Applicability and Limitation of Using PMU Data for High-Frequency Oscillations

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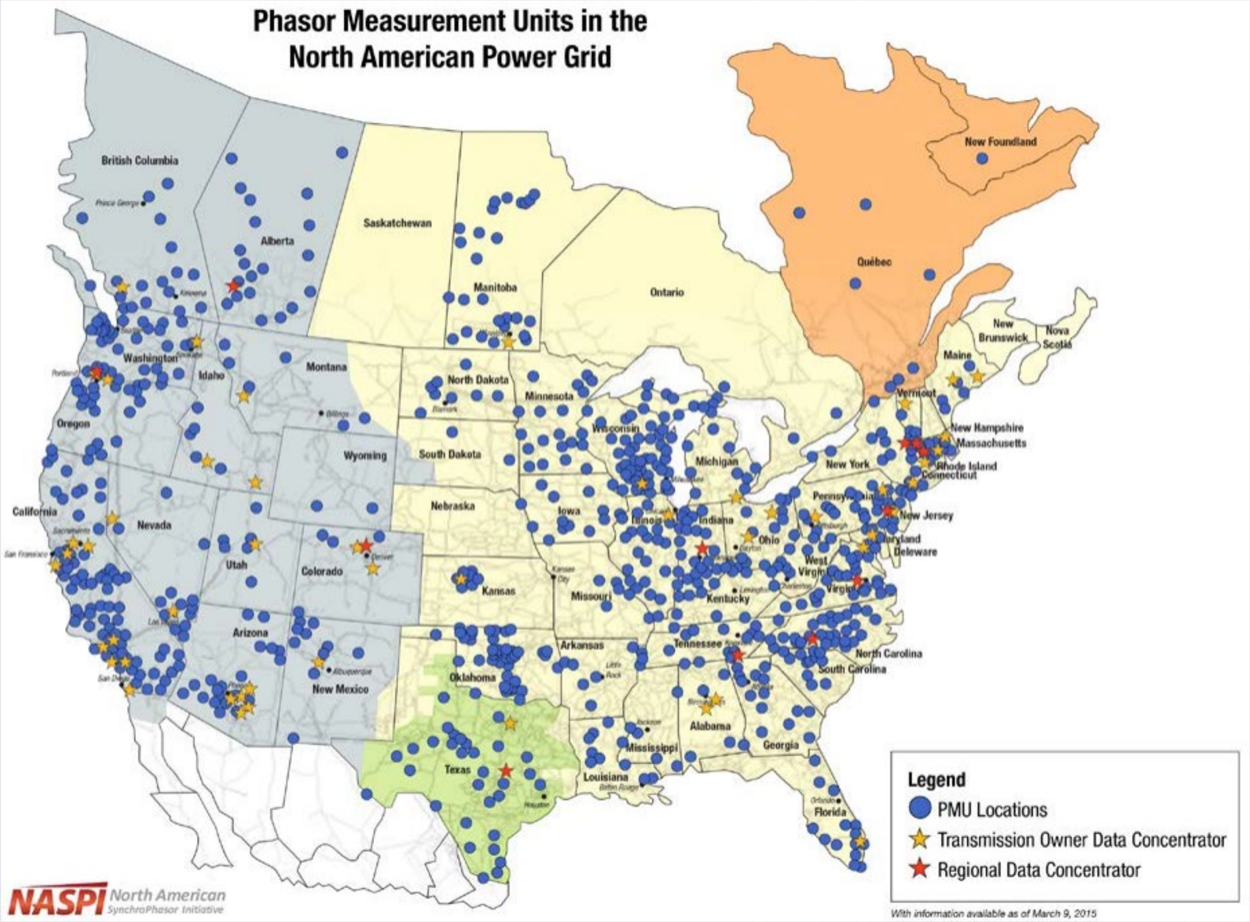
Background

- As of 2023, 2500+ PMUs have been deployed across the nation's bulk power systems [1].
- PMU data can be used both online and offline for enhancing situational awareness.
- Ref. [2] reported that PMU may suffer from aliasing effect, and its filters may attenuate frequencies above 5 Hz.

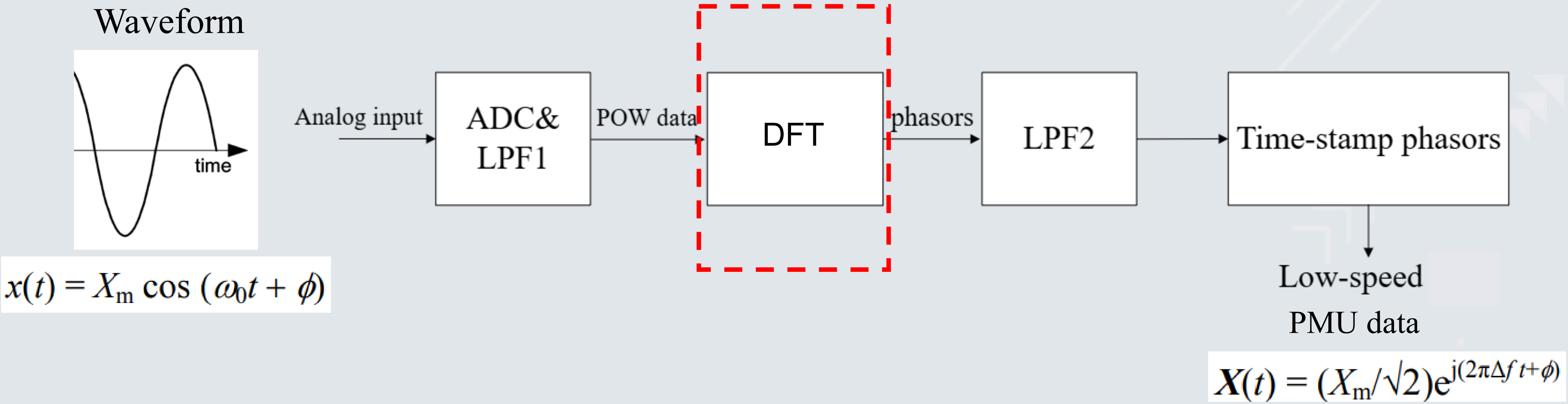


[3] NASPI. "Diagnosing Equipment Health and Mis-operations with PMU data." *NASPI Report, May 2015*.

[1] DOE, "Big Data Synchrophasor Analysis," https://www.energy.gov/oe/big-data-synchrophasor-analysis#:~:text=Phasor%20measurement%20units%20(PMUs)%20have,the%20condition%20of%20the%20grid.

[2] Follum, J., et al. "Phasors or waveforms: considerations for choosing measurements to match your application." *PNNL-31215. Richland, WA: Pacific Northwest National Laboratory.* 2021.

Typical Measurement Process in PMU



PMU phasor signal processing model [4]

- Well-known issues: Attenuation by LPF2, aliasing effect by low reporting rate.
- Main question: How accurate is DFT-based phasor if there are high-frequency oscillations?

[4] A. J. Roscoe, I. F. Abdulhadi and G. M. Burt, "P and M Class Phasor Measurement Unit Algorithms Using Adaptive Cascaded Filters," in IEEE Transactions on Power Delivery, vol. 28, no. 3, pp. 1447-1459, July 2013

[5] IEEE Standard for Synchrophasor Measurements for Power Systems," in *IEEE Std C37.118.1-2011 (Revision of IEEE Std C37.118-2005)* , vol., no., pp.1-61, 28 Dec. 2011

Test 1 – PMU Data for Low-Frequency Oscillations

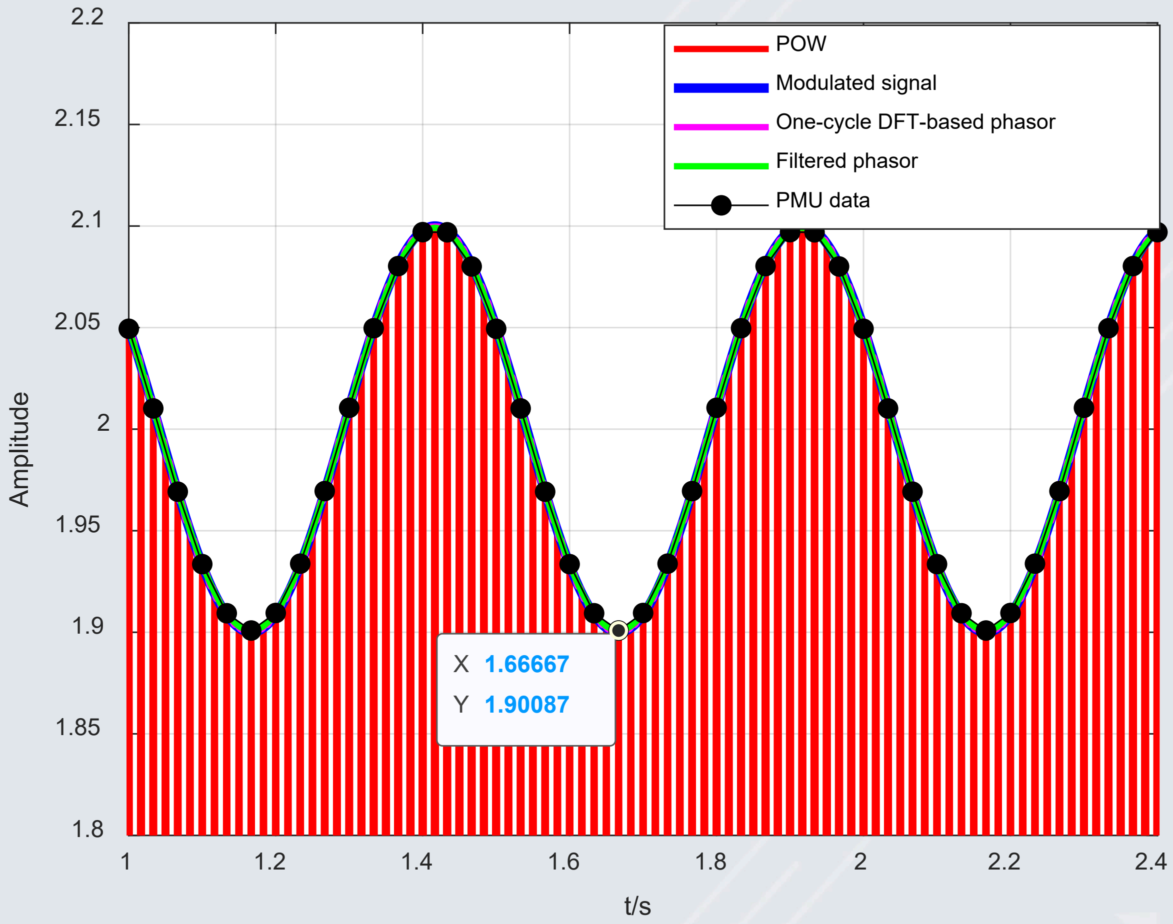
- Synthesized signals – waveform with mag-modulated oscillations

$$v(t) = A[1 + m\cos(2\pi f_{os} t + \varphi_2)] \cdot \cos(2\pi f_1 t + \varphi_1)$$

A = 2, m = 5%, f_{os} = 2 Hz, f_1 = 60Hz

  - ➢ Sampling rate: 128 spc (7,680 samples/sec)
  - ➢ Window length: 1 cycle
  - ➢ PMU reporting rate: 30 fps

- DFT-based phasor is accurate for modulated 2-Hz PoW signal.



Test on modulated 2-Hz PoW signal

UTSA

Test 2 – PMU Data for High-Frequency Oscillations

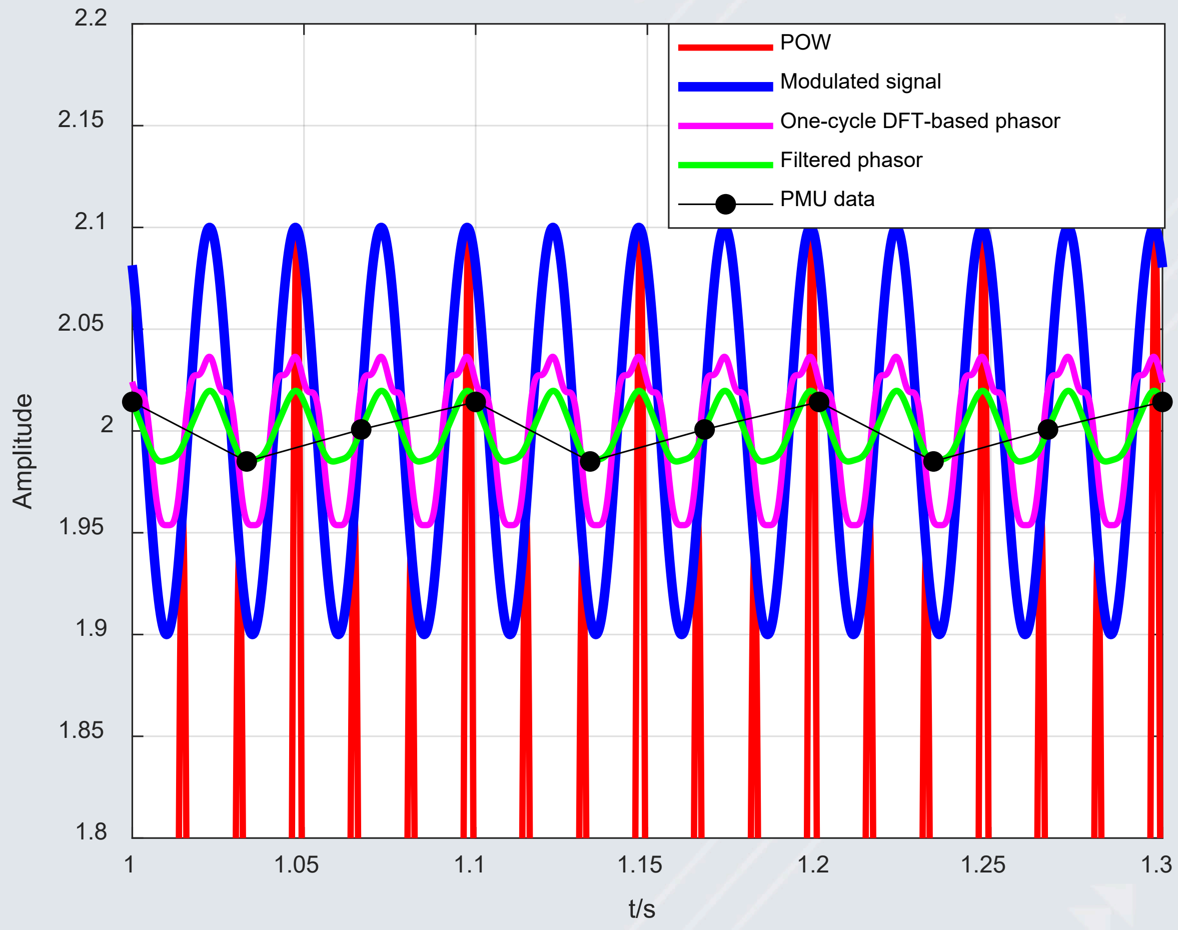
- Synthesized signals – waveform with mag-modulated oscillations

$$v(t) = A[1 + m\cos(2\pi f_{os}t + \varphi_2)] \cdot \cos(2\pi f_1 t + \varphi_1)$$

A = 2, m = 5%, f_{os} = 40 Hz, f_1 = 60Hz

  - Sampling rate: 128 spc (7,680 samples/sec)
  - Window length: 1 cycle
  - PMU reporting rate: 30 fps

- DFT-based phasor is **NOT** accurate
  - Differences between **blue** and **pink** curves are caused by 1-cycle DFT
  - Differences between **pink** and **green** curves are caused by LPF2
  - Differences between **green** and **black** curves are caused by the low reporting rate



Test on modulated 40-Hz PoW signal

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The Phasor Distortion Caused by DFT Method

$$X_{\mathrm{amp}}(t)=\sqrt{X_{\mathrm{r}}^{2}(t)+X_{\mathrm{i}}^{2}(t)}\approx A\left[1+m\frac{2}{N}\frac{\sin\left(\frac{\pi f_{\mathrm{os}}N}{f_1}\right)}{f_{\mathrm{os}}\pi(4f_1^2-f_{\mathrm{os}}^2)}(2f_1^3-f_{\mathrm{os}}^2f_1)\cos(2\pi f_{\mathrm{os}}t+\varphi_1)+r(t)\right]$$

- DFT distortion increases with
  - ➢ Window length N
  - ➢ Oscillation frequency fos
- M-class PMUs incline to cause attenuation and phase flip than P-class counterparts.

[6] Bowen Ou, Bin Wang, et al, "Applicability and Limitation Analysis of PMU Data and Phasor Concept for Low- and High- Frequency Oscillations,“ Under review

Phase Flip Phenomenon Induced by DFT

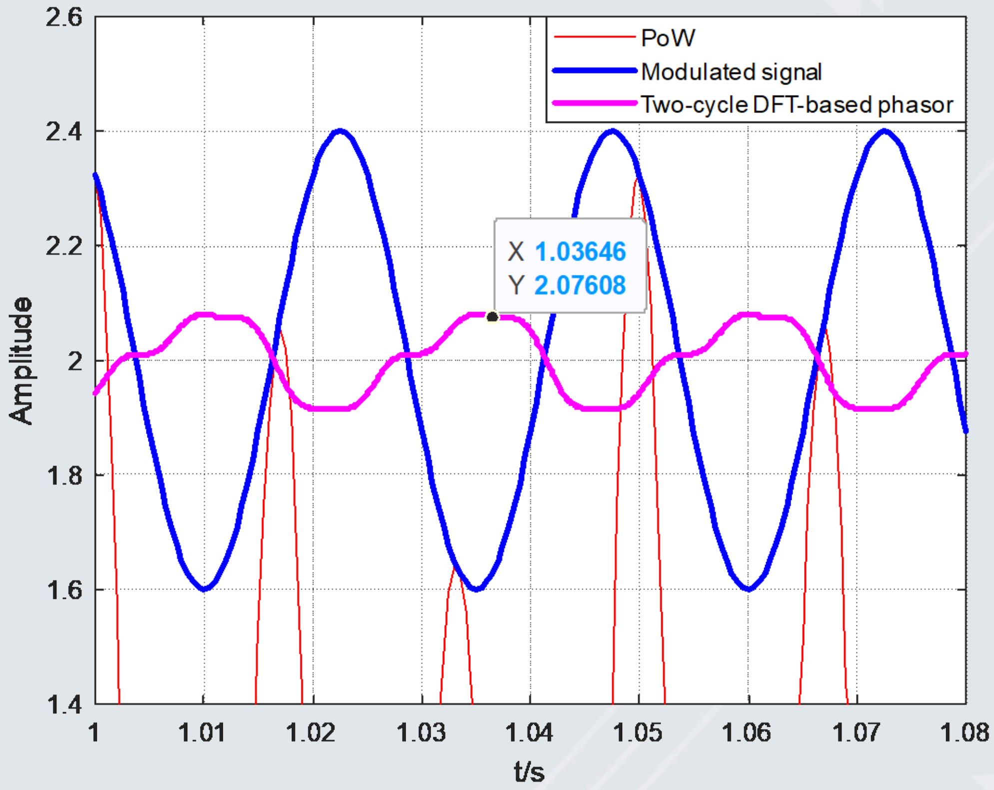
- Consider

$$v(t) = A[1 + m\cos(2\pi f_{os} t + \varphi_2)] \cdot \cos(2\pi f_1 t + \varphi_1)$$

2   20%   40 Hz   60Hz

  - ➢ Sampling rate: 128 spc (7,680 samples/sec)
  - ➢ Window length: 2 cycles

- DFT-based phasor result by Matlab built-in fft: $F_{gain} \approx -0.2$
  - ➢ Oscillation amplitude seen by 2-cycle DFT is 20% of the ground truth
  - ➢ Oscillation phase seen by 2-cycle DFT is 180-degree shifted from the ground truth



Test on modulated 40-Hz PoW signal

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Conclusion and Implications

- Today's PMUs which rely on the DFT-based method have intrinsic limitations for capturing the characteristics of the high-frequency oscillations waveform.
- Phase flips may lead to the inaccuracies of oscillation analysis applications. For example, oscillation source localization.
- Improve phasor estimation algorithm vs. employ the PoW data sampled by DFR.