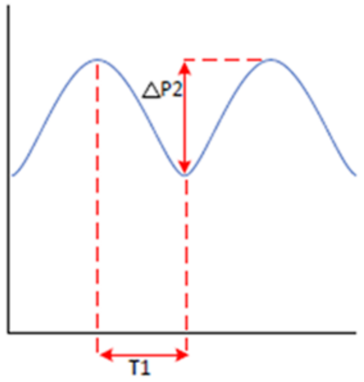

Figure 9.1-2: Active Power Criterion for ΔP2 and T1, Example 2

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

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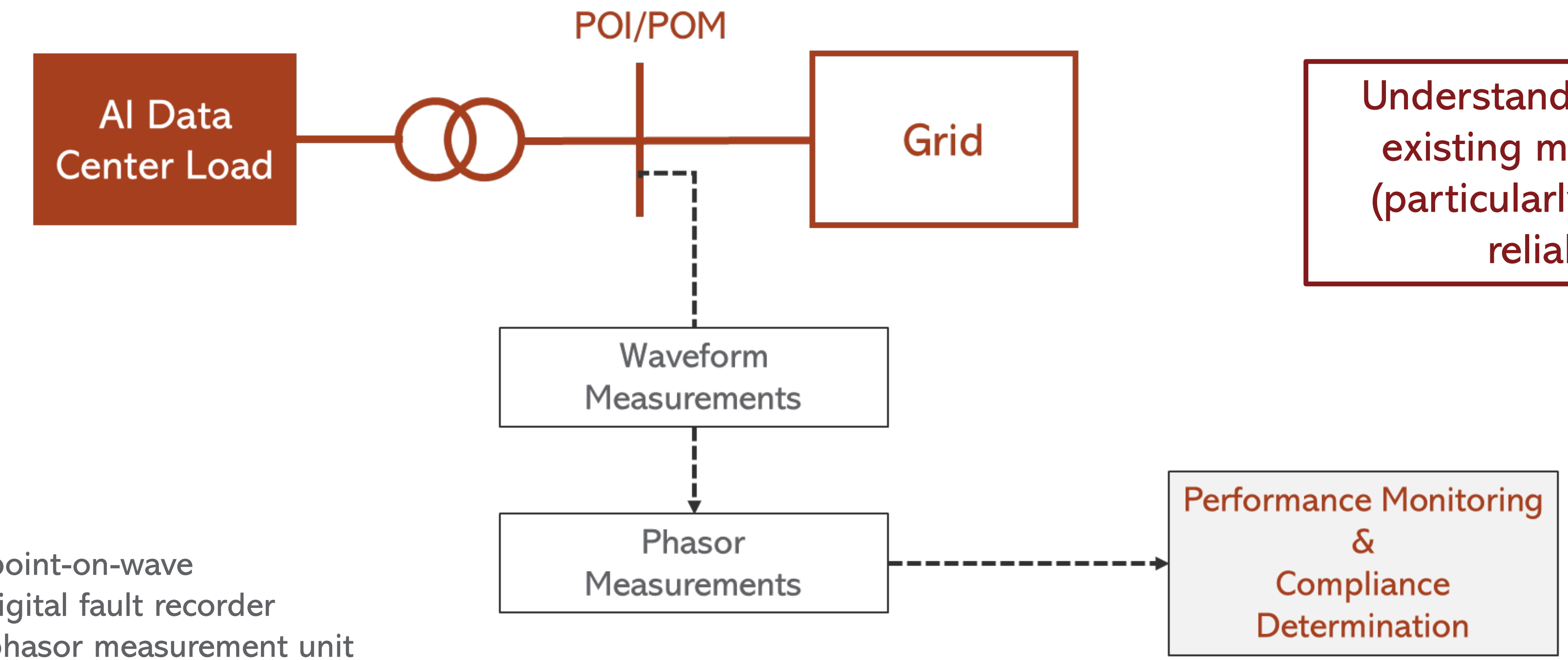
Measurement Systems for Performance Monitoring

- 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

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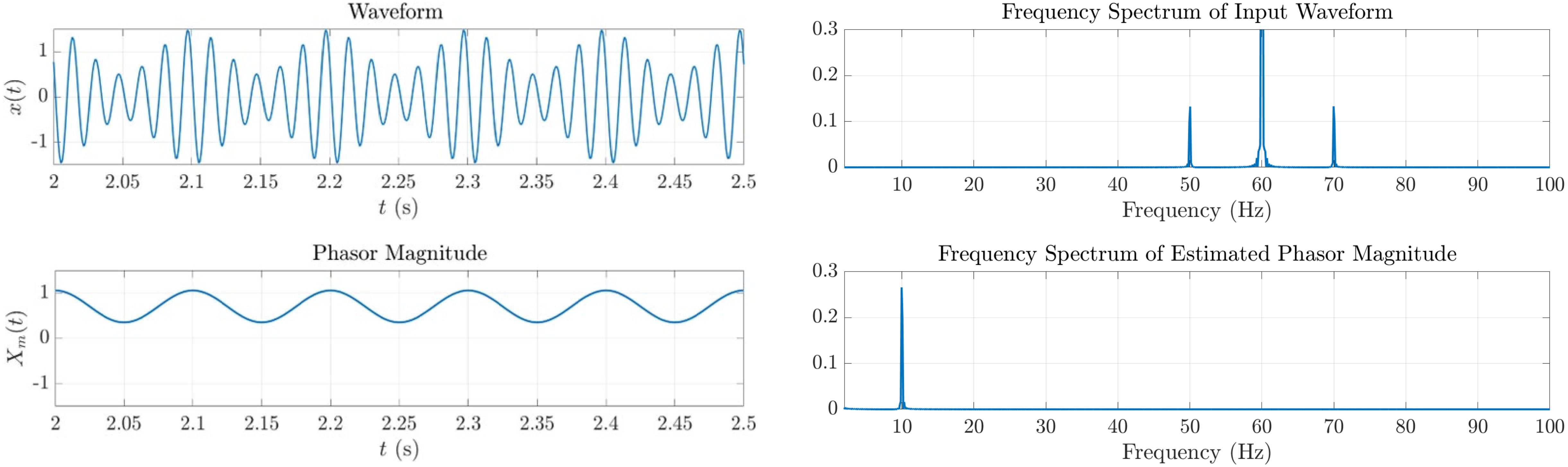
Oscillations in Phasors vs. Waveforms

- Phasors are derived measurements from waveforms -- so it is important to know how oscillations in waveform domain are represented in phasors
- **Equivalence:** Inter-harmonic sideband frequencies around the fundamental at $f_0 \pm \Delta f$ Hz in waveform $\Leftrightarrow \Delta f$ Hz oscillation in phasor



Phasor estimators are designed to preserve the sideband components $f_0 \pm \Delta f$ only up to a Δf frequency range

This presents a major limitation in observing oscillations with PMUs

NASPI Performance Boundaries of PMU

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- 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

- No expectation from commercial PMUs to meet any accuracy requirements outside these frequency ranges

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

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- 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 when monitoring higher-frequency oscillations
  - **Reporting rate** of the PMUs (e.g., 30/60/120 fps)
    - Determines the theoretical limit on the observable frequencies in the measurement reports
  - **Low pass filtering** in the phasor estimation
    - Designed to retain the fundamental components in waveforms, these filters suppress sideband spectral components that are sufficiently far from the nominal system frequency

- There may be other limiting factors specific to the algorithm used for phasor estimation

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Impact of PMU Reporting Rate

- In PMUs, the estimated phasors are down-sampled to match the reporting rate of data streaming (typically, 30/60/120 fps)

- Reporting rate sets a theoretical limit on the maximum observable frequency in measurement

Oscillations with frequencies greater than Nyquist frequency (= half of the reporting rate) cannot be observed in the reported measurements

  - Example: A PMU reporting at 30 fps cannot capture oscillations above 15 Hz

- Oscillations with frequency above Nyquist limit will be aliased to image frequencies
  - Anti-aliasing filters are present in PMUs to minimize the impacts of image frequencies

- However, increasing the reporting rate alone will not capture all higher frequencies

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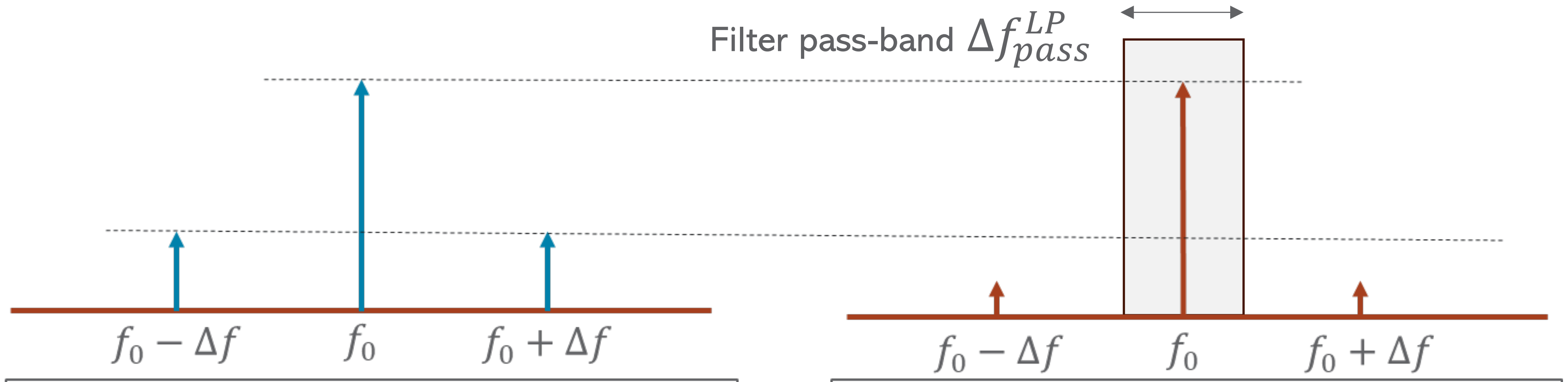
Impact of Low-Pass Filters in PMUs

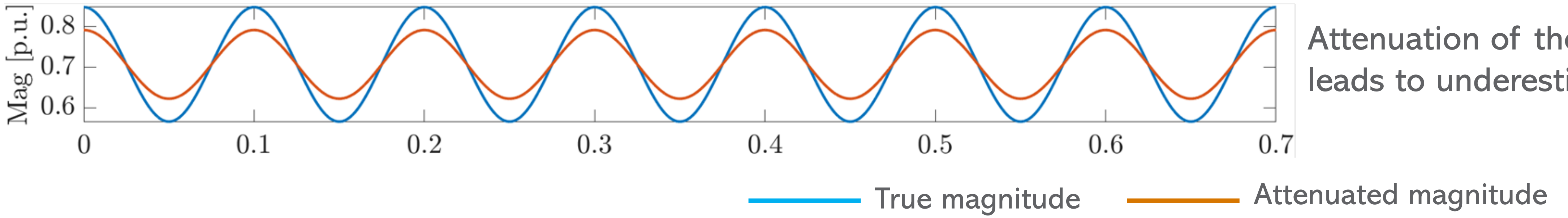
- There are additional low-pass filters in the phasor estimation
  - Designed to be narrow-band around the fundamental to suppress high-frequency components and maintain TVE requirements
- Amplitudes of the sideband components at $f_0 \pm \Delta f$ in the input waveform outside the filter passband are attenuated



Magnitude of frequency components in the input waveform

Filtering in PMU attenuates the magnitudes of the sidebands

Attenuation for a component at Δf is determined by the filter's magnitude response $W(\Delta f)$ at that frequency

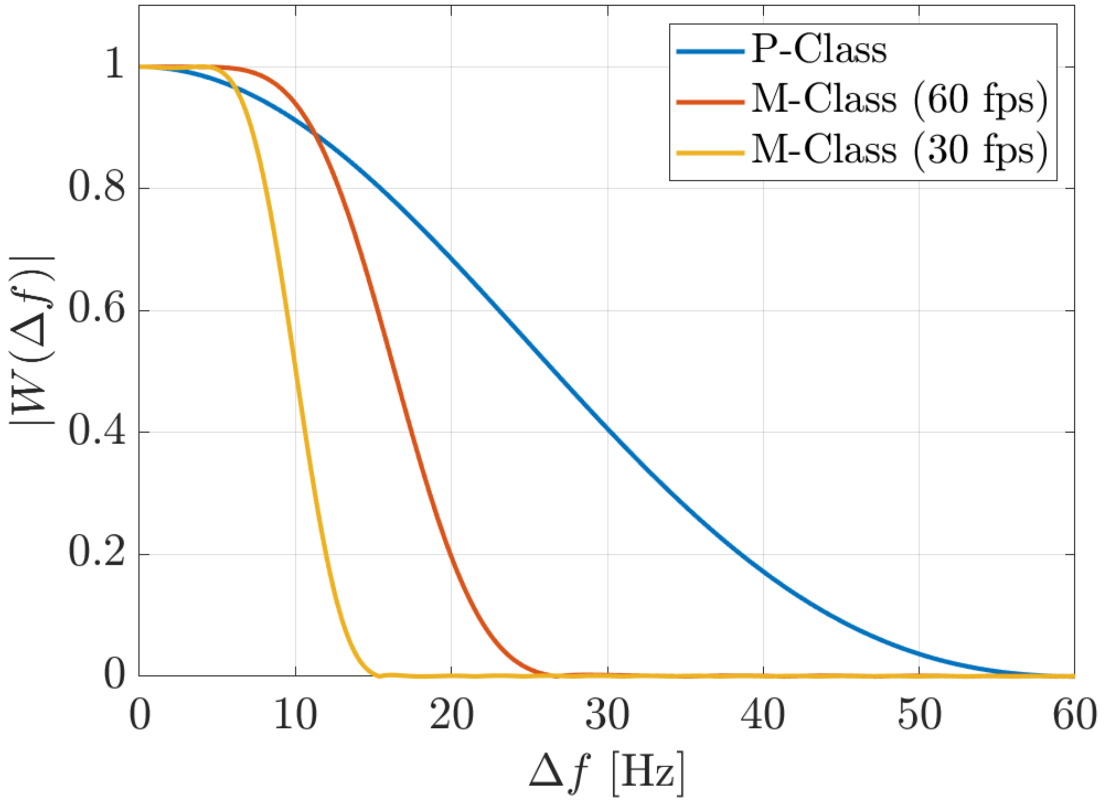


Attenuation of the sideband components leads to underestimation of phasor oscillation

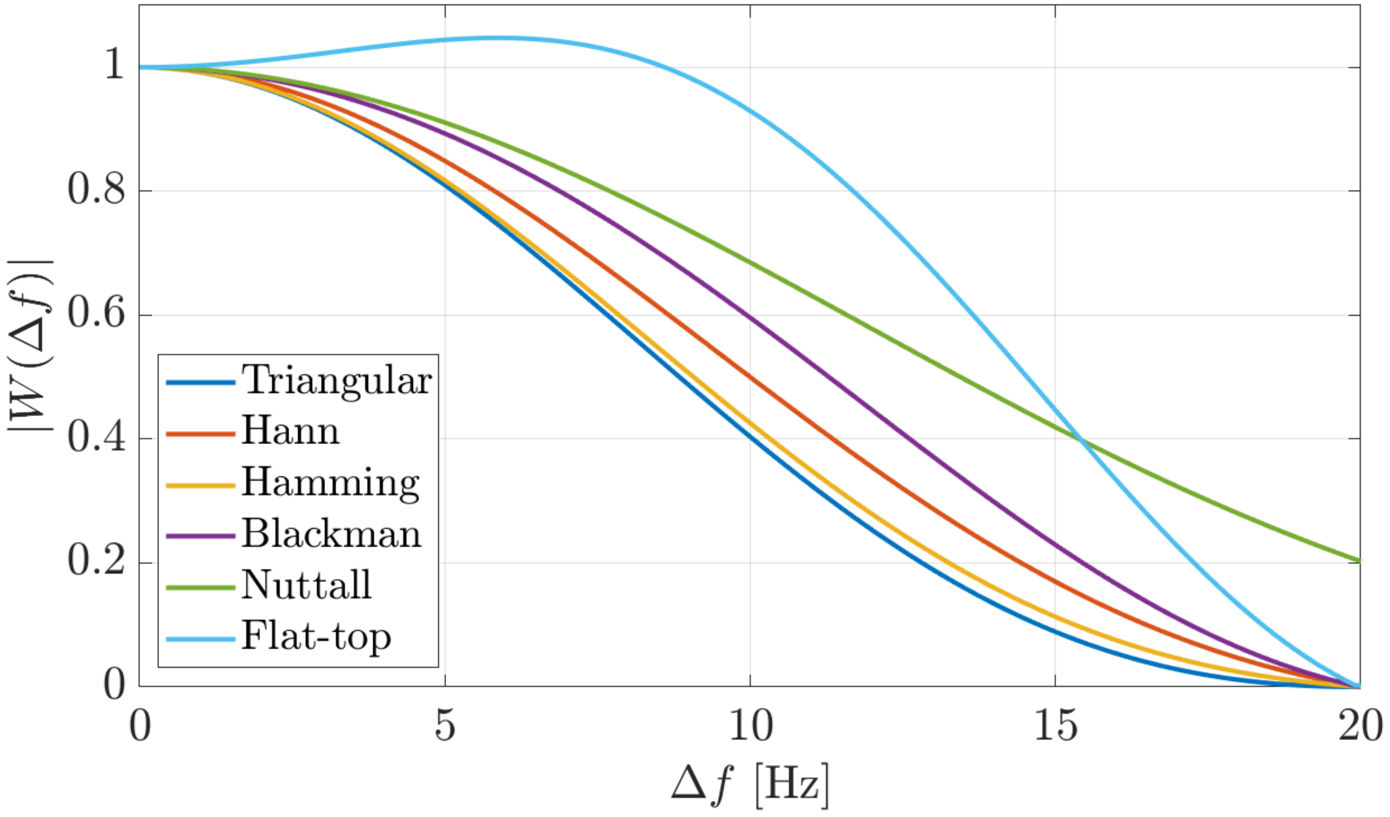
Filter-Related Oscillation Attenuation in Phasor Estimates

- Attenuation behavior of some commonly used filters in PMUs

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



Other commonly used filters in commercial PMUs



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

An Example of a Real-World Event

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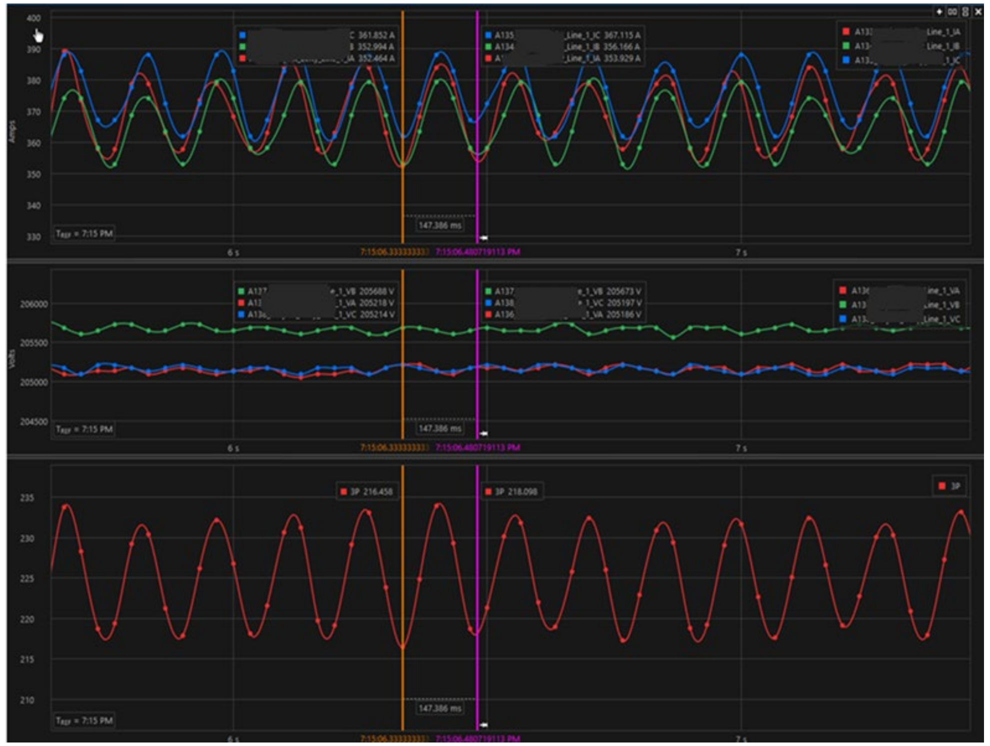
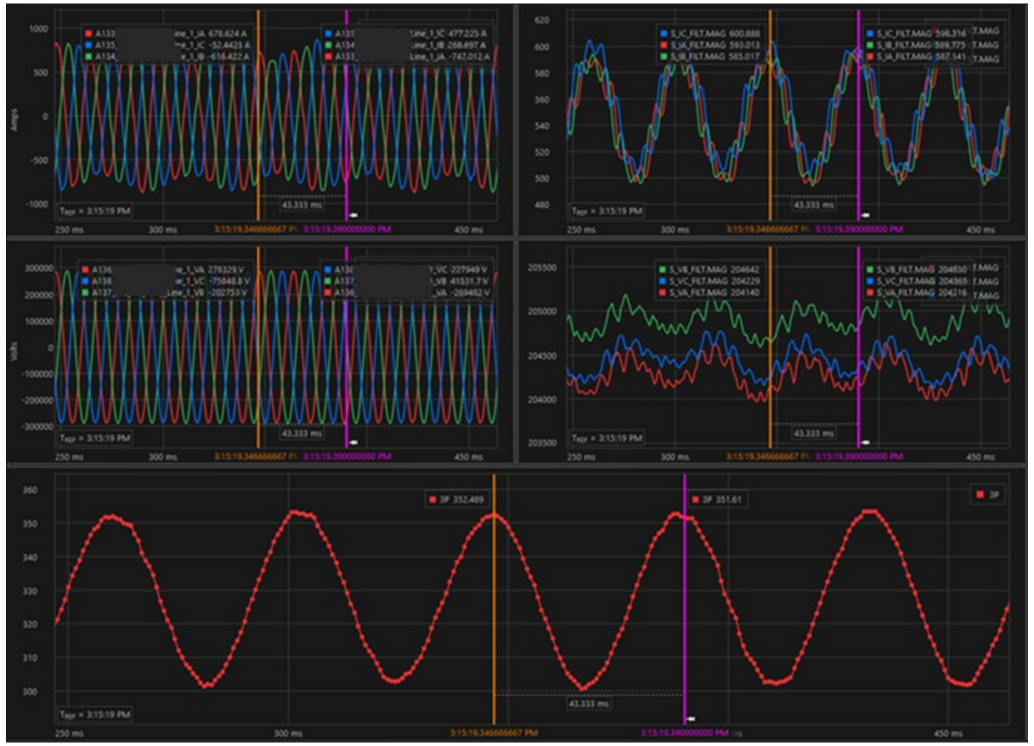
- ERCOT reported a large load oscillation event that was observed differently in PMU and POW measurements
  - **PMU Data (at 30 fps):** reported oscillation frequency as 7.5 Hz and peak-to-peak magnitude as 15-20 MW
  - **DFR Data (at 20 samples/cycle):** reported oscillation frequency as 23 Hz and peak-to-peak magnitude as 50 MW

Oscillation in PMU data was aliased to a different frequency and significantly attenuated

PMU Data



DFR Waveform Data



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

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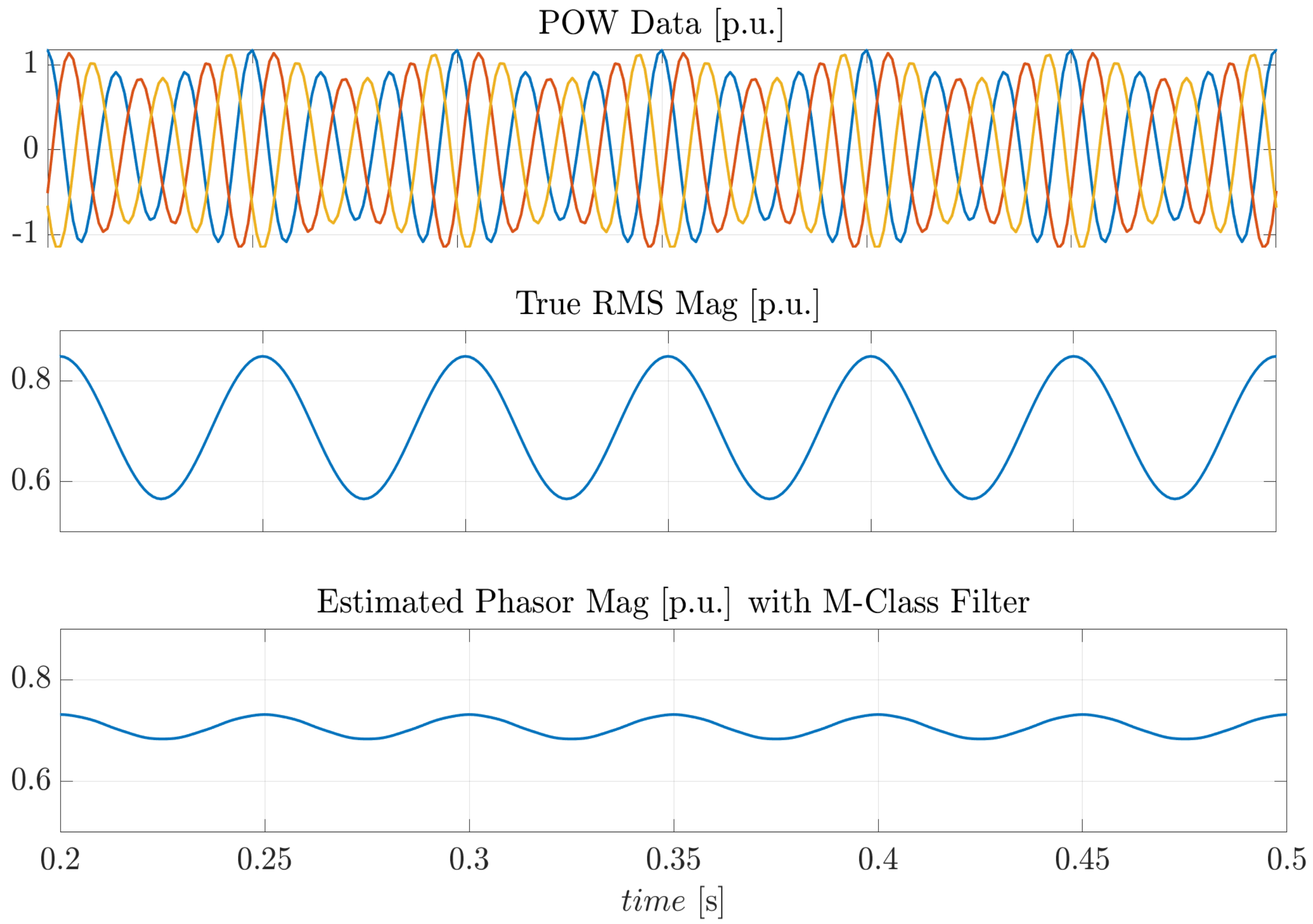
A Simulation Example

- **Synthetic three-phase POW data:** fundamental at 60 Hz and two sidebands at 40 Hz and 80 Hz
  - Representative of a true phasor oscillation at 20 Hz with 0.25 p.u. p-p amplitude

- **Phasor estimation** using reference M-Class filter from IEEE Std.
  - 60-fps M-class filter attenuates oscillation from 0.25 to 0.05 p.u.

With a 60-fps PMU, oscillation frequency at 20 Hz is preserved but the amplitude is significantly attenuated

- Attenuated amplitude has serious implication in oscillation detection and utility-specified compliance evaluation



Implication of PMU Amplitude Attenuation in Compliance and Monitoring (1)

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- Attenuated oscillation estimates can lead to optimistic compliance assessments and inaccurate reliability evaluations
- We highlight this limitation by comparing against oscillation limits from a representative performance requirement (from PSEG Long Island Power Authority)
  - PSEG's reliability requirement is based on evaluation on instantaneous POW measurements

PSEG LIPA's Oscillation Limit

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

- POW data at 600 Hz or higher to calculate instantaneous power
- Perform FFT on instantaneous power for a 1-s window and average amplitude estimates for each frequency over past 10 s
- Amplitude average in 5-55 Hz range must be below 3.5 MW

We evaluate the same requirement with PMU data to show attenuated phasor amplitude can fail to detect critical oscillations

Implication of PMU Amplitude Attenuation in Compliance and Monitoring (2)

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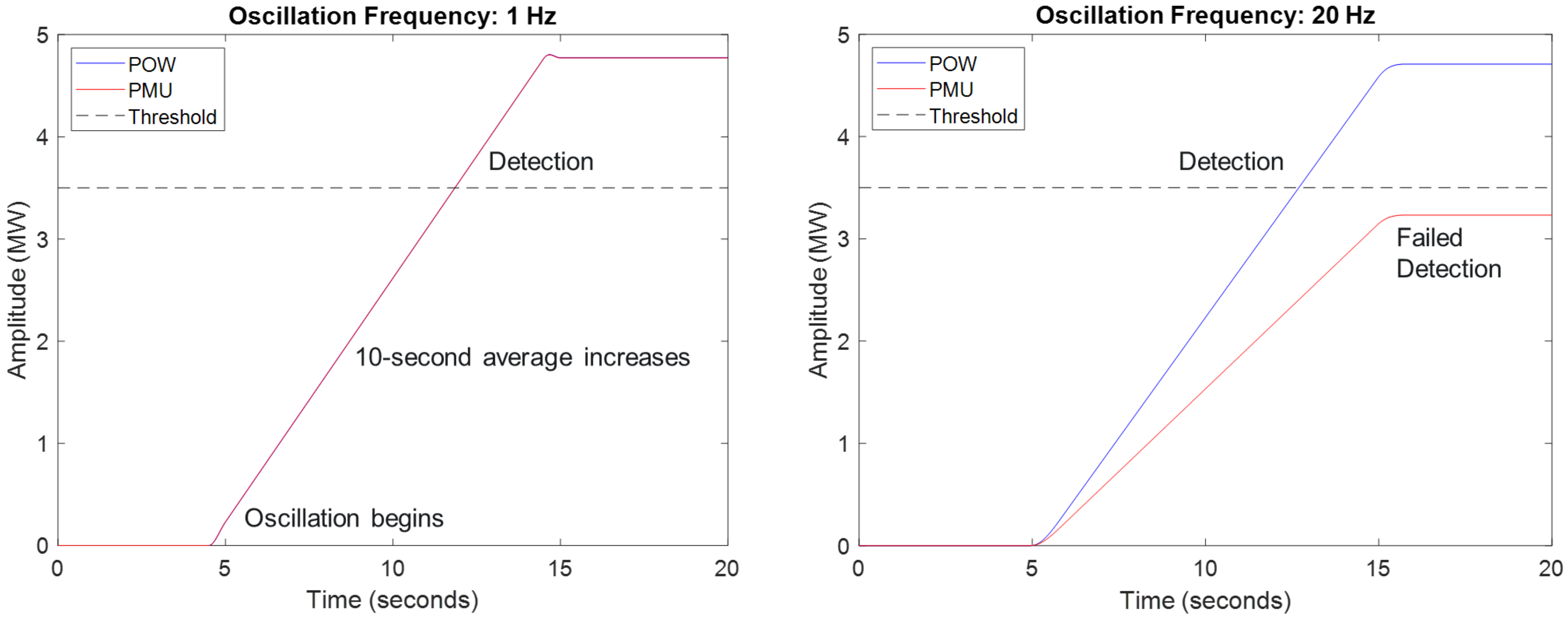
- Synthetic data: two instances of oscillation – **low-frequency (1 Hz)** and **high-frequency (20 Hz)** both with amplitude larger than 3.5 MW detection threshold
  - Phasor estimation performed using IEEE reference algorithm with 120-fps P-class filter

Oscillation is detected by PMUs when at 1 Hz, not detected when at 20 Hz



For detecting high-frequency oscillations, POW data-based detectors are more reliable

Monitoring Based on POW Measurements

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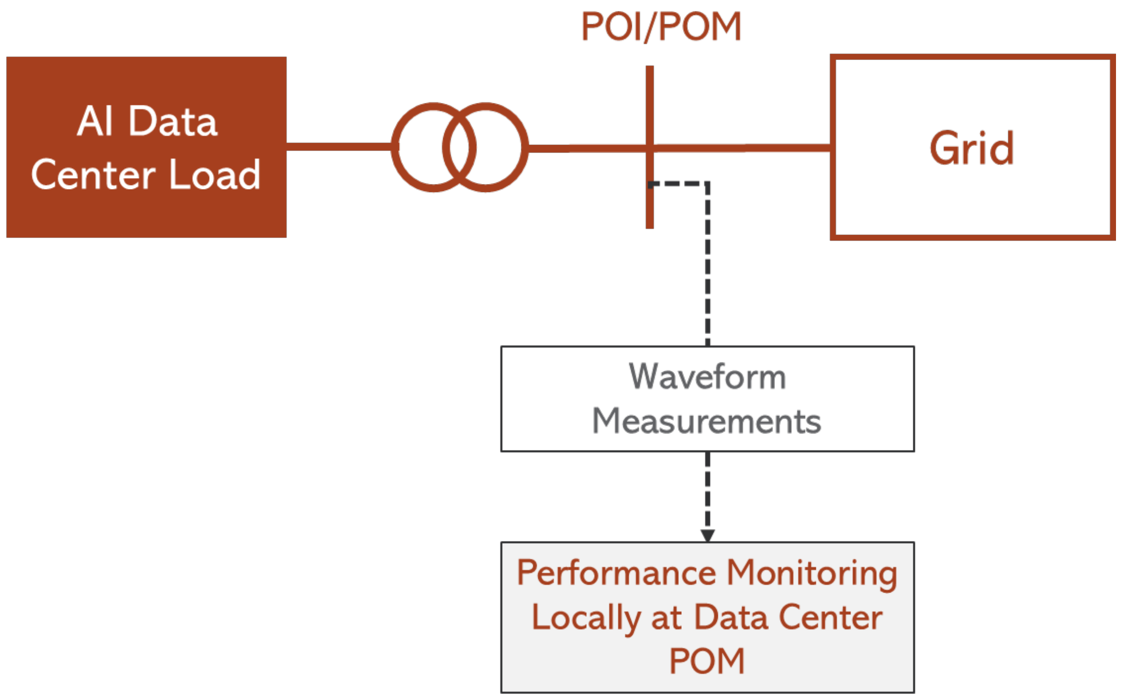
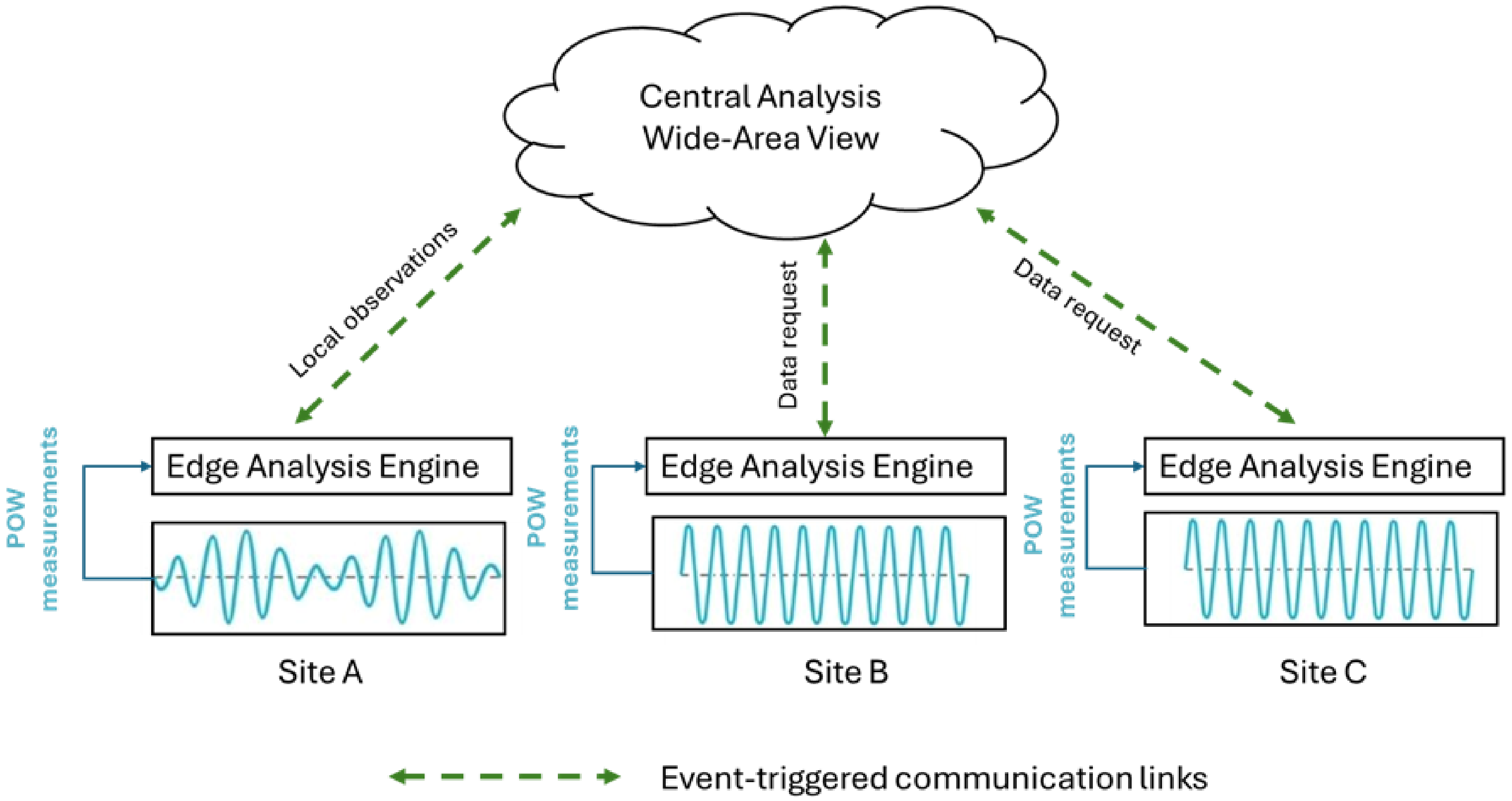
- Limitations of PMUs motivate the use of POW data for monitoring high-frequency oscillations
- POW measurements offer significantly higher temporal resolution and do not suffer from estimation-related attenuation
  - But there are other challenges related to data acquisition, transmission, and storage
- POW measurements in protection and monitoring have traditionally been event-triggered
  - For load oscillation monitoring, event-triggering not be suitable – continuous monitoring necessary
- Existing communication infrastructure designed for PMU data transport not equipped to stream large volumes of POW data
  - Upgrading these communication and storage systems to support continuous waveform streaming would require substantial investments

New monitoring architectures needed that leverage the high fidelity of POW measurements while avoiding the burdens of continuous streaming

Monitoring Based on POW Data

- Emerging solutions could include distributed and hybrid architectures for POW-based monitoring
  - High-resolution waveform measurements are processed locally at the measurement site and only summarized monitoring results are communicated to centralized utility servers
  - Leverages the fidelity of waveform measurements while significantly reducing the communication and storage burden





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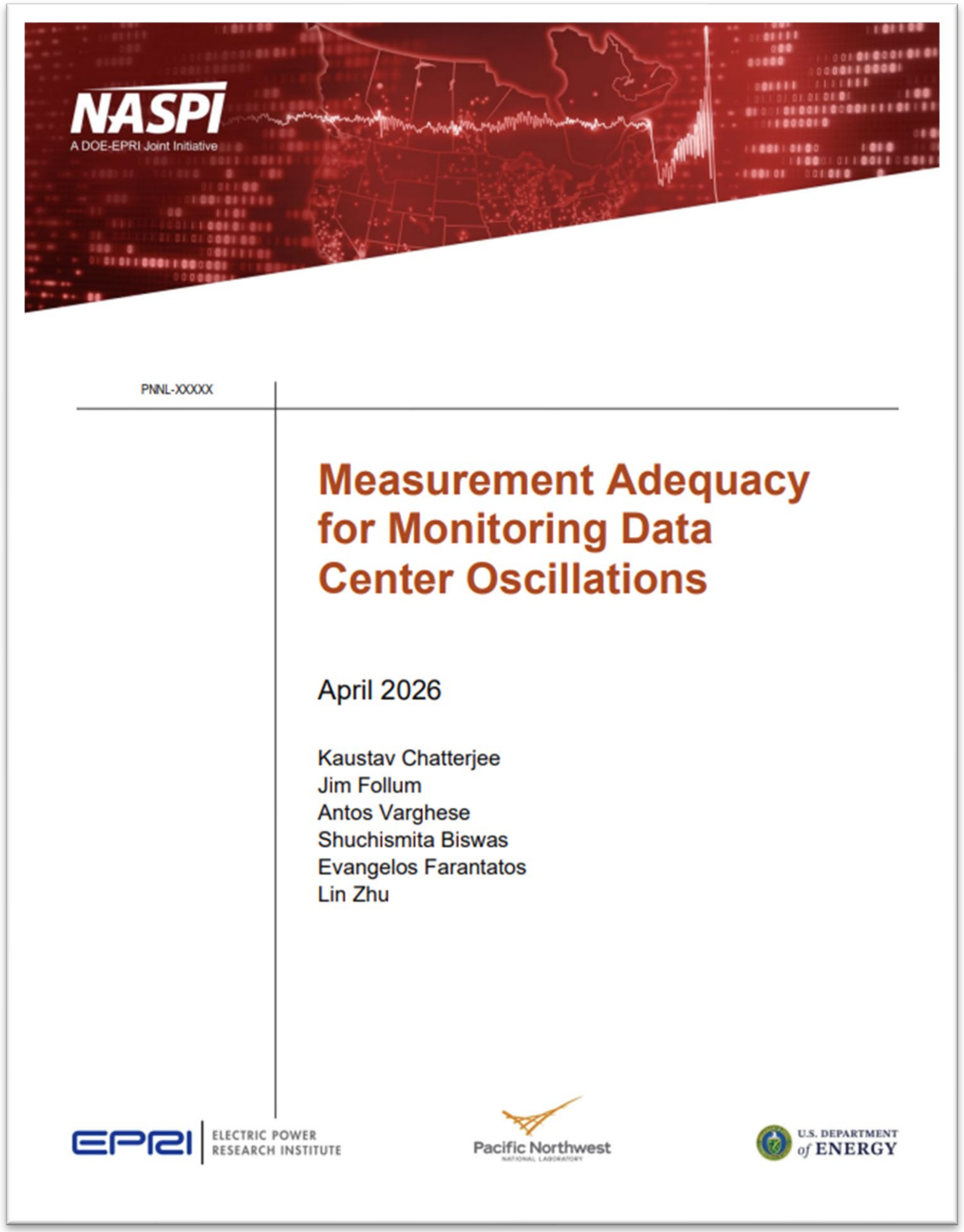
Summary and Conclusions

- PMUs are not well-suited to monitor oscillations that are higher than 5 Hz
- Even with higher reporting rates, internal filters in the estimation algorithms may attenuate oscillation magnitudes at higher frequencies
- Attenuated oscillation amplitudes from PMU estimates can incorrectly assess a critical oscillation as benign
- POW measurements more suited to monitor high-frequency oscillations
- High data volume and limited streaming bandwidth limits centralized analysis of continuous POW data
- Distributed architectures for POW-based monitoring are emerging

A follow-on NASPI report will cover these aspects in detail (to be released in April)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Thank you

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