Locating oscillation sources for power system stability monitoring using synchro-waveform data

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Outline

1. Power system oscillations viewed from waveforms
2. Phasor oscillations are caused by interharmonics
3. Practical application: oscillation source location
4. Conclusions and takeaways

The phenomena of power system oscillations

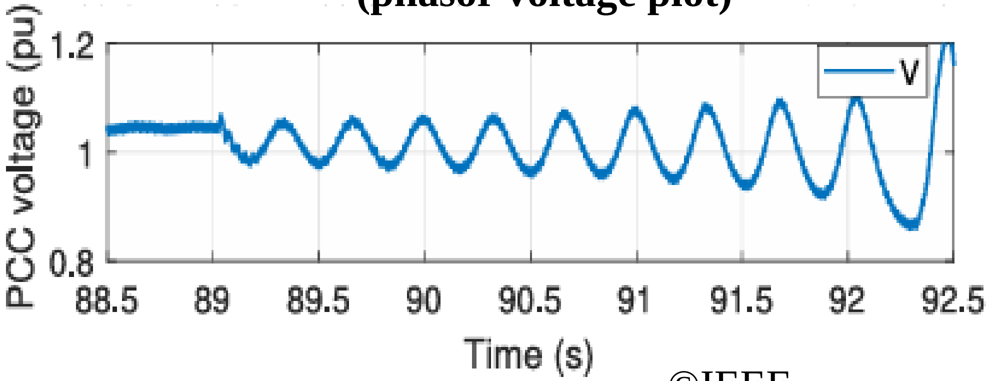
1. Power system oscillations have been a system stability concern over the years

2. There is a renewed interest in oscillations due to:
   a. IBR Interconnections
   b. Increased monitoring capabilities such as PMUs

3. Almost all monitoring activities and stability studies are based on phasor representations of the phenomena

4. For example, efforts have been made to use PMU data to locate sources causing oscillations

Example of an IBR oscillation event (phasor voltage plot)



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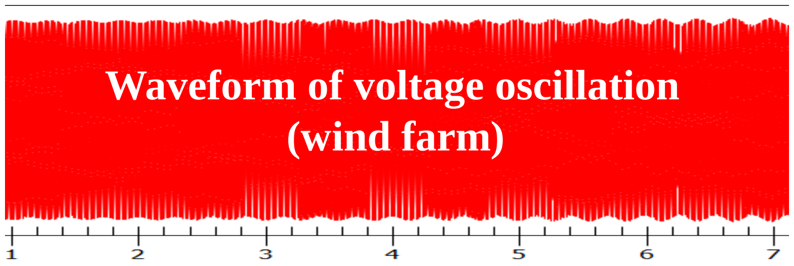
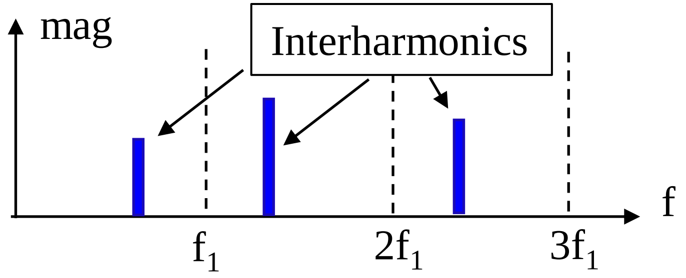
Oscillations seen from the waveform perspective

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



1. It exhibits a beating wave pattern => Let’s do spectral analysis
2. The beating patterns are caused by spectral components called 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



Part 2

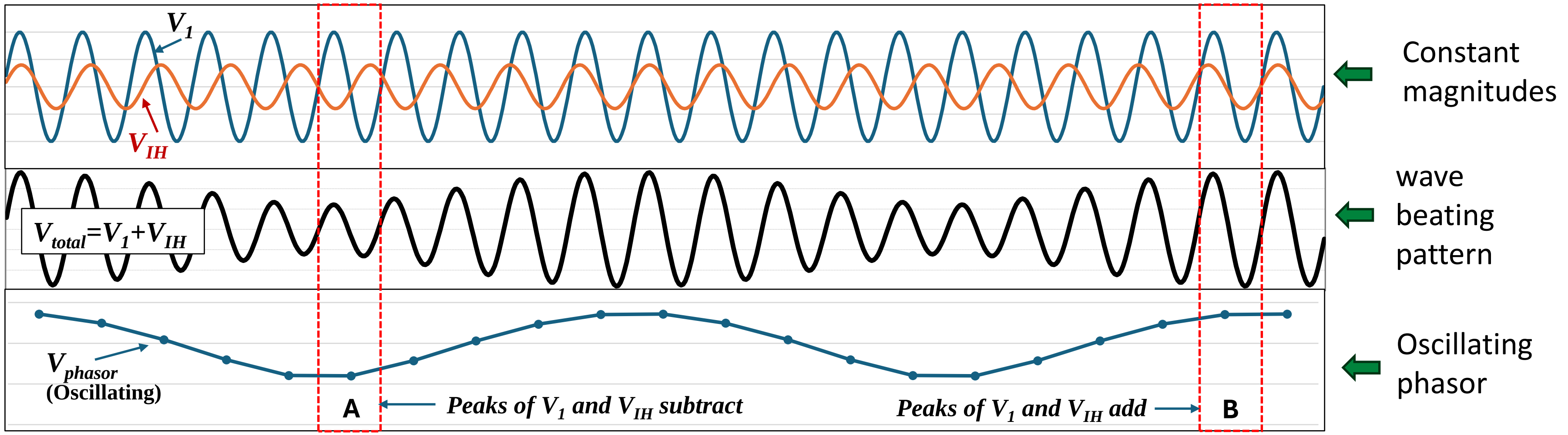
Phasor oscillations are caused by interharmonics

How does interharmonics cause phasor oscillation?

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

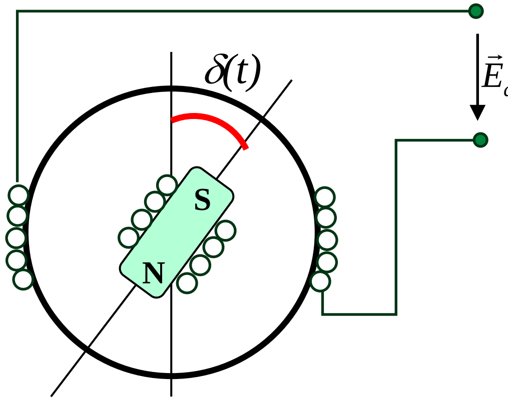


Note: Proof of the necessary condition can be found from a paper shown at the end

New insight 1 - synchronous generator (SG) rotor oscillation

Traditional understanding: SG rotor oscillation produces a voltage with oscillating phase angle

Is this correct really?



$$\vec{E}_a = 1\angle\delta(t)\,pu\,?$$

$$e_a(t) = \frac{d(M_{af}i_f)}{dt} = MI_{fDC}\frac{d}{dt}\{\cos[\omega_1 t + \delta_0 + \Delta\delta\cos(\omega_{os}t)]\}$$
$$= MI_{fDC}\,\omega_1\sin(\omega_1 t + \delta_0)$$
$$+ K_1\sin[(\omega_1 + \omega_{os})t + \theta_1] + K_2\sin[(\omega_1 - \omega_{os})t + \theta_2]$$
$$+ \text{high order interharmoics}$$

$$\delta(t) = \delta_0 + \Delta\delta\cos(\omega_{os}t)$$

$$M_{af} = M\cos[\omega_1 t + \delta(t)]$$

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

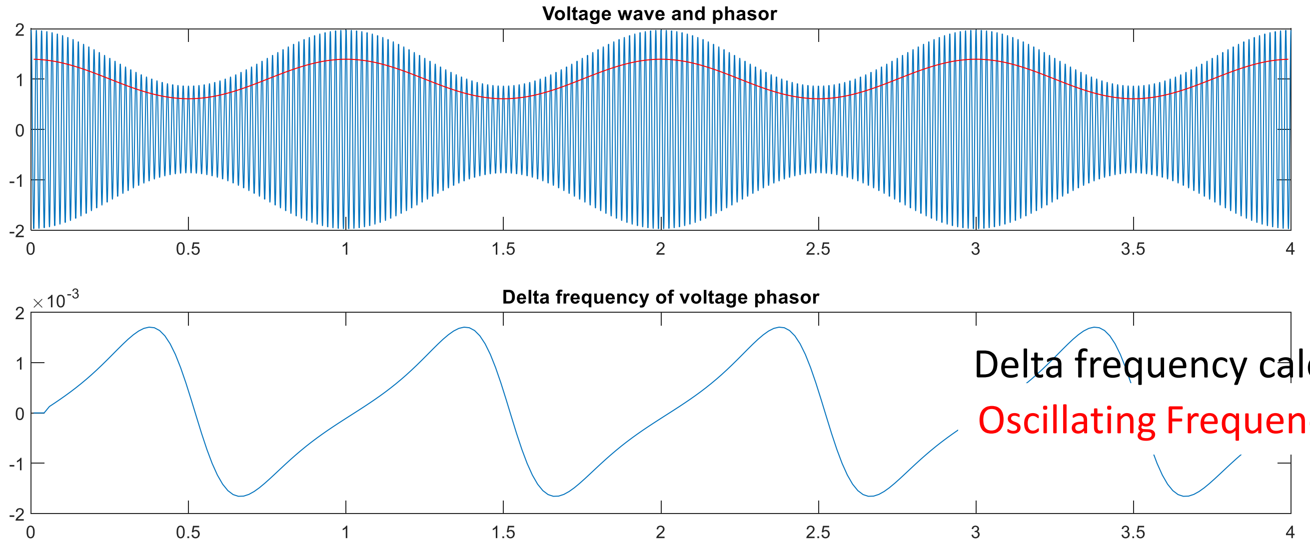
$$i_f(t) = I_{fDC}$$

- Rotor oscillation generates two interharmonic voltages, not an oscillating voltage phase angle!
- In fact, the fundamental frequency voltage's angle δ does not oscillate;
- Phasor voltage angle oscillation is at best an approximation.

New insight 2: Does the frequency really oscillate?

Waveform:

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



Delta frequency calculated by PMU

Oscillating Frequency?

- This waveform has three components with constant frequencies
- But the PMU phasor result shows that the frequency oscillates!

Important Takeaways

- 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;
- Phasor was introduced to represent **constant sinusoidal waves**, not **beating waves**. Therefore, it is an approximation.

General cause means: Interharmonics cause the (apparent) phasor oscillation

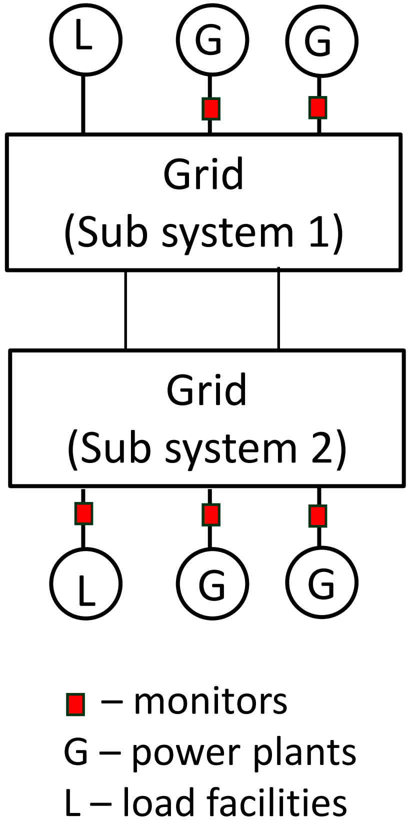
Specific cause means: each oscillation event has specific causes of interharmonic generation

Part 3

A Practical Application – Oscillation Source Location

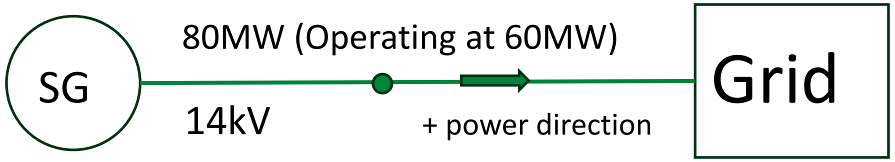
Interharmonic power-based oscillation source locator

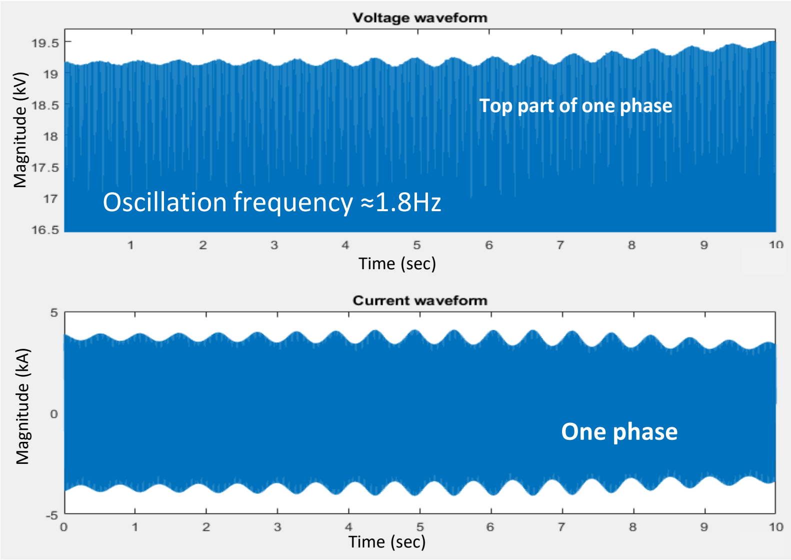
- Oscillation means there are interharmonics;
- **Active powers (at the IH frequencies) are needed to drive the propagation of the interharmonic voltages and currents in the grid;**
- **Therefore, interharmonic power producers are sources causing oscillations;**
- By checking the amount of IH powers produced by various components, we can locate the oscillation sources and rank their impact;
- This simple idea is applicable to both forced and natural oscillations

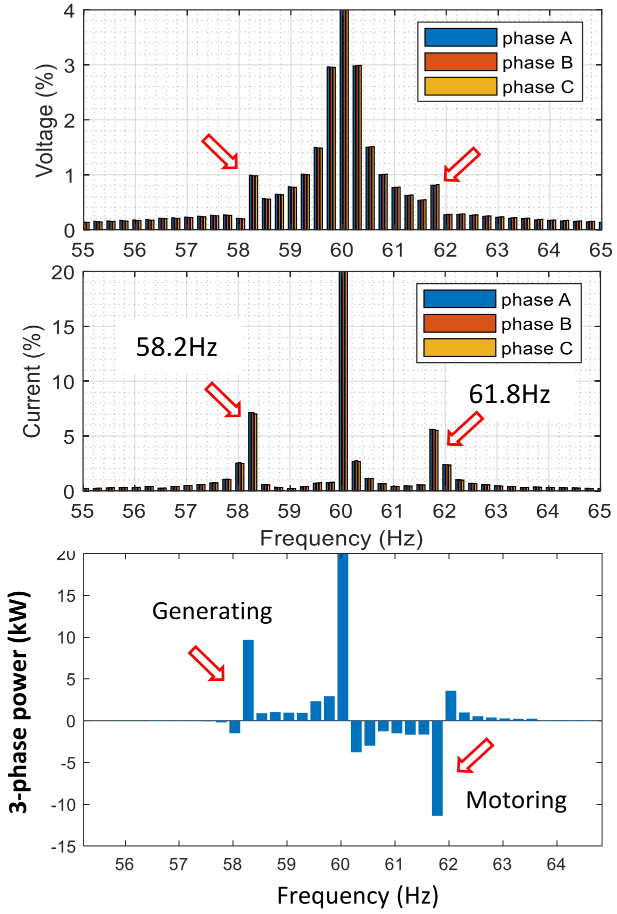


Field Measurement Results

Case 1: Synchronous Generator (SG)

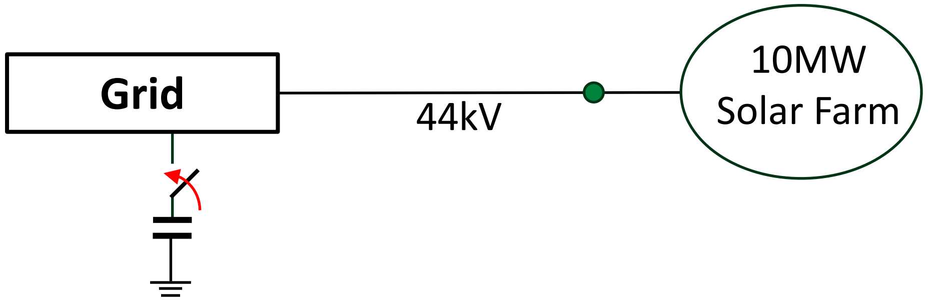


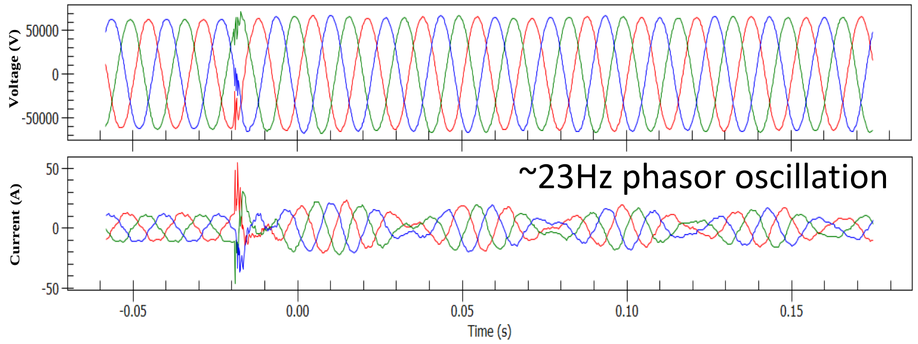


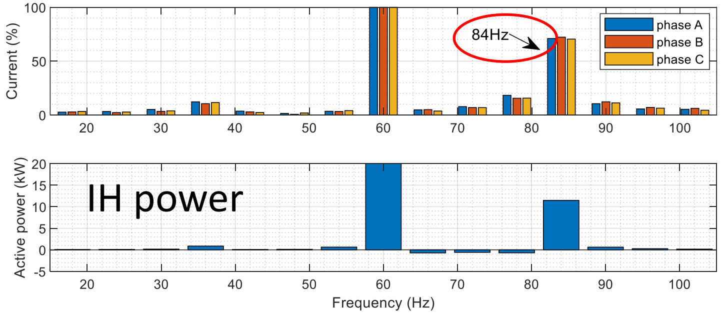


Field Measurement Results

Case 2: Solar Farm





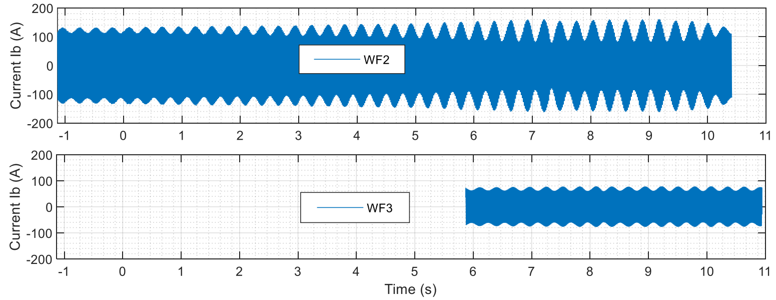


Solar inverter phase-lock loop could not track system frequency

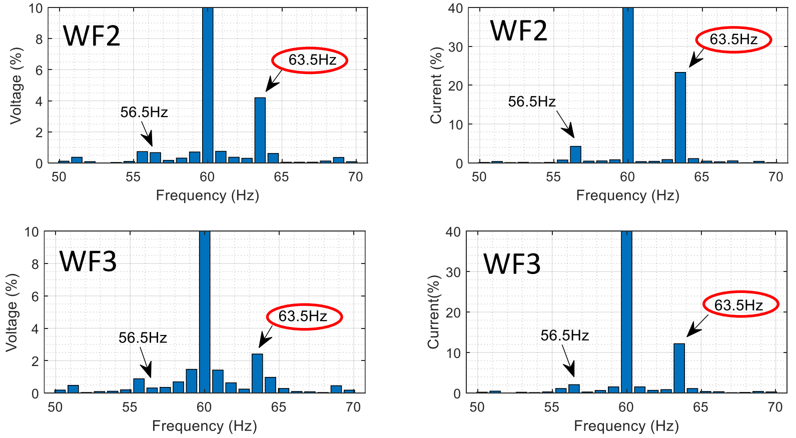
Field Measurement Results

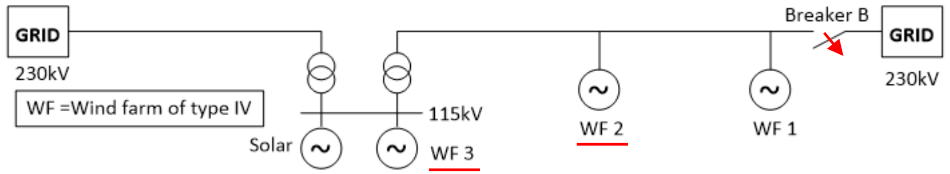
Case 3: Two Wind Farms (WFs)

Current waveforms

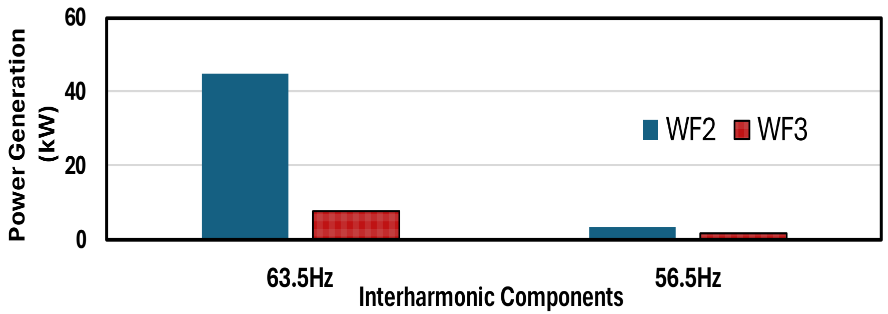


Voltage and current spectrums





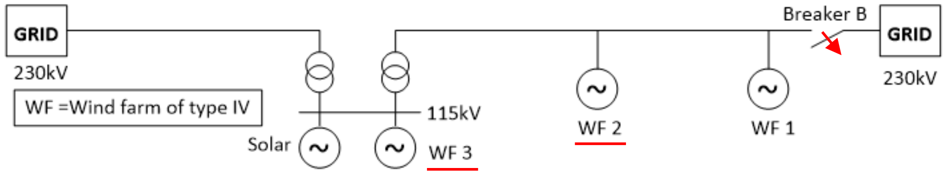
Comparing average IH powers of two WFs:



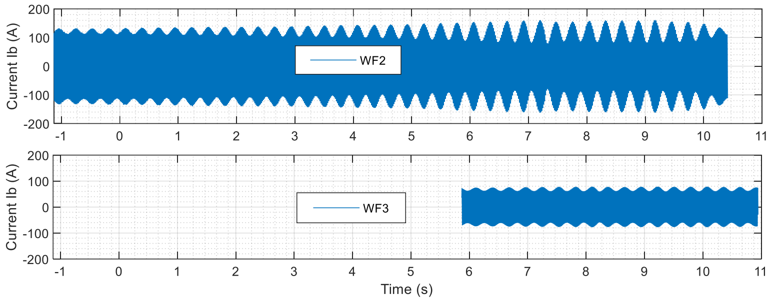
- **Both WFs contribute to the oscillation**
- **WF2 is the main contributor among the two**

The Role of Synchronized Waveforms

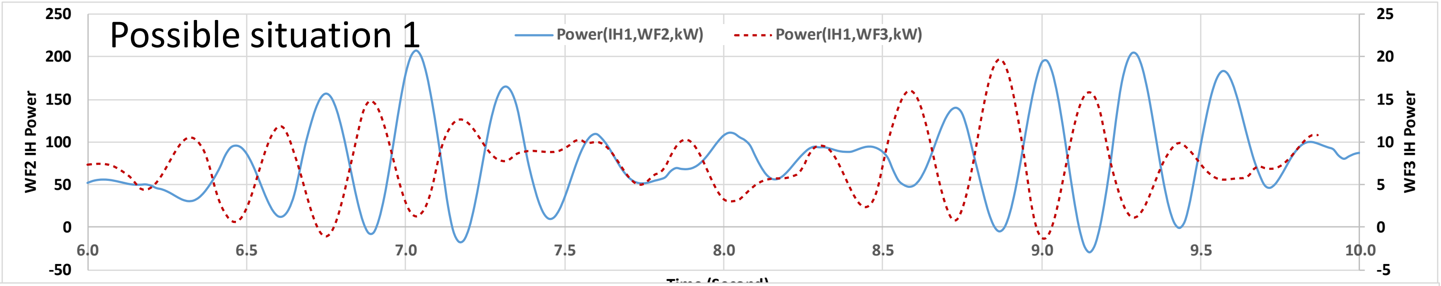
Why are synchronized waveform data needed?

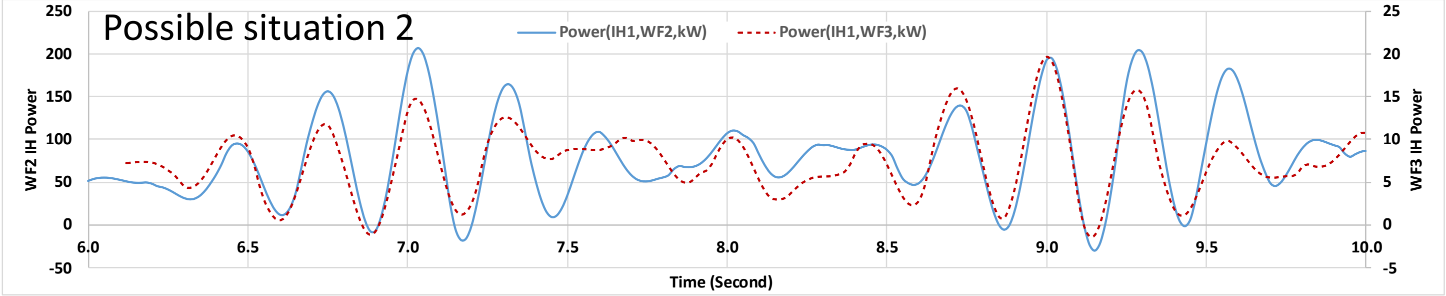


Current waveforms



Trends of interharmonic powers of the two wind farms





Synchronization of the two trends is needed

Important Takeaways

- If oscillation occurs, there are interharmonics,
- This remains true regardless of the types of generators or loads involved,
- Interharmonic active power can help to locate oscillation sources. This idea is quite basic in view of the law of energy conservation.

Conclusions

- It is natural to investigate beating waves (i.e., phasor oscillations) using waveform data
- Interharmonics of the waveform offer many insights, and various innovative applications can be developed
- One example is oscillation source location, and it could become an exemplary application for the synchrowaveform data
- Based on power quality monitoring experiences, there are no difficulties to implement such applications
- Research is still needed to improve signal processing algorithms for interharmonic extraction

Please let me know if I can help.

Or contact: wxu@ualberta.ca

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.