NASPI Work Group Meeting and Vendor Show

Investigating Power System Oscillations Using Waveform (POW) Data

Presentation by
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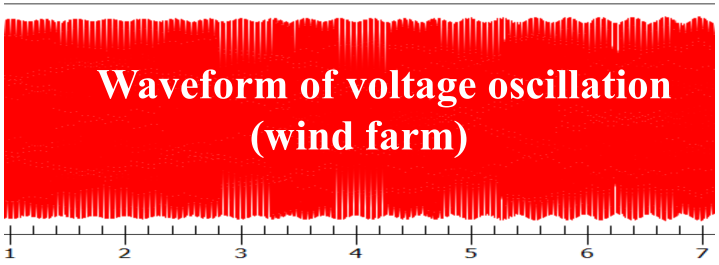
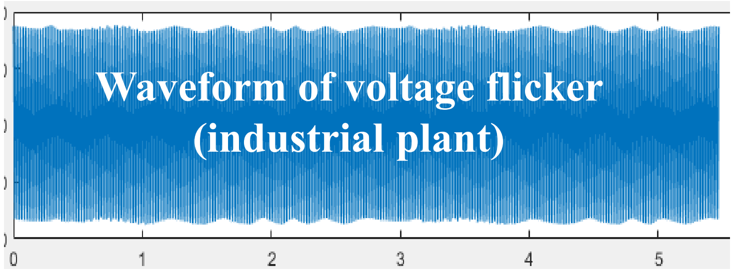
1. The phenomena of power system oscillation

- **Power system oscillation is a system stability concern over the years;**
- **There is a renewed interest in oscillations due to IBR interconnections and increased monitoring capabilities;**
- **NASPI has made a lot of contributions to oscillation monitoring using phasor data;**
- **Almost all stability-related investigations are based on phasor representations**

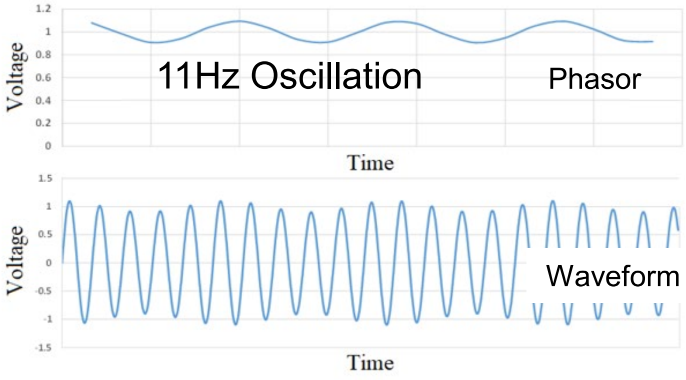
Have you ever wondered what the waveform underlying an oscillating phasor looks like?

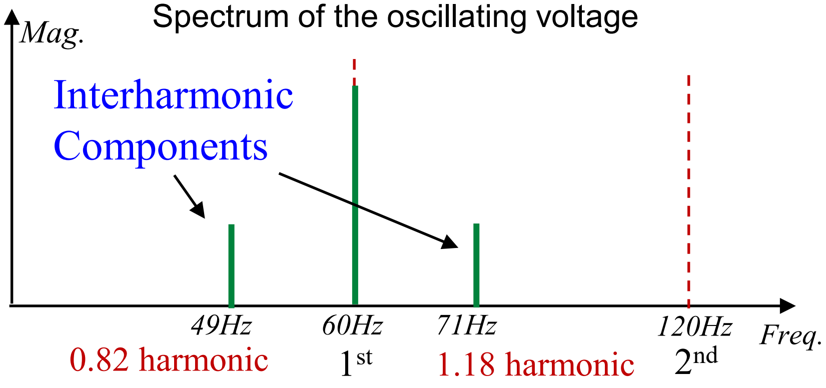




- Beating wave patterns are seen
- Beating is caused by interharmonics
- Are oscillations caused by interharmonics as well?

2. What are interharmonics?





IEC 61000-4-30 definition: Interharmonics (IHs) are spectral components which reside between harmonic frequencies. Interharmonics here refers to both spectral components below and above fundamental frequency f_1

$$\vec{V}(t) = [1 + m\cos(\omega_{os}t)]\angle\delta$$

$$v(t) = \sqrt{2}V_1[1 + m\cos(\omega_{os}t)]\cos(\omega_1 t + \delta)$$

$$= \sqrt{2}V_1\cos(\omega_1 t + \delta) + \frac{mV_1}{\sqrt{2}}\{\cos[(\omega_1 + \omega_{os})t + \delta] + \cos[(\omega_1 - \omega_{os})t + \delta]\}$$

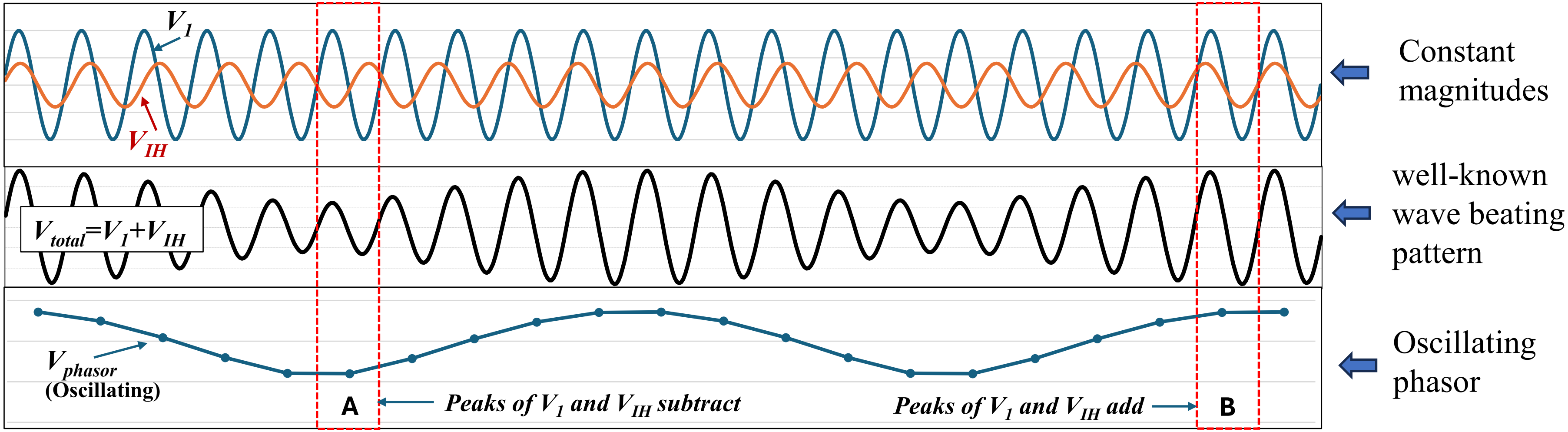
Interharmonic components

2.1 Interharmonics cause phasor oscillation

Finding 1: Existence of interharmonic components is the necessary and sufficient condition of phasor oscillation

A 60Hz wave containing one IH: $v_{total}(t) = v_1(t) + v_{IH}(t) = \sin(2\pi f_1 t) + 0.3 \times \sin(2\pi f_{IH} t + \theta_{IH})$

PMU definition of (measured) 60Hz phasor: $\vec{V}_{phasor}(k) = \frac{1}{\sqrt{2}T_1} \int_{(k-1)T_1}^{kT_1} w(t)v(t)e^{-j2\pi f_1 t} dt$ ⇨ RMS



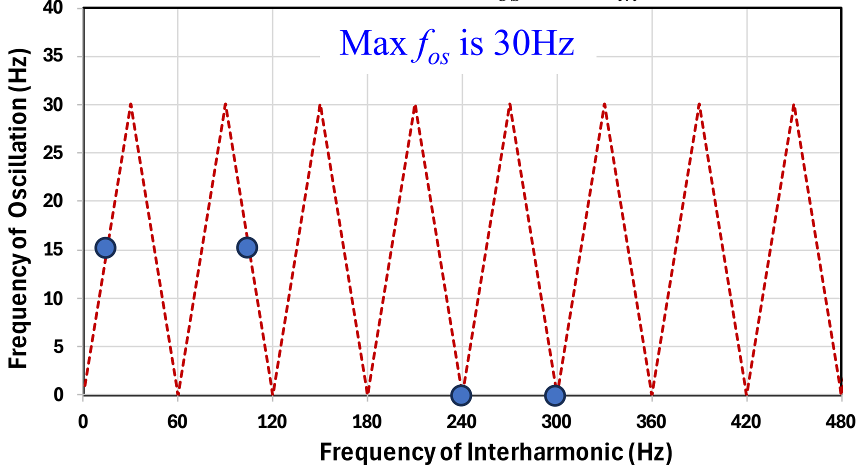
Note: Proof of the necessary condition can be found from a paper shown at the end

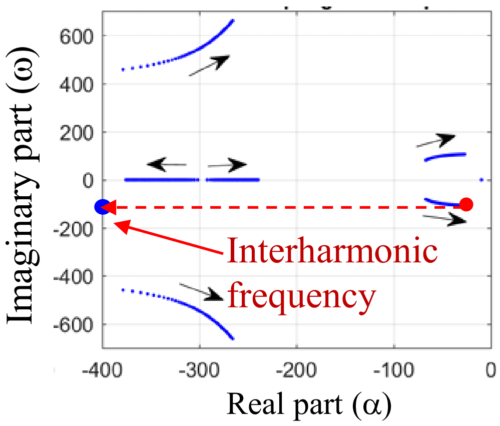
2.2 Clarification of four frequencies

- Frequency of (phasor) oscillation, f_{os}
- Frequency of critical eigenvalue or pole, f_{pole}
- Natural frequency of a circuit/grid, $f_{natural}$
- Frequency of interharmonic, f_{ih}

$$f_{ih} = f_{pole} = f_{natural}$$

Relationship of f_{os} and f_{ih}





Eigenvalue Plot of Linearized EMT model

- Phasor has a "sampling rate" of 60Hz, so it cannot report oscillations higher than 30Hz
- This is why oscillations above 30Hz has not been reported. But they do exist (see later)
- There is no such thing as (oscillatory) harmonic instability

2.3 Relationship between interharmonics and phasor oscillation

Important takeaway

- **Oscillation is the appearance of a waveform beating pattern in the phasor domain;**
- **The beating pattern, in turn, is created by interharmonics interacting with the fundamental frequency wave since their peaks are not synchronized;**
- **Therefore, the presence of interharmonics is the general cause of phasor oscillations**

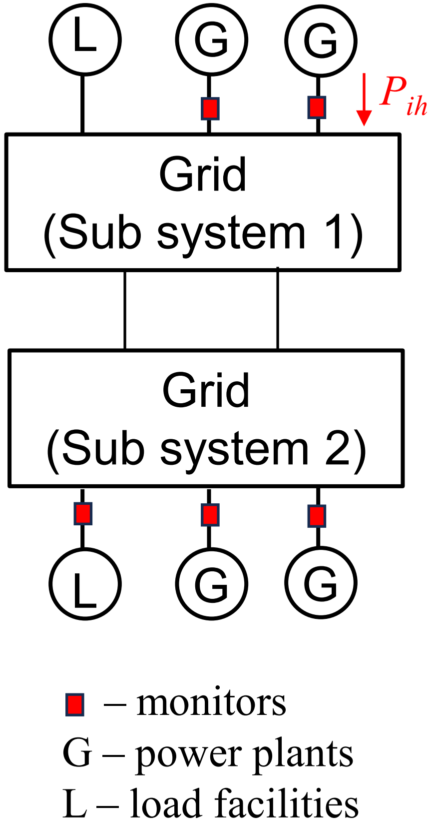
"General cause" means the following: Each oscillation event has its specific cause, such as rotor oscillation. However, when viewed from the electrical perspective, it shows as beating voltage and current waveforms. The beating pattern is caused by interharmonics. This conclusion is applicable to all types of phasor oscillation phenomena, regardless of their specific causes

Analogy: right-side eigenvalues "cause" instability in general, interharmonics "causes" oscillations in general

3.1 Potential applications

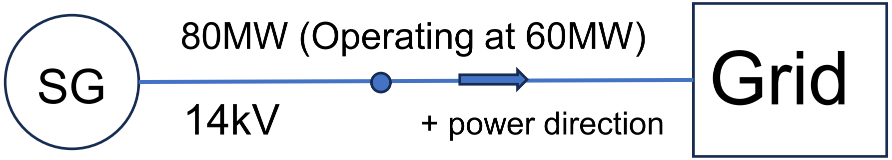
One example application: Oscillation Source Location

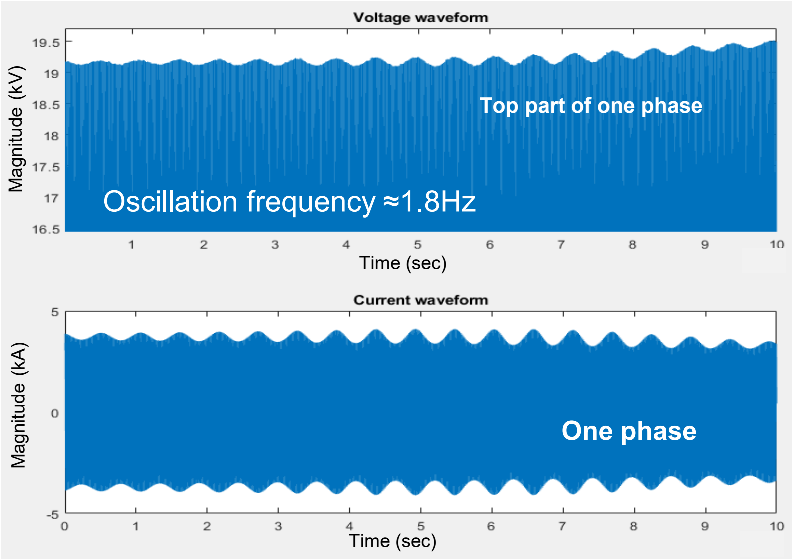
- Oscillation means there are beating voltage and current waveforms;
- The beating waveforms are caused by interharmonic voltages and currents;
- Powers (at the IH frequencies) are needed to drive the propagation of the interharmonic voltages and currents in a system;
- Therefore, interharmonic power producers are sources causing oscillations
- By checking the amount of IH powers produced by various components, we can locate the oscillation sources and rank their impact

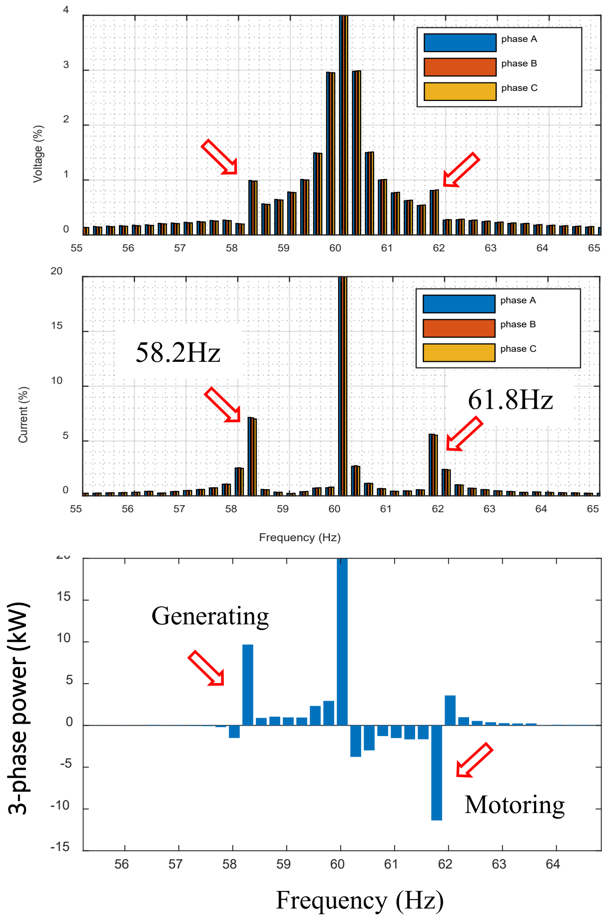


3.2 – Field measurement results

Case 1: Synchronous generator (SG)



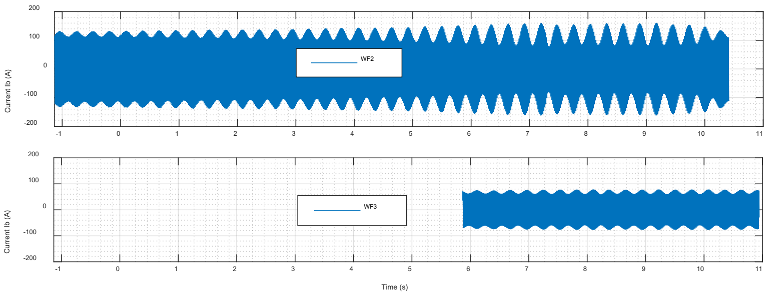




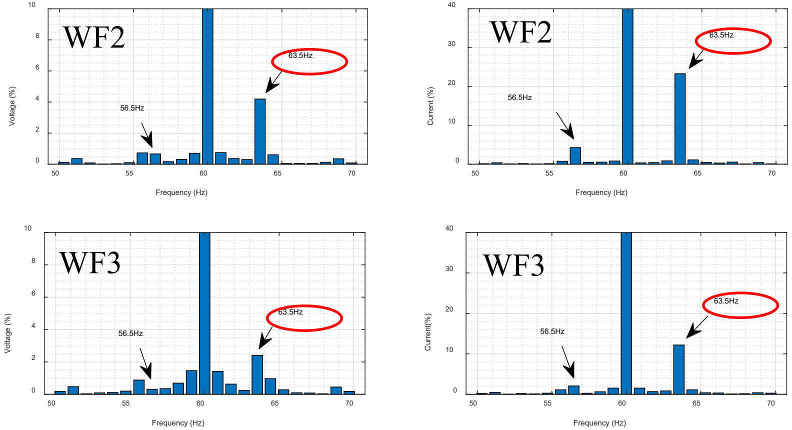
3.2 – Field measurement results

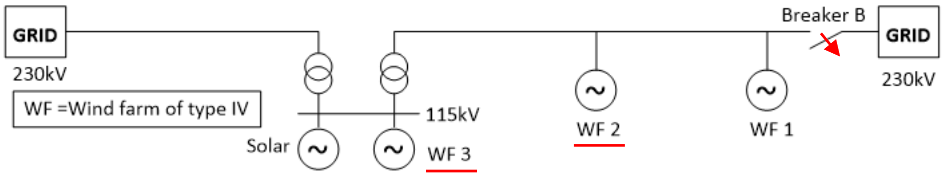
Case 2: Wind farms (WF)

Current waveforms

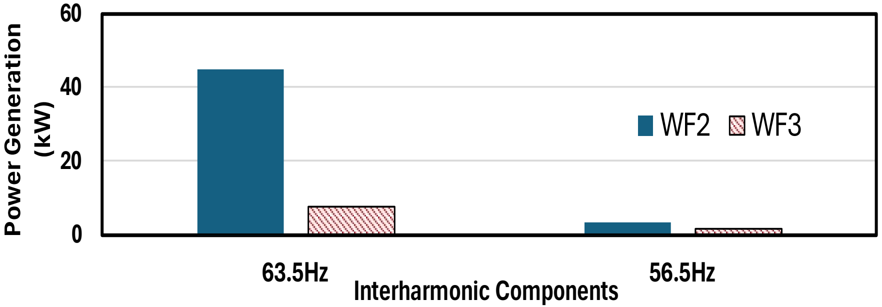


Voltage and current spectrums





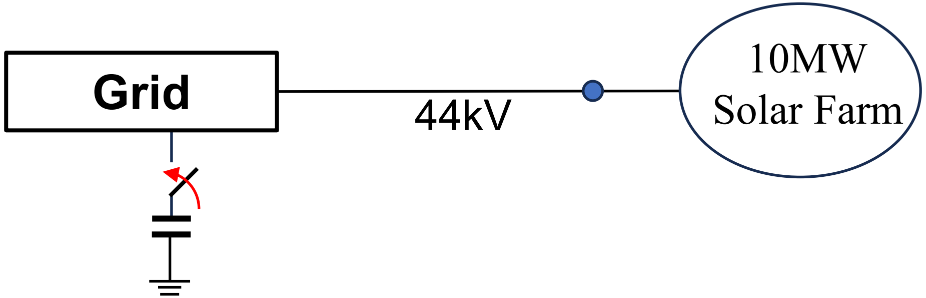
Comparing average IH powers of two WFs:

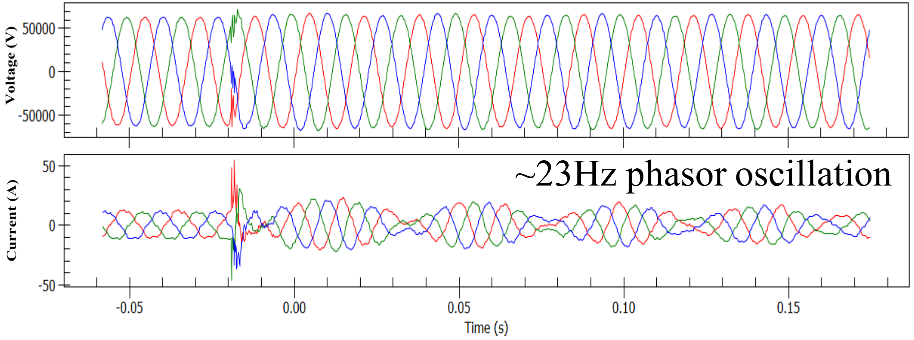


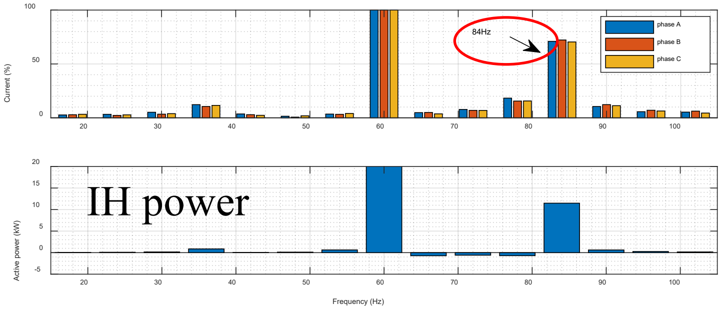
- **Both WFs contribute to the oscillation**
- **WF2 is the main contributor among the two**

3.2 – Field measurement results

Case 3: Solar Farm



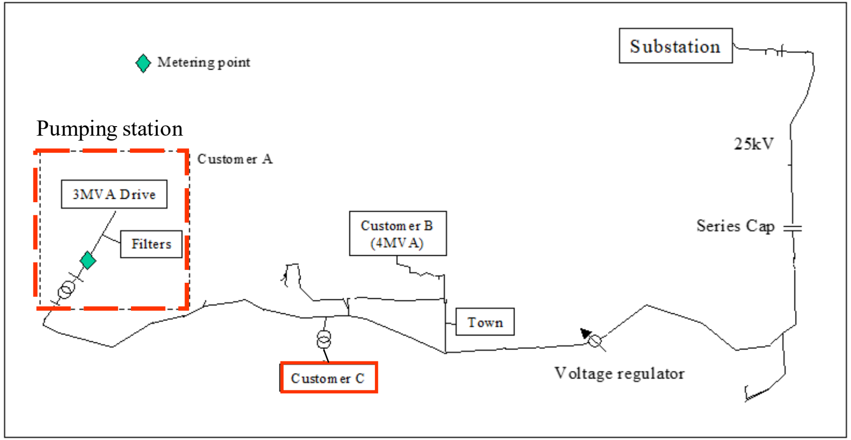


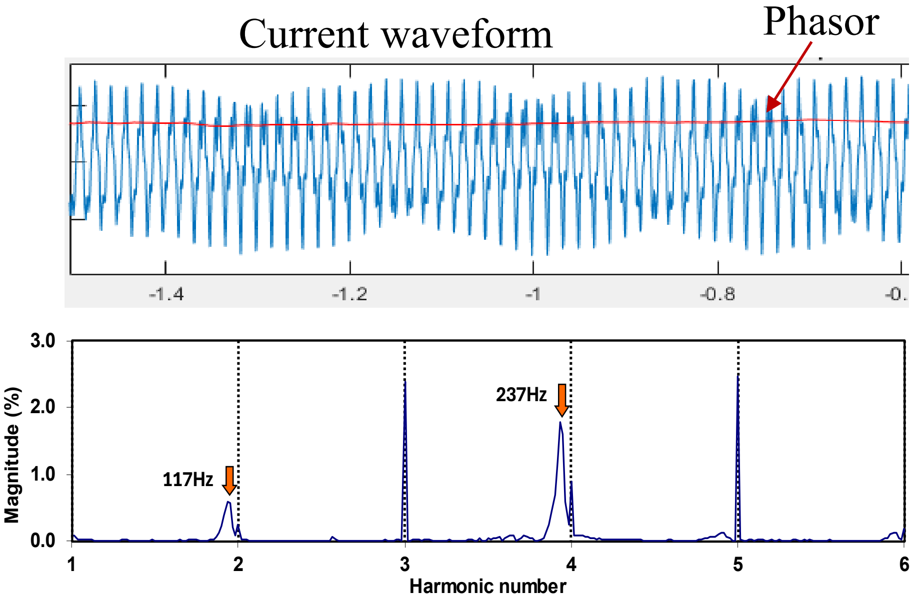


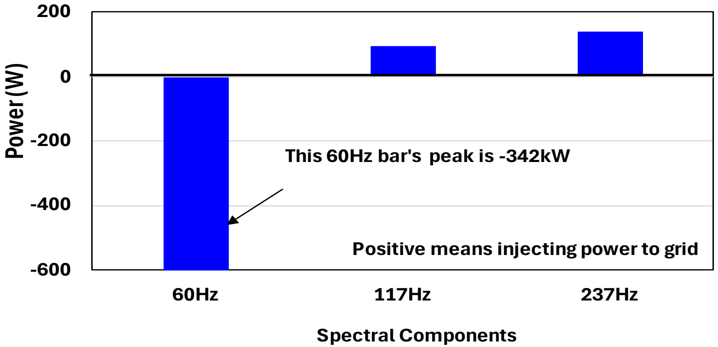
This case shows that the IH frequency is far away from 60Hz, so 60Hz phasor-based system model cannot be used to analyze such cases since $Z_{@ih}$=/=$Z_{@60Hz}$

3.2 – Field measurement results

Case 4: Industrial plant







4.1 Which one is more fundamental: phasor or interharmonic?

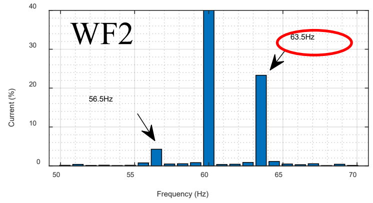
Many phasor user's perspective: Phasor is more fundamental since an oscillating phasor modulates the waveform. The modulation leads to the emergence of interharmonics:

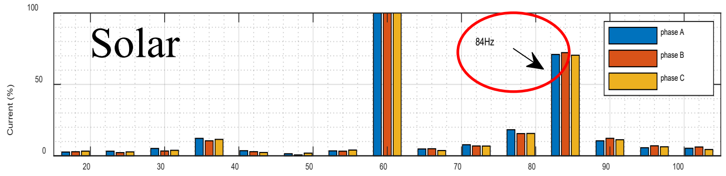
$$v(t)=\sqrt{2}V_1[\underline{1+m\cos(\omega_{os}t)}]\cos(\omega_1 t+\delta)=\sqrt{2}V_1\cos(\omega_1 t+\delta)+\underline{\frac{mV_1}{\sqrt{2}}}\{\cos[\underline{(\omega_1+\omega_{os})}t+\delta]+\cos[\underline{(\omega_1-\omega_{os})}t+\delta]\}$$

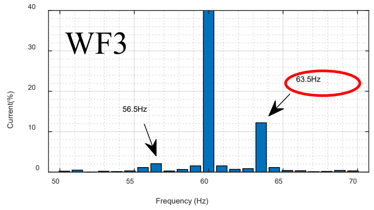
IH1 IH2

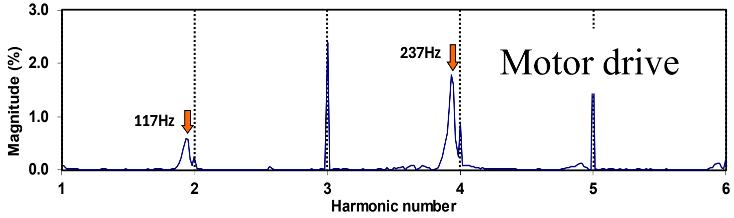
Response 1: Observations from 3 out of 4 field data

Interharmonics don't come in pairs of equal magnitude and don't have frequencies symmetrical to f_1



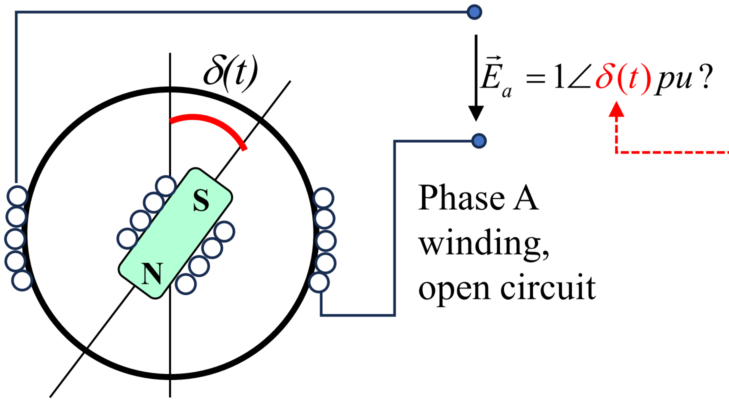






4.2 Which one is fundamental: phasor or interharmonic?

Response 2: Synchronous generator's rotor oscillation produces interharmonic voltages, not phasor-modulated voltage



$$e_a(t) = \frac{d(L_{af} i_f)}{dt} = M_f I_{f0} \frac{d}{dt}\{\cos[\omega_1 t + \delta_0 + \delta_0 m \cos(\omega_{os} t)]\}$$

$$= M_f I_{f0} \omega_1 \sin(\omega_1 t + \delta_0)$$

$$+ K_1 \sin[(\omega_1 + \omega_{os})t + \theta_1] + K_2 \sin[(\omega_1 - \omega_{os})t + \theta_2]$$

$$+ \textit{high order interharmoics}$$

$$\delta(t) = \delta_0[1 + m\cos(\omega_{os} t)]$$

$$L_{af} = M_f \cos[\omega_1 t + \delta(t)]$$

$$e_a = \frac{d(L_{af} i_f)}{dt}$$

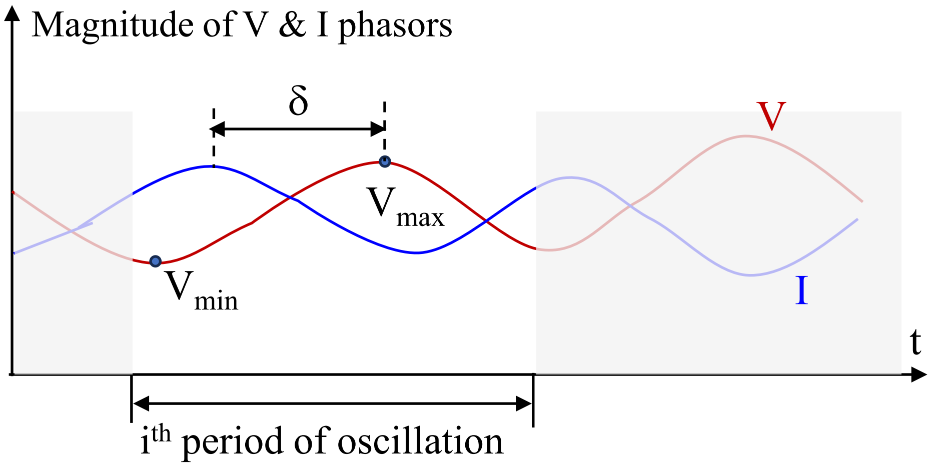
- **Phasor is developed to represent a <u>constant sinusoidal waveform</u>**
- **Using phasor to characterize a <u>beating waveform</u> is an approximation**

4.3 Salvage the phasor data for source location

It is possible to estimate the interharmonic powers from phasor data if the oscillation frequency is very low (<2~3Hz). Then PMU data help source location for such cases

PMU data at the terminal of a generator:

$$V_k \angle \alpha_k, I_k \angle \beta_k \quad k = 1 \dots N \;\; \textit{for one oscillation period}$$



Algorithm:

For the i[th] oscillation period:

$$\Delta V = (V_{max} - V_{min}) / 2$$
$$\Delta I = (I_{max} - I_{min}) / 2$$

$$P_{os} = \Delta V \Delta I \cos(\delta)$$

$$P_{IH} = \frac{P_{os}}{N} \sum_{k=1}^{N} \cos(\alpha_k - \beta_k)$$

- cos(δ)>0 means it is a source
- $|P_{IH}|$ reveals the degree of impact

5 Conclusions and takeaways

- **Phasor oscillation is an appearance of a beating waveform. The beating is caused by interharmonics;**
- **Therefore, waveform data and its interharmonics can bring new insights to power system oscillations;**
  - Locating oscillation sources
  - Identifying components that amplify oscillations
- **Interharmonic analysis is essential if the interharmonic frequencies are far away from the fundamental frequency, which is the case involving IBRs;**
- **For synchronous generator oscillations, however, the phasor data may still be useful for source location if the interharmonic powers can be estimated properly from the data.**

Thank you

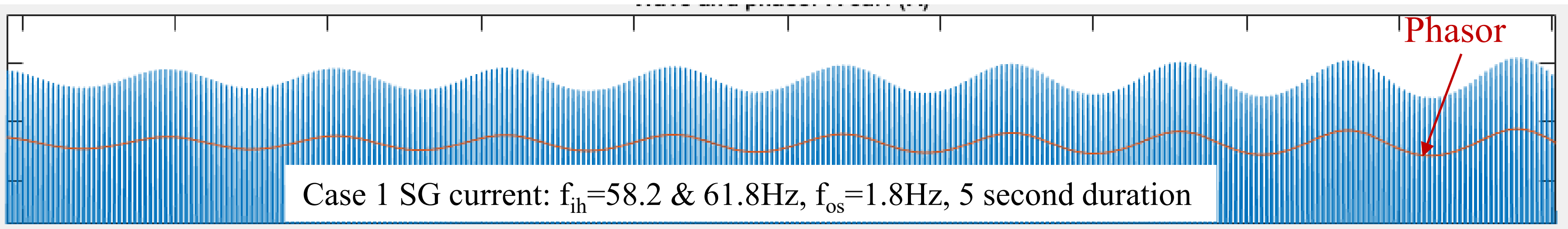
I welcome any questions and comments you may have

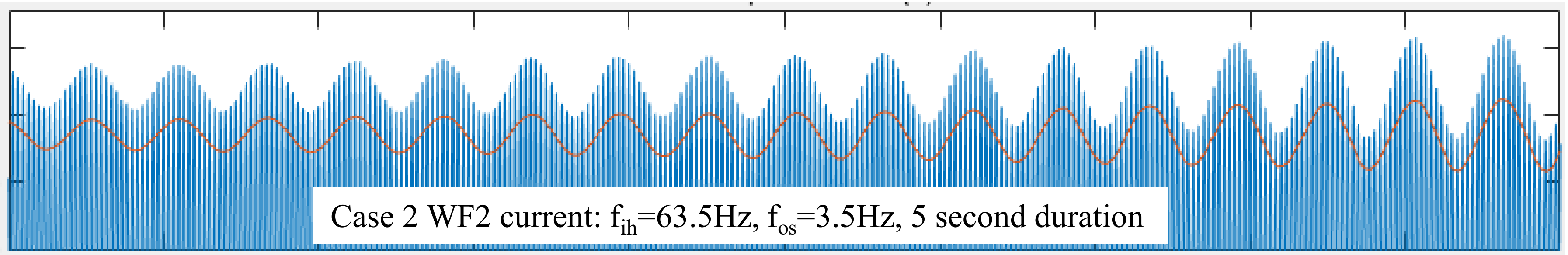
More information can be found from the following paper:

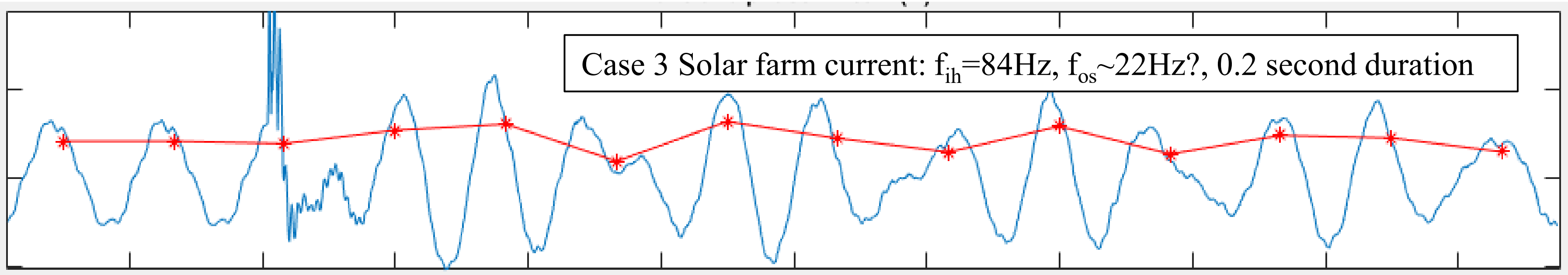
W. Xu, J. Yong, H. J. Marquez and C. Li, "Interharmonic Power – A New Concept for Power System Oscillation Source Location," in IEEE Transactions on Power Systems, doi: 10.1109/TPWRS.2025.3535863.

Appendix for Additional Information

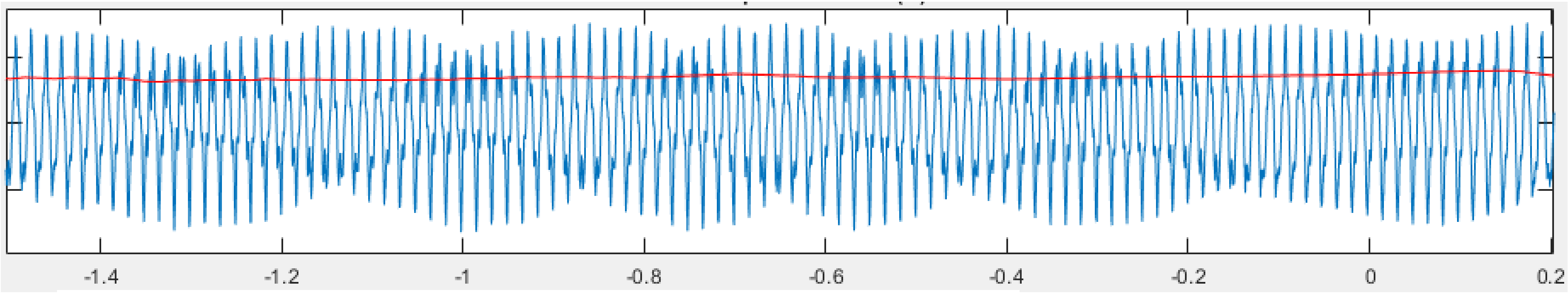
A.1 Phasors of measured data





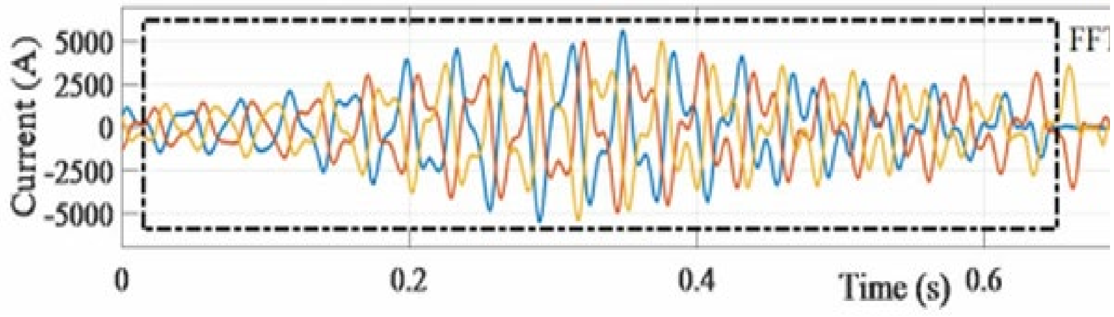


A.1 Phasors of measured data

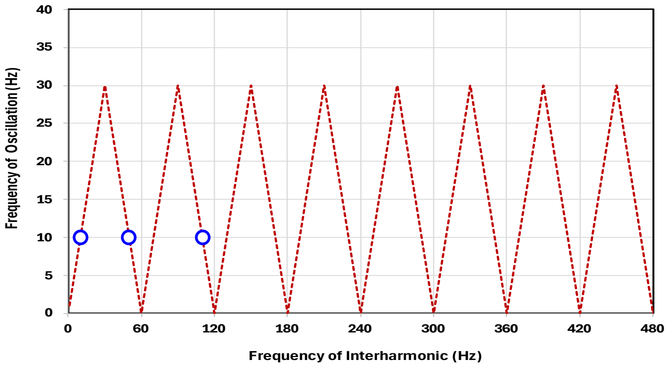


Case 4 VFD current: f_{ih}=117Hz & 237Hz, f_{os}=?Hz, 1.7 second duration

Another IBR farm case (©IEEE), f_{ih}~30Hz, f_{os}=?



Can phasor be used to characterize the above data?



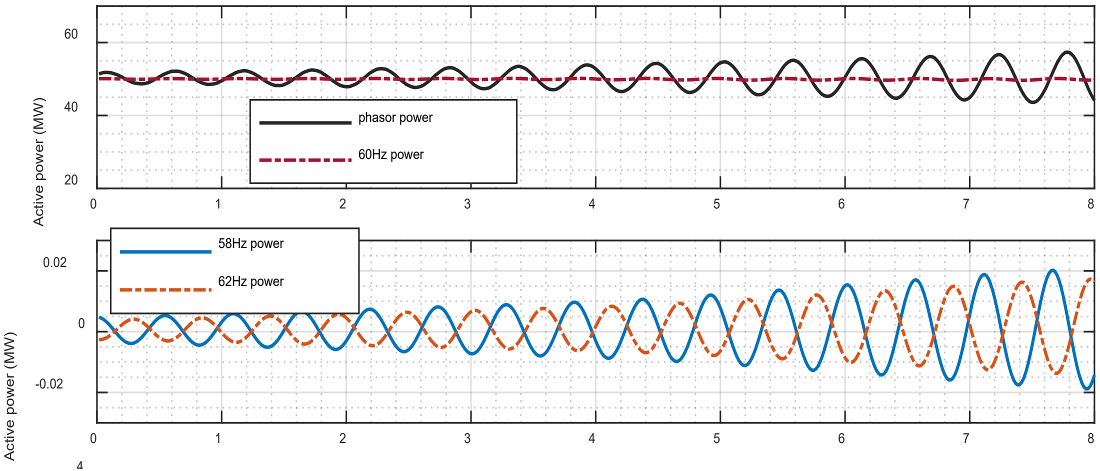
Multiple aliasing-like effects compound together to form a phasor

A.2 What is the meaning of oscillating phasor power?

$$P_{total} = \frac{1}{T_{os}} \int_{t_0}^{t_0+T_{os}} v(t) \times i(t) dt = P_1 + P_2 + \ldots + P_k + \ldots \qquad P_k = V_k I_k \cos(\theta_k) \qquad k - IH\ component$$

Case of synchronous generator (SG)

Trend of phasor, 60Hz and interharmonic powers

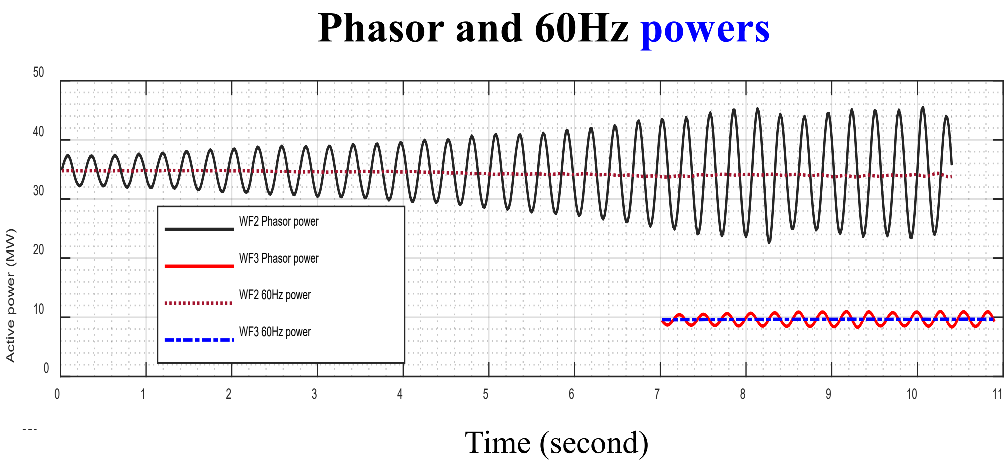


4

- Fundamental frequency (60Hz) power does not have noticeable oscillation;
- Phasor power oscillates. But it is supposed to represent 60Hz power;
- What does oscillating phasor power really represent?
- Can it be used for oscillation source location?

A.2 What is the meaning of oscillating phasor power?

Case of wind farms (WF)

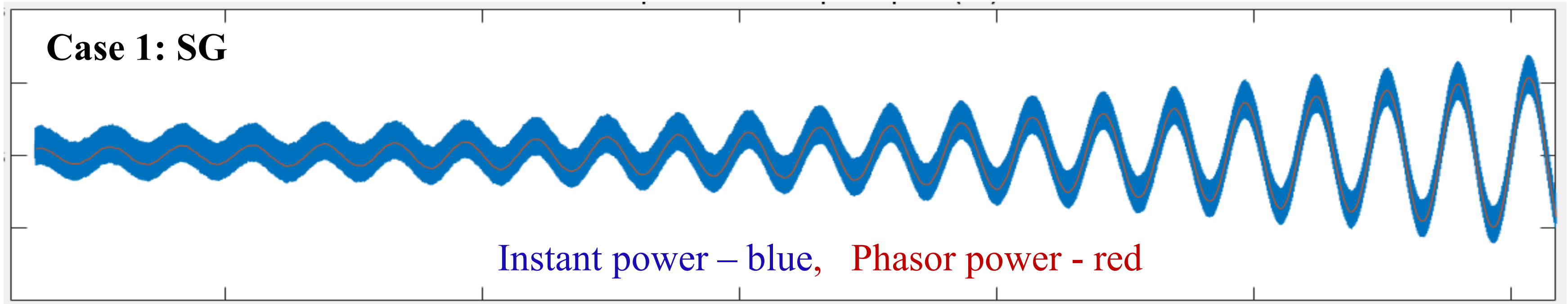


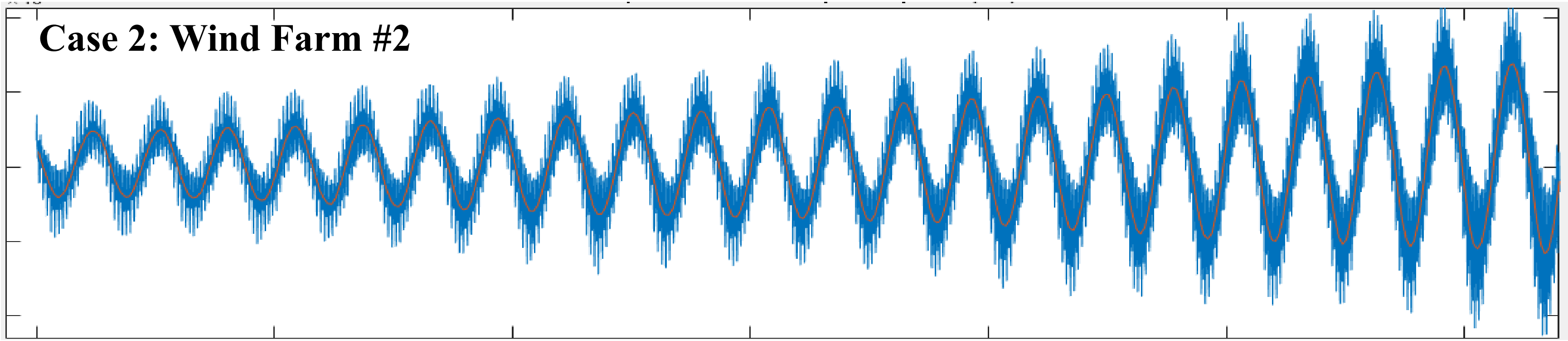
- Instant voltage and current (i.e. waveforms) are true variables per the laws of physics
- Phasors voltage and current are engineer-created indices for constant sinewaves
- Phasor power is derived from phasors, so it is also a construction assuming constant sinewaves
- Therefore, what does a non-constant, oscillating phasor power really mean?

A.3 Three-phase phasor power versus instant power

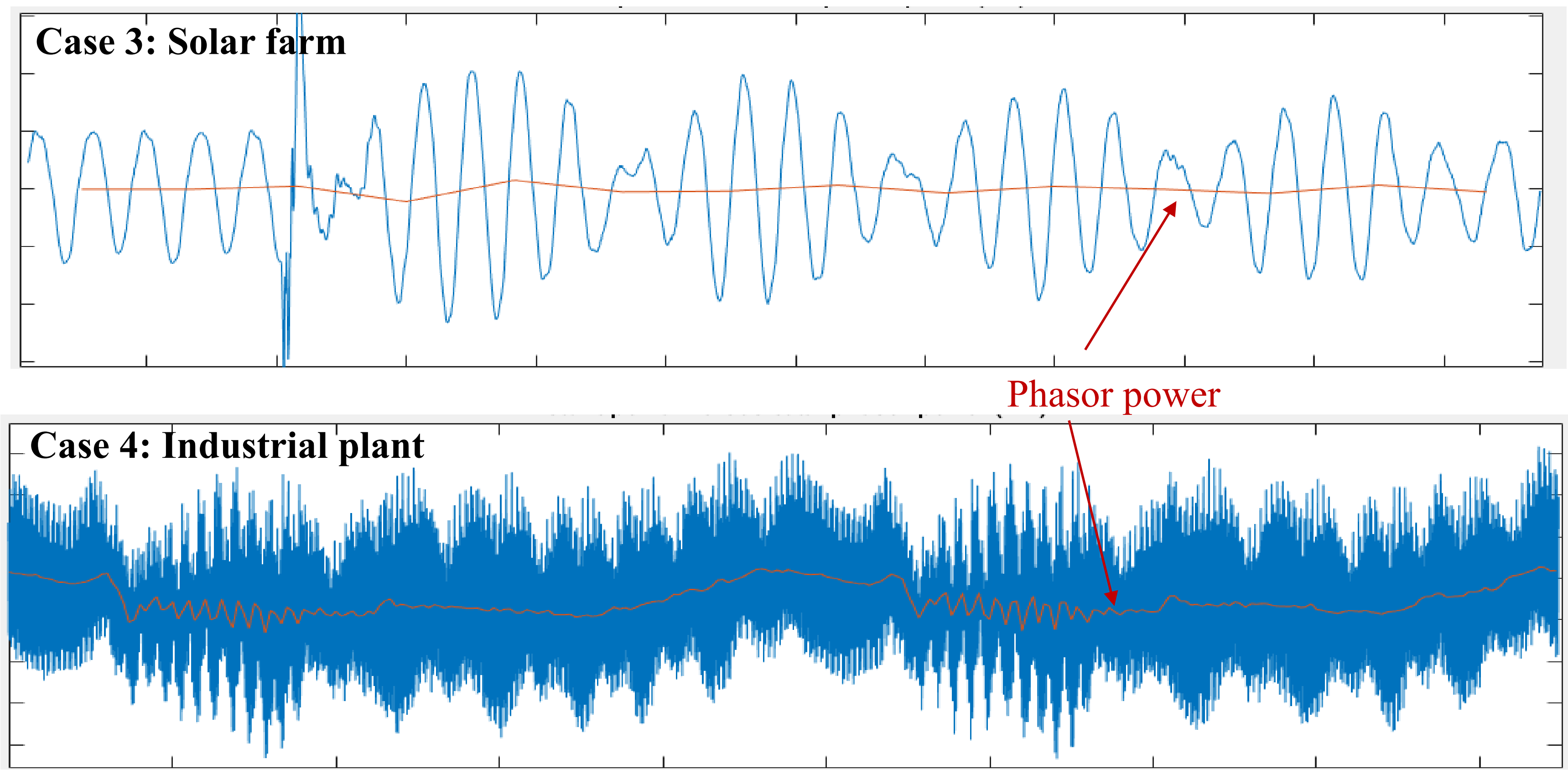
$$P_{instant} = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t)$$

(Active Power is the average of instant power)





A.3 Three-phase phasor power and instant power



A.4 IH active power versus Phasor active power

Using spectral analysis (k means kth spectral component)

$$P_{total} = P_1 + P_2 + \ldots + P_k + .. = V_1 I_1 \cos(\theta_1) + V_2 I_2 \cos(\theta_2) + \ldots.. + V_k I_k \cos(\theta_k) + \ldots.$$

- Only voltage and current of same frequency can result in active power, i.e. there is no cross-frequency coupling in terms of active power generation and propagation
- Thus, the power associated with a specific frequency can be easily determined

Using phasor power

$$P_{phasor} = V_{phasor} I_{phasor} \cos(\theta_{phasor}) \neq P_{total} \neq P_1$$

$$\vec{V}_{phasor}(k) = \frac{1}{\sqrt{2T_1}} \int_{(k-1)T_1}^{kT_1} v(t) e^{-j2\pi f_1 t} dt$$

$$V_{phasor} = f(V_{1,} \ldots V_k \ldots), \quad I_{phasor} = g(I_{1,} \ldots I_k \ldots), \quad \theta_{phasor} = y(\theta_{1,} \ldots \theta_k \ldots),$$

i.e. phasor is a nonlinear combination of multiple spectral components including the effect of aliasing. It is not possible to extract power component for a particular frequency