IEEE PES Synchrowaveform Task Force
Webinar

Why Waveform Data is Necessary for Monitoring and Analyzing Power System Oscillations

Presentation by
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Outline

1. Background: power system oscillations
2. Relationship between phasor oscillations and interharmonics
3. Potential applications and field measurement results
4. Discussion on phasor data versus waveform data
5. Conclusions and takeaways

1. Background: Power System Oscillations

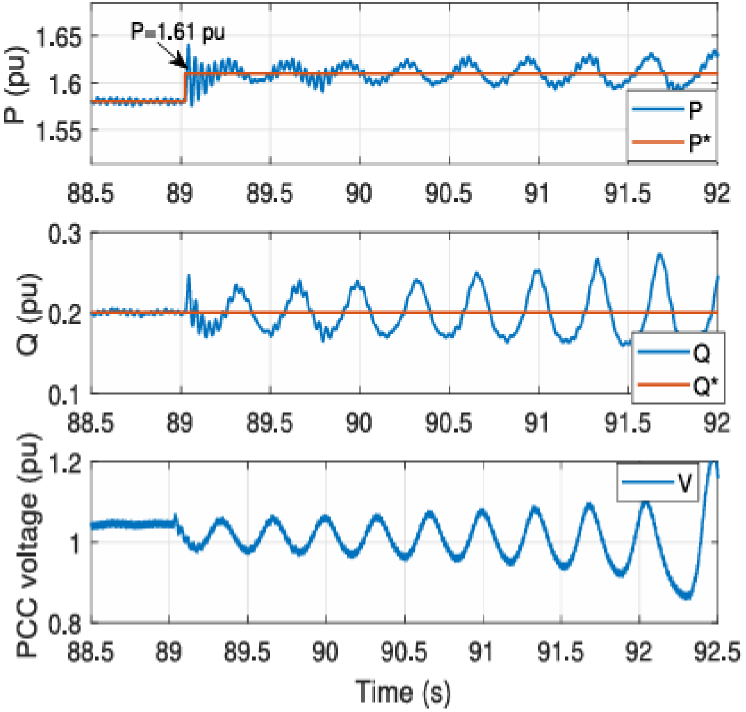
1. Background – the phenomena of power system oscillation

- **Oscillation is related to small-signal stability of a power system and its generators**
- **The phenomena have been known for many years.**
- **Power system stabilizer was invented to damp oscillations of synchronous generators in 1980's**

Recent developments:

1. **Inverter-Based Resources (IBRs) have renewed attention on oscillations**
2. **Increased grid monitoring capability has made oscillation events more visible**

Example of an IBR oscillation event



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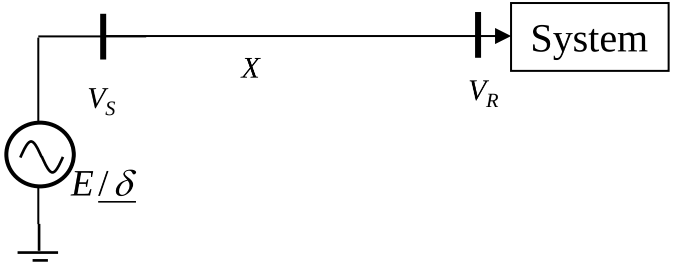
1. Background – Monitoring of power system oscillations



- Angle plays an important role in system stability
- Measuring angles can improve stability monitoring
- PMUs can measure angles, so they serve a unique role in stability monitoring

Oscillation monitoring using PMU and WAMS

- Find the characteristics of an oscillation event, such as the frequencies of oscillation, and "mode shape"
- Locate the sources of oscillation
- One example is Eastern Interconnection Situation Awareness and Monitoring System

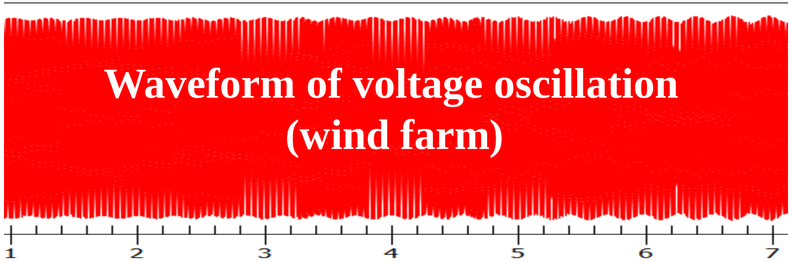
Simplest PMU
phasor definition:

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

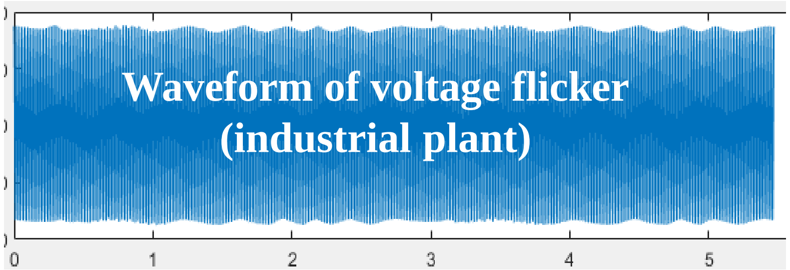
Power system oscillations are high profile events of significant concerns to system operators

1. Background – Voltage flicker versus voltage oscillation

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



Waveform of voltage oscillation (wind farm)

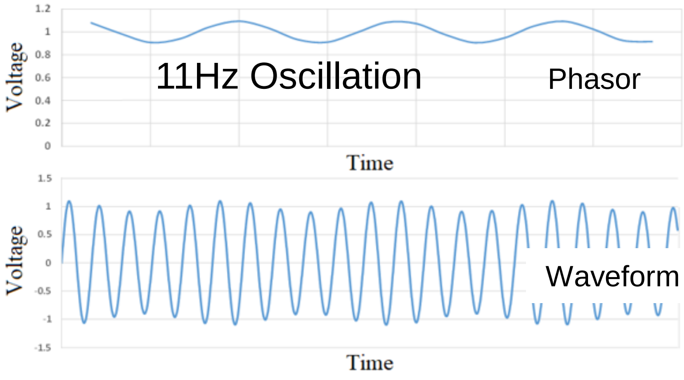


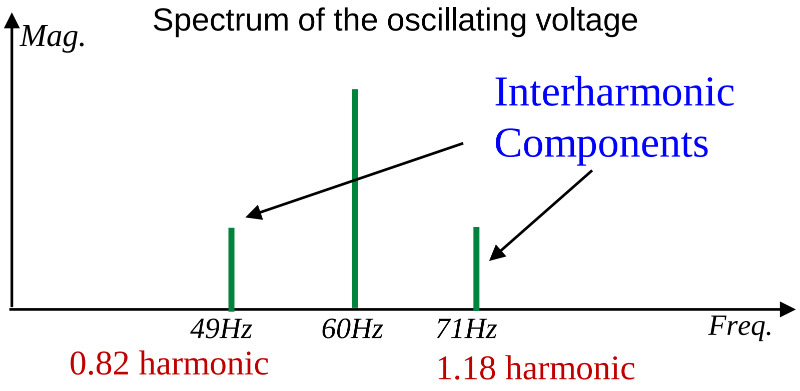
Waveform of voltage flicker (industrial plant)

- **Both exhibit a beating wave pattern.**
- **The power quality community knows for years that voltage flicker is linked to interharmonics.**
- **Interharmonics have made it easy to investigate voltage flicker problems, such as locating flicker sources**
- **Do phasor oscillations have a connection to interharmonics as well?**

2. Relationship between phasor oscillations and interharmonics

2.0 What are interharmonics?





IEC 61000-4-30 definition: Interharmonics (IHs) are spectral components whose frequencies are not integer multiple of f_1, i.e. $f_{IH}/f_1 \neq$ integer. Interharmonics here refers to both spectral components below and above fundamental frequency f_1

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

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

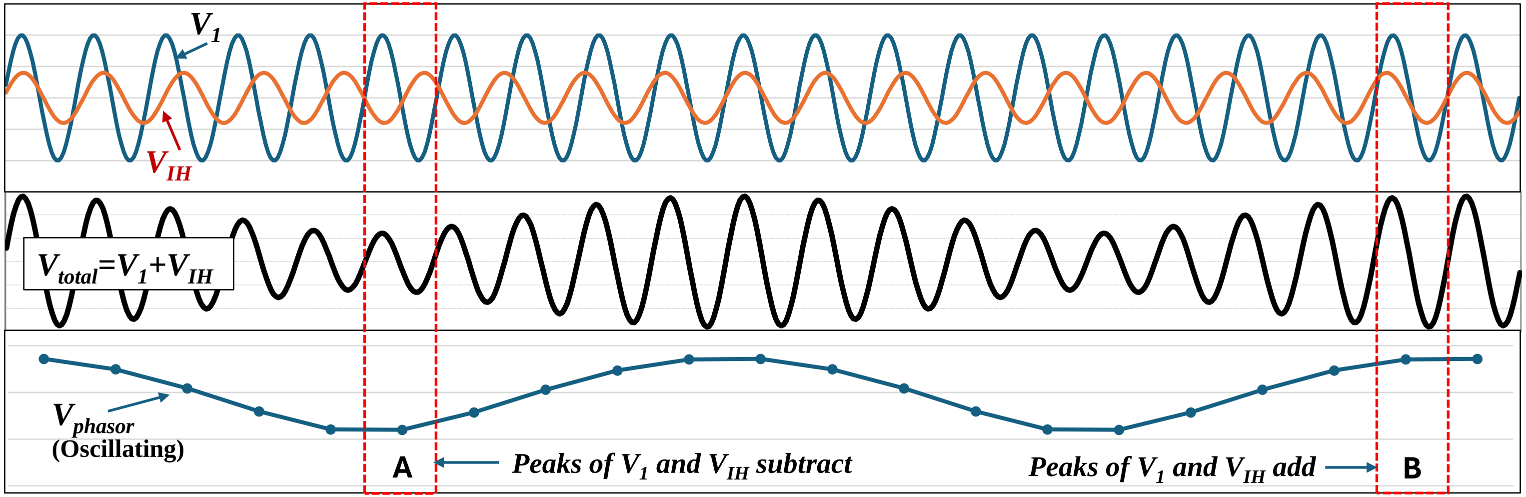
$$=\sqrt{2}V_1\cos(\omega_1 t+\delta)+\frac{mV_1}{\sqrt{2}}\{\cos[\underline{(\omega_1+\omega_{os})}t+\delta]+\cos[\underline{(\omega_1-\omega_{os})}t+\delta]\}$$

2.1 The phenomenon of beating wave

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



Constant magnitudes

well-known wave beating pattern

Oscillating phasor

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

2.1 The phenomenon of beating wave

Important takeaway

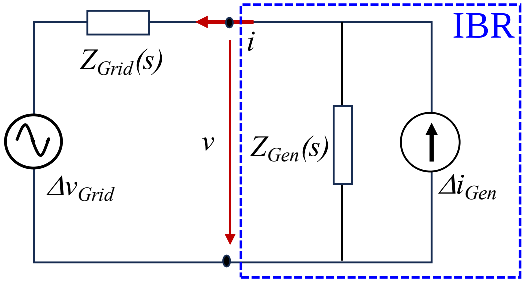
- **Oscillation is the appearance of a waveform beating pattern in the phasor domain;**
- **The beating pattern, in turn, is created by interharmonics interacting with the fundamental frequency wave;**
- **Therefore, the presence of interharmonics is the <u>general cause</u> of <u>phasor oscillations</u>**

<u>"General cause" means the following:</u> Each oscillation event arises from a specific cause, such as rotor oscillation. However, when viewed from an electrical perspective, they are all related to beating voltage and current waveforms. These beating waveforms are a result of the presence of IH components. This conclusion is applicable to all types of phasor oscillation phenomena, regardless of their individual mechanisms.

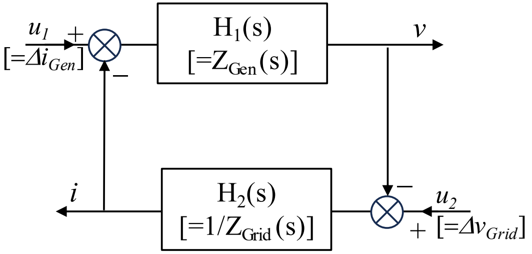
Phasor oscillations versus power system oscillations

2.2 Inverter oscillation

Theorem 2: Generation of interharmonic power (by, for example, a negative R) is the <u>necessary condition</u> of small-signal instability of IBR (and SG) systems.



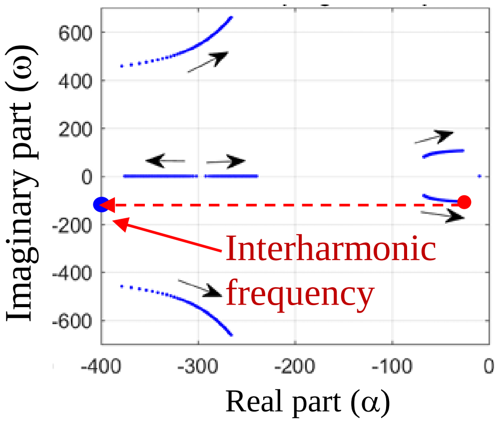
a) Circuit model (linearized system)



b) Feedback model

Eigenvalue plot of linearized <u>waveform model</u> of the system

For example, L is modeled as sL not as $jX_{@60Hz}$



System eigenvalues are known to have frequencies. These frequencies are the interharmonic frequencies we are talking about here.

Note: Proof is explained in a paper shown at the end

2.3 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}**

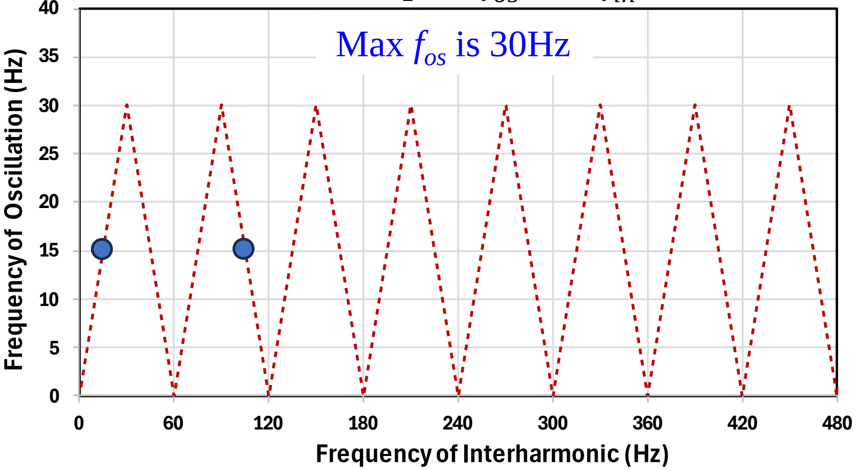
$$f_{ih} = f_{pole} = f_{natural}$$

Frequency of the wave causing beating

$$f_{os} = | f_{ih} - hf_1 |$$

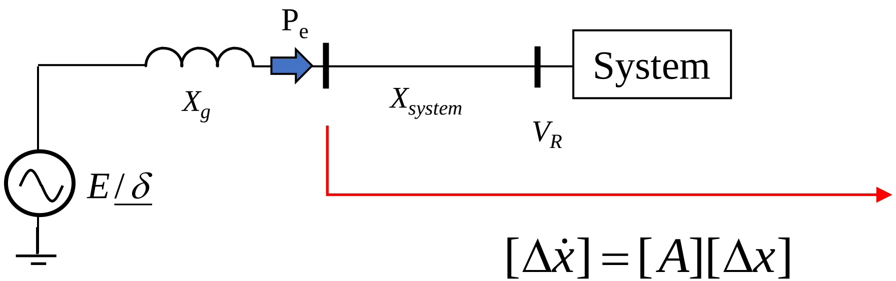
Frequency of resulting beating pattern

Relationship of f_{os} and f_{ih}

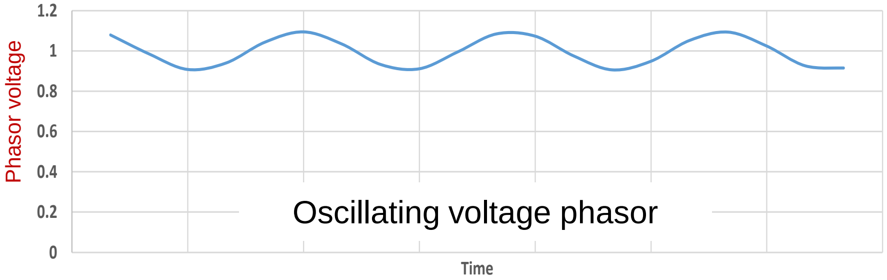


- Phasor has a "sampling rate" of 60Hz, so it cannot report oscillations higher than 30Hz.
- This is why oscillations above 30Hz has not been reported. But they do exist (see later)

2.4 New Interpretation of synchronous generator oscillation



$$[\Delta\dot{x}] = [A][\Delta x]$$



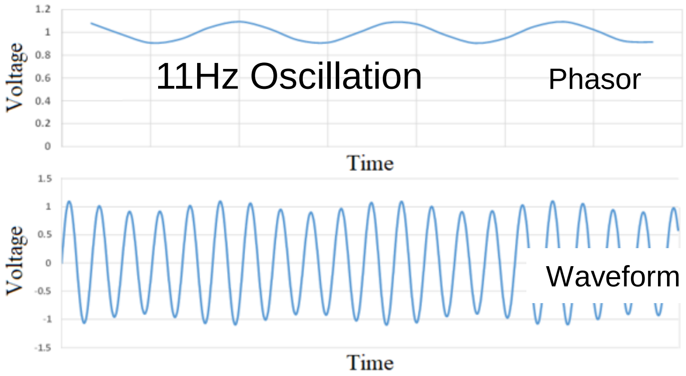
Question:

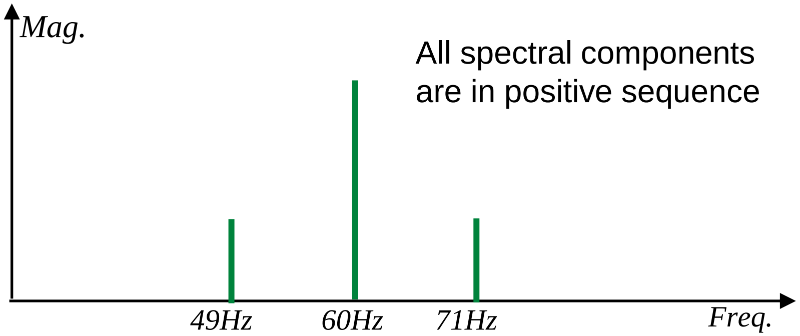
- Why there are oscillation, even oscillatory instability problems in SG connected systems?

Traditional answers in textbooks:

- There is a lack of damping in the system or the excitor needs tuning
- An eigen-value of the state matrix [A] has a positive real part

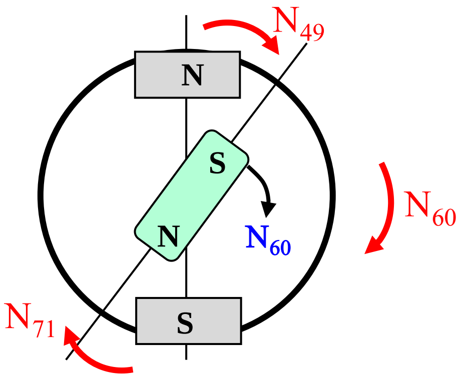
2.4 New Interpretation of synchronous generator oscillation





All spectral components are in positive sequence

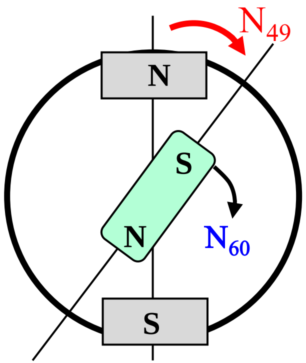
The above results indicate that the SG airgap actually experiences three rotating magnetic fields:



- M-field of 60Hz component: rotating at $N_{60} = 120 f_{60} / p = N_s$
- M-field of 71Hz component: rotating at $N_{71} = 120 f_{71} / p$
- M-field of 49Hz component: rotating at $N_{49} = 120 f_{49} / p$

N_s=synchronous speed=rotor speed, p=number of poles

2.4 New Interpretation of synchronous generator oscillation



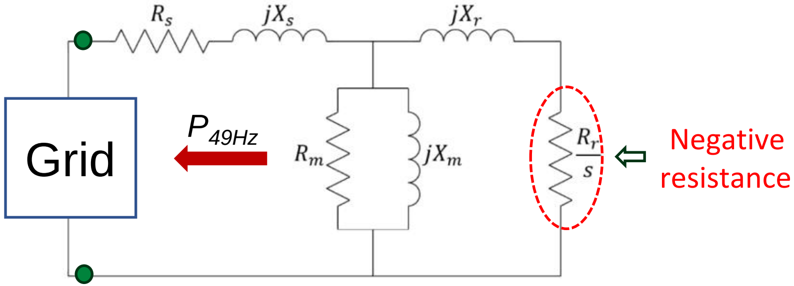
Examine the 49Hz magnetic field further:

- The 49Hz M-field rotates at N_{49} speed
- The rotator rotates at N_{60} (i.e. synchronous) speed
- Therefore, the rotor rotates faster than the 49Hz m-field
- Thus, the SG behaves as an induction generator w.r.t. to the 49Hz field
- 49Hz power is generated and injected into the grid

With respect to the 49Hz rotating field,
the rotor slip is

$$s_{49} = \frac{N_{stator-49} - N_{rotor}}{N_{stator-49}} = \frac{N_{49} - N_{60}}{N_{49}} = \frac{49-60}{49} = -0.22$$

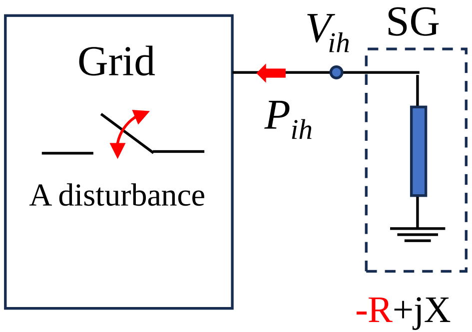
Negative slip



Equivalent circuit at 49Hz – induction generator

2.4 New Interpretation of synchronous generator oscillation

Interharmonic interpretation of SG oscillation:



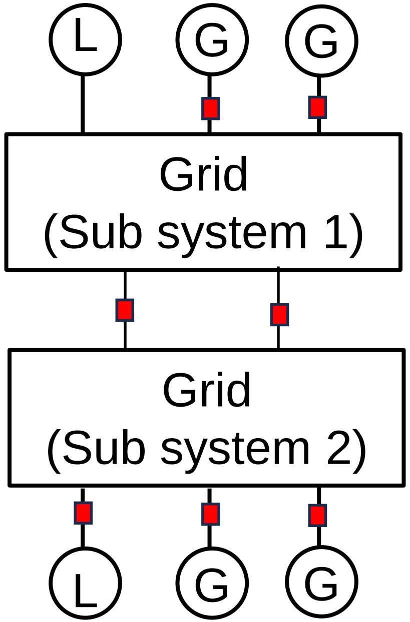
- A disturbance introduces various spectral components in V,
- One spectral component is, say, 49Hz,
- This component causes multiple SGs to produce power at 49Hz like an induction generator (i.e. –R)
- This power enters the grid. If it cannot be consumed by the grid (due to, for example, resonance at this frequency),
- It will set up increasingly higher 49Hz voltages and currents in the system, leading to more 49Hz power injections from the SGs,
- This positive feedback loop results in oscillatory instability of the generators and grid

3. Potential applications and field measurement results

3.1 Potential applications

One example application: Oscillation Source Location

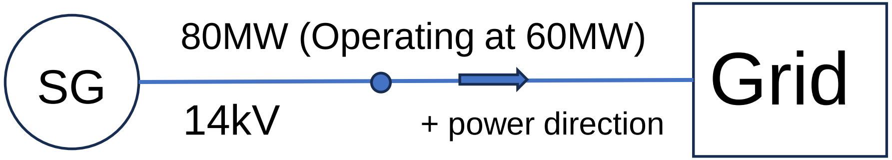
- Oscillation means there are beating voltage and current waveforms;
- The beating waveforms are caused by interharmonic voltages and currents;
- Powers (at the IH frequencies) are needed to drive the propagation of the interharmonic voltages and currents in a system;
- Therefore, interharmonic power 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



🟥 – monitors
G – power plants
L – load facilities

3.2 – Field measurement results

Case 1: Synchronous generator (SG)



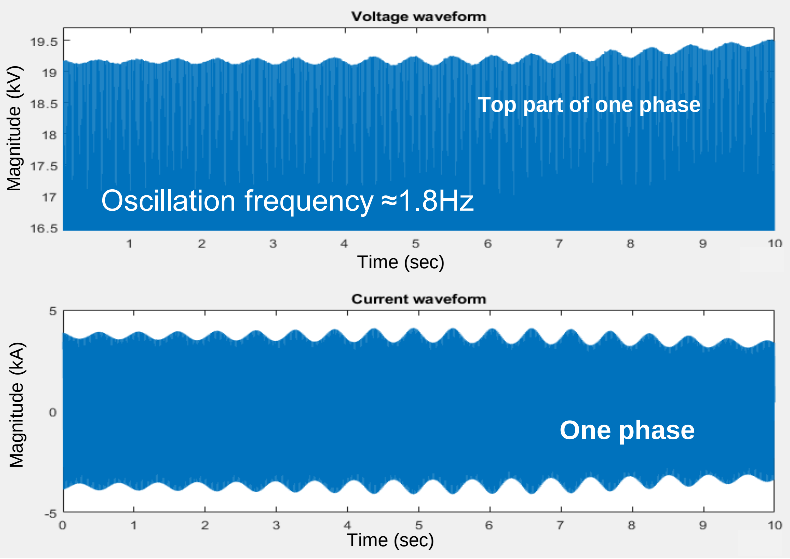
SG

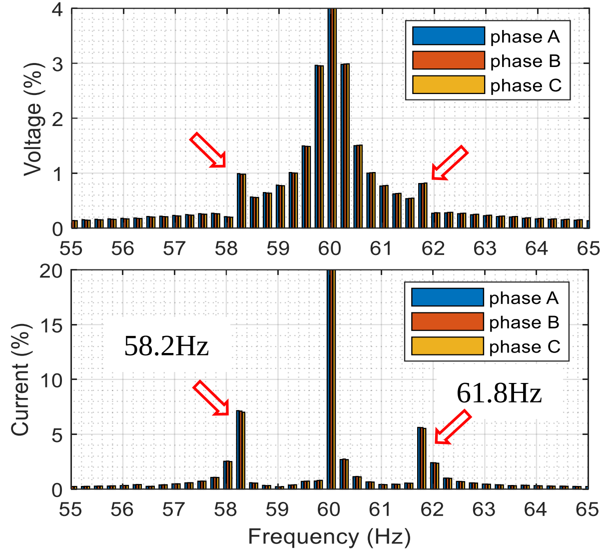
80MW (Operating at 60MW)

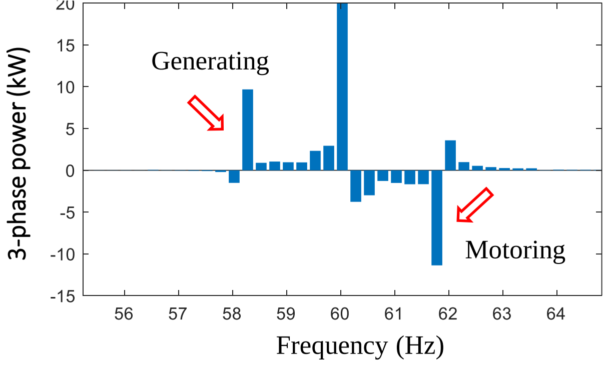
14kV

+ power direction

Grid

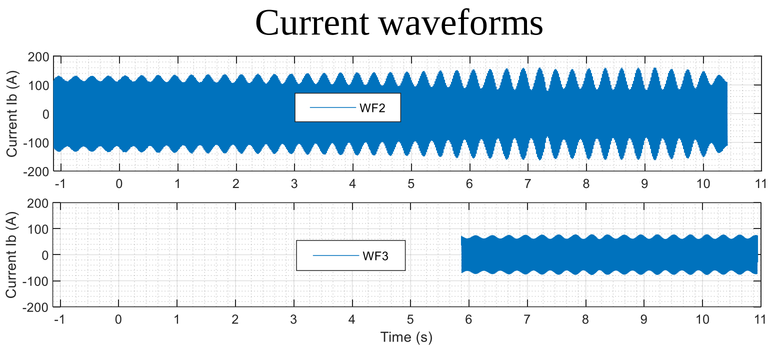


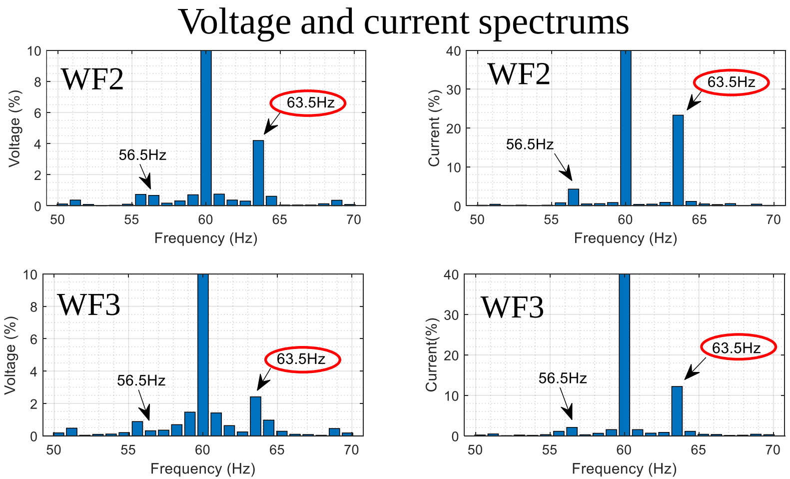


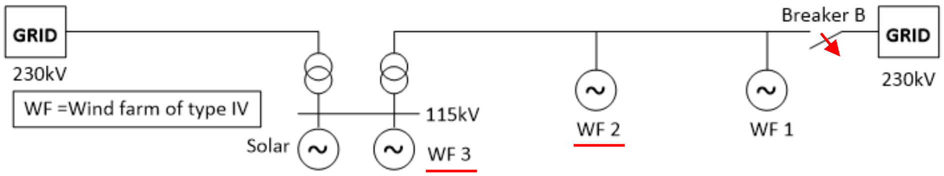


3.2 – Field measurement results

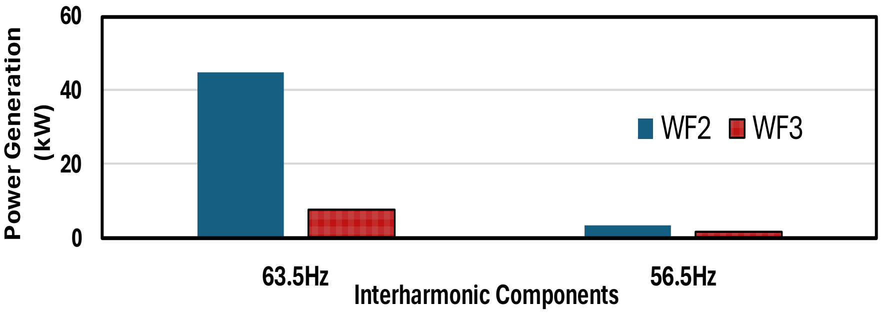
Case 2: Wind farms (WF)


Current waveforms


Voltage and current spectrums



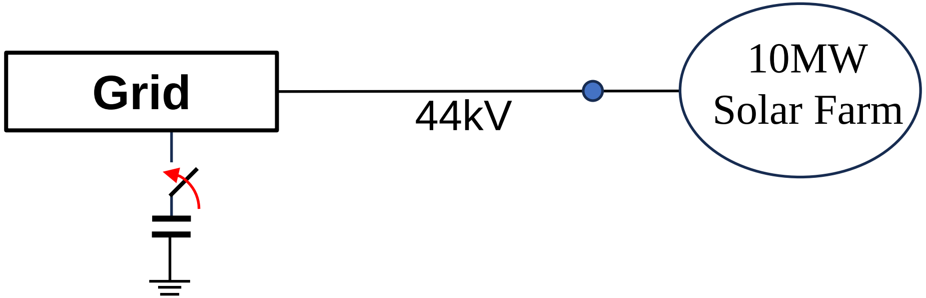
Comparing average IH powers of two WFs:

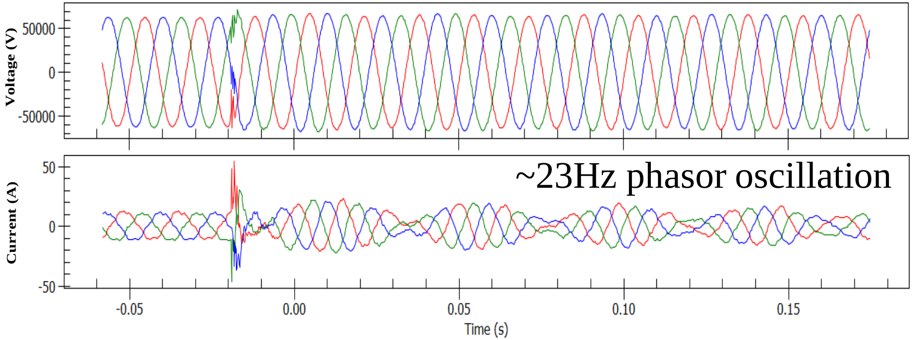


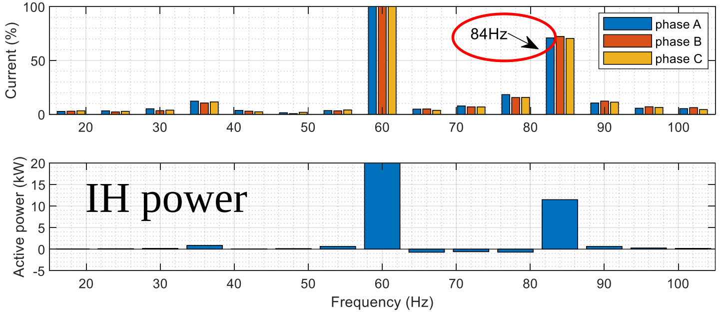
- **Both WFs contribute to the oscillation**
- **WF2 is the main contributor among the two**

3.2 – Field measurement results

Case 3: Solar Farm



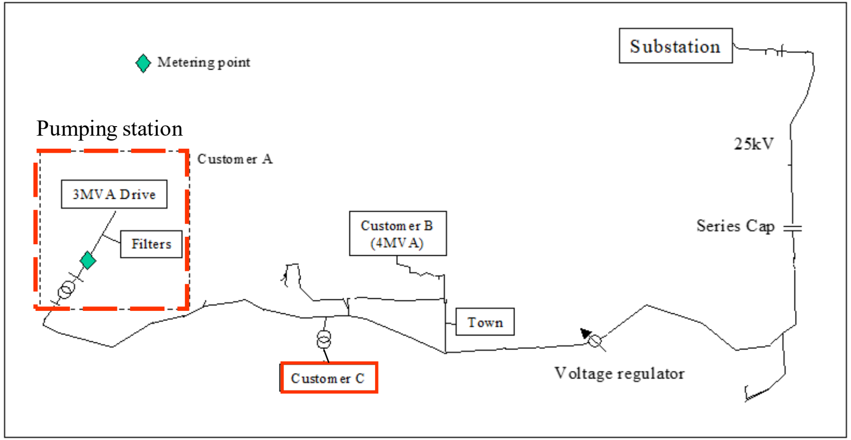

~23Hz phasor oscillation

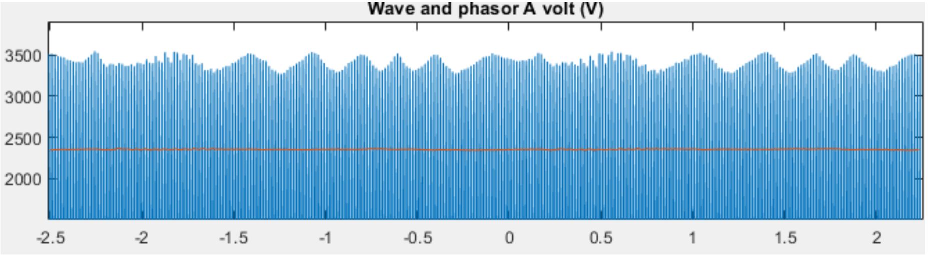

IH power

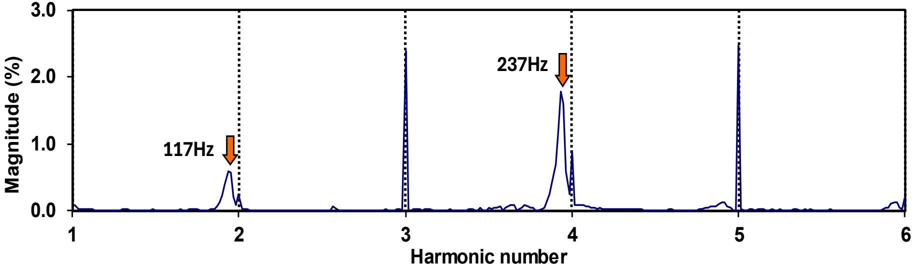
This case shows that the IH frequency is far away from 60Hz, so 60Hz phasor-based system model cannot be used to analyze such cases

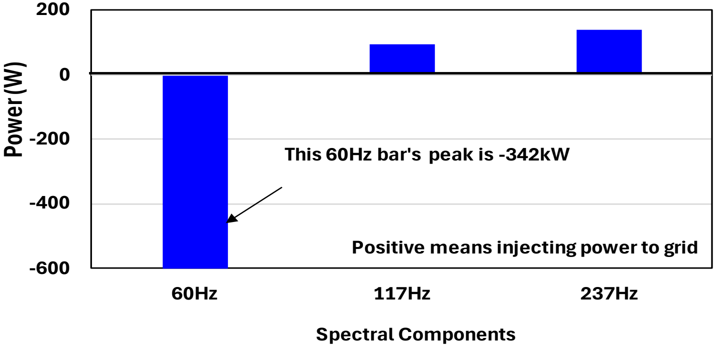
3.3 – Field measurement results

Case 4: Industrial plant









3.4 – Summary

- **Four field measurement cases have shown that interharmonics are indeed involved in phasor oscillations;**
- **This new insight has led to an immediate application – locating oscillation sources**
- **Additional applications include:**
    - Identify resonate components amplifying oscillations (see paper)
    - Participation factors for impedance-based stability analysis (see paper)
    - Direct measurement of the critical eigenvector
    - Oscillation damping using active interharmonic filter
    - Interharmonic-based relay for instability mitigation ….

Interharmonics can only be extracted from waveform data,
so waveform data is necessary for such applications

4. Discussion on
phasor data versus waveform data

4.1 Solving a simple circuit

4.2 Phasors of the measured data

4.3 What is the meaning of oscillating phasor power?

4.1 Solve a simple circuit

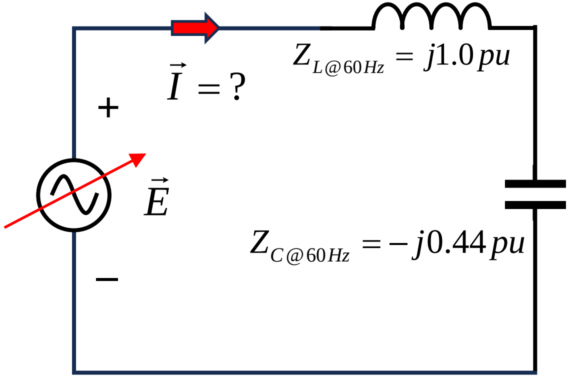
Which one is more fundamental: oscillating phasors or interharmonics?

Beating waveforms (i.e. IH) lead to oscillating phasors:

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

Oscillating phasors result in interharmonics:

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



$\vec{E}(t) = [1+0.1\cos(2\pi f_{os}t)]\angle 0^o\ pu$ An oscillating source

$$\vec{I} = \frac{\vec{E}}{Z_L+Z_C} = \frac{\vec{E}}{j1.0-j0.44} = [1.78+0.18\cos(2\pi f_{os}t)]\angle -90^o$$

Is this solution correct?

4.1 Solve a simple circuit

What are the true frequencies experienced by the L and C components?

Phasor $\vec{E}(t) = [1+0.1\cos(2\pi f_{os} t)]\angle 0^o \quad pu$

It actually means the following voltage:

$$e(t) = \sqrt{2}[1+0.1\cos(2\pi f_{os} t)]\cos(2\pi f_1 t + 0)$$

$$= 1.414\underline{\cos(2\pi f_1 t)} + 0.071\cos(\underline{2\pi f_{IH1}} t) + 0.071\cos\underline{(2\pi f_{IH2}} t)$$

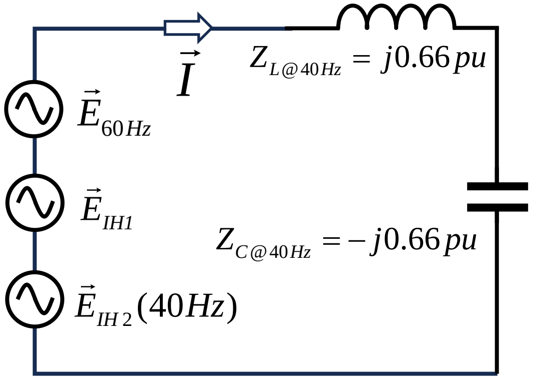
$$f_{IH1} = f_1 + f_{os}, \quad f_{IH2} = f_1 - f_{os}$$

Main findings:

1) E is composed of three constant phasors

2) If f_{os}=20Hz, it follows f_{IH1}=80Hz, f_{IH2}=40Hz. These are interharmonic components

3) A correct way to solve the problem is the superposition method shown on the right



b) Interharmonics-based solution

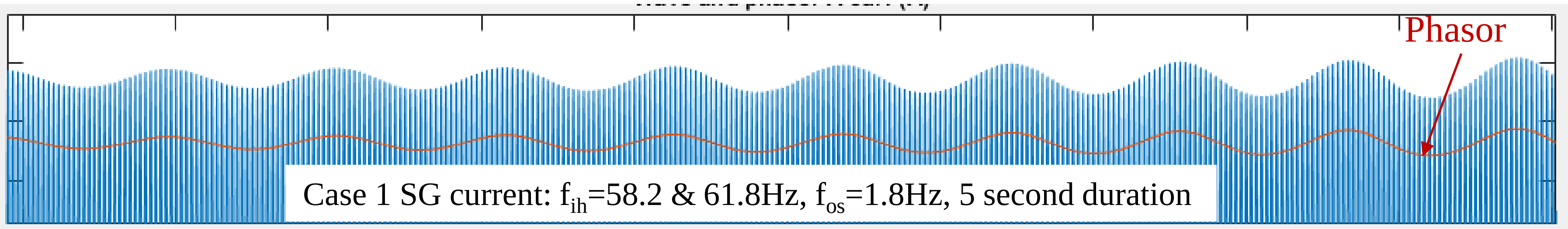
Solution of current caused by E_{IH2}:

$$\vec{I}_{IH2} = \vec{E}_{IH2} / (j1.0h - j0.44/h)$$
$$= \vec{E}_{IH2} / (j0.66 - j0.66) = \infty$$

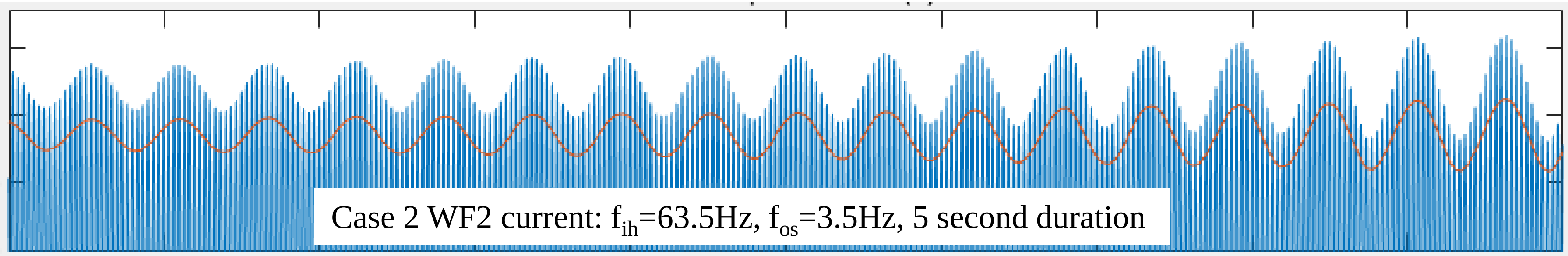
h=40/60

We get an infinity current I at IH2, which means that the correct answer for current phasor is infinity!

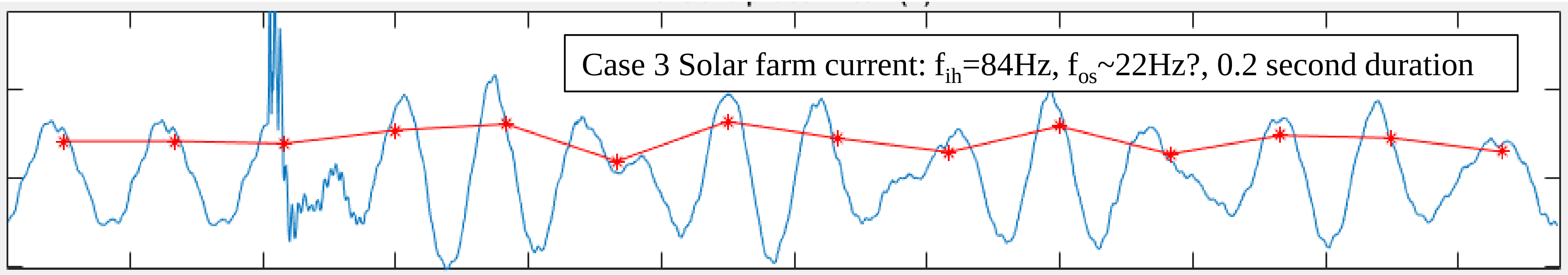
4.2 Phasors of measured data



Case 1 SG current: $f_{ih}=58.2$ & 61.8Hz, $f_{os}=1.8$Hz, 5 second duration

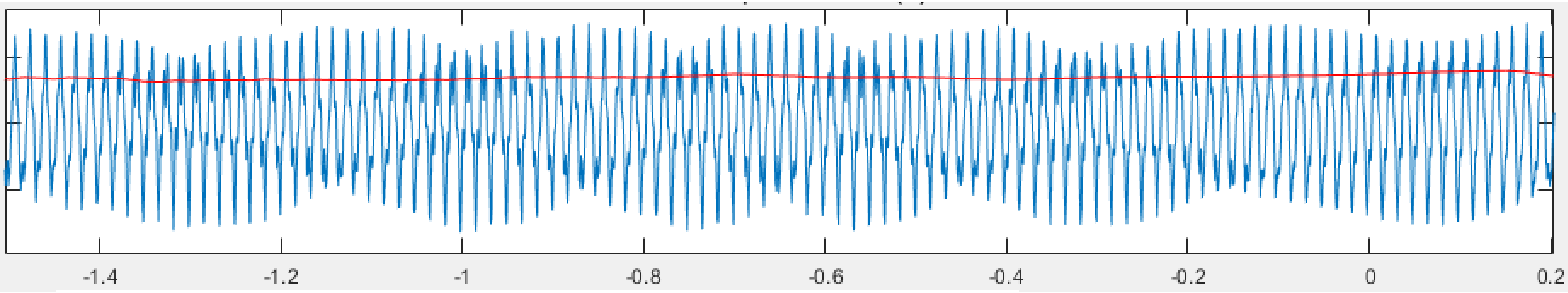


Case 2 WF2 current: $f_{ih}=63.5$Hz, $f_{os}=3.5$Hz, 5 second duration



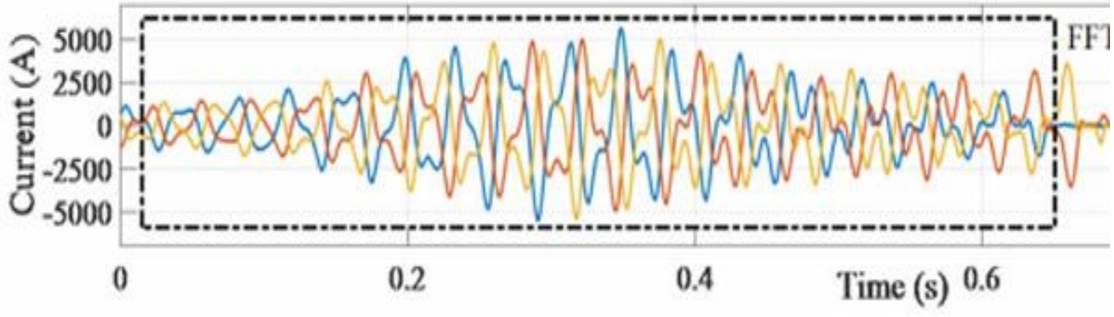
Case 3 Solar farm current: $f_{ih}=84$Hz, $f_{os}\sim 22$Hz?, 0.2 second duration

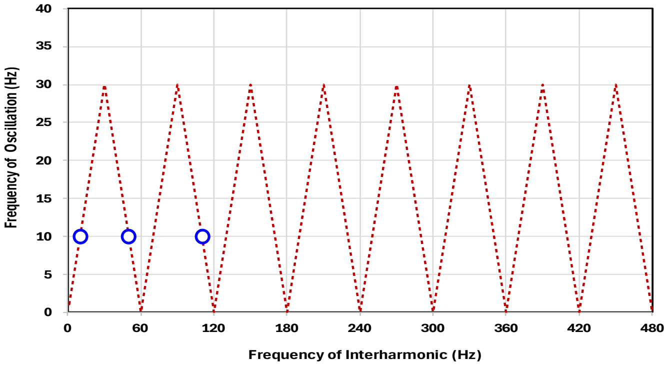
4.2 Phasors of measured data



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}=?





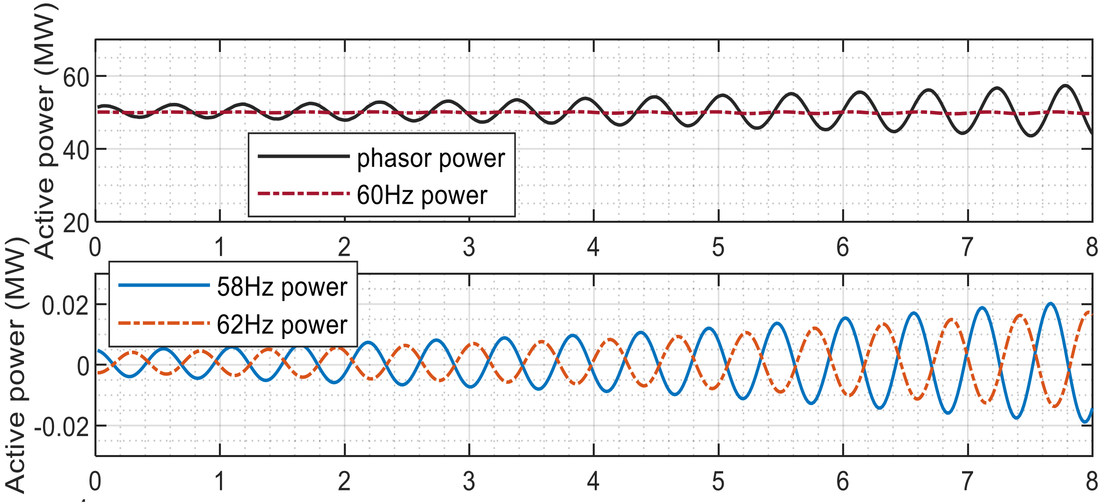
Multiple aliasing-like effects compound together to form a phasor

4.3 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)

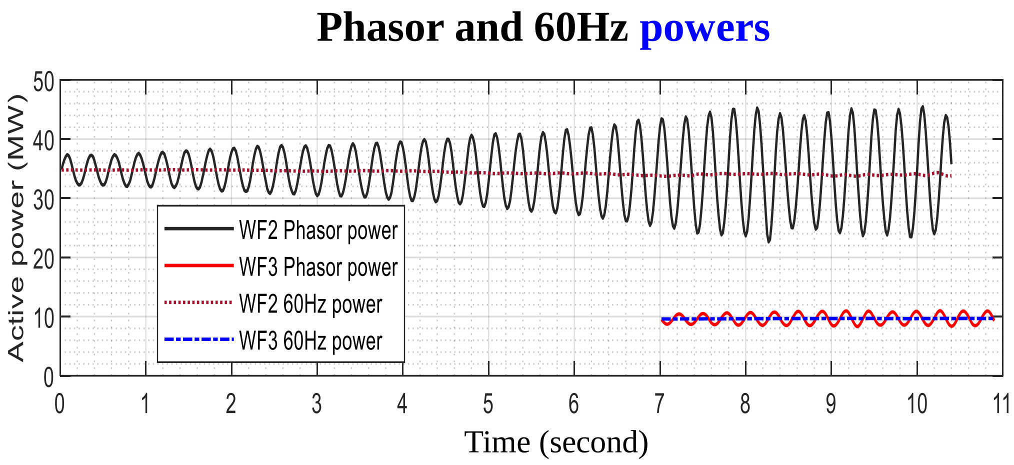
Trend of phasor, 60Hz and interharmonic powers



- 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?

4.3 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?

4.4 Summary

- **Phasor is conceived to represent a constant sinusoidal waveform**
- **Using phasor to characterize a beating waveform is an approximation**
- **This approximation breaks down if the natural frequencies of a system (i.e. interharmonic or modal frequencies) are not close to 60Hz**
- **Since IBRs and converters can produce interharmonics at various frequencies, there is no guarantee that the phasor approximation will continue to work**
- **Therefore, it is the time for us to adopt waveform data for power system oscillation monitoring and analysis**

5. Conclusions and Takeaways

5.1 Main findings

- Phasor oscillation is the appearance of a waveform beating pattern;
- The beating pattern, in turn, is caused by interharmonics interacting with the fundamental frequency wave;
- To gain insights on an oscillation event, it is important to investigate the interharmonics contained in the waveform data;
- Phasor is conceived to model constant sinusoidal waves, not beating waveforms;
- Therefore, phasor has limitations to model power system oscillations, which has become more evident for systems with IBRs and converters

5.2 Potentials of synchrowaveform data

- 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 a killer 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

Thank you

I welcome any questions and comments you may have

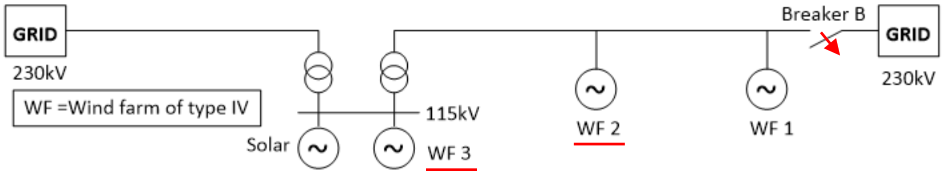
More information can be found from the following paper:

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.

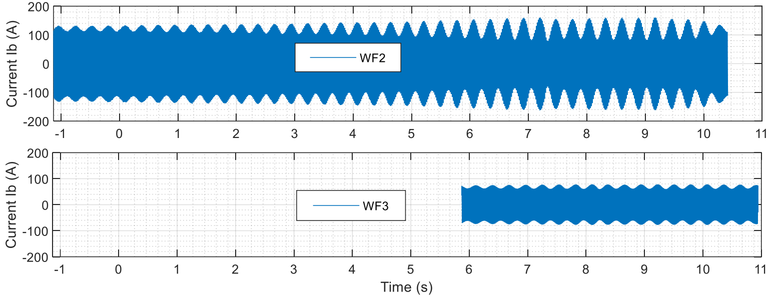
This presentation and an Excel demo will be shared with the TF

A.1 – The role of synchronized waveforms

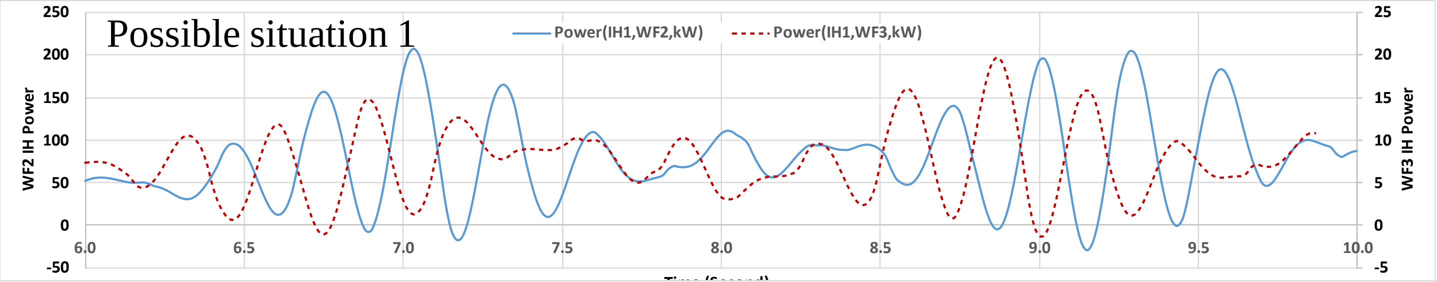
Wind farm case

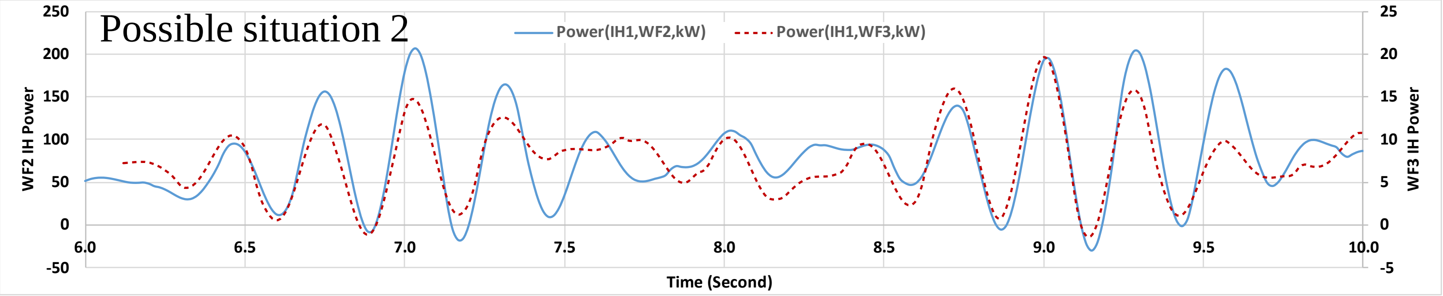


Current waveforms



Trend of interharmonic powers of the two wind farms

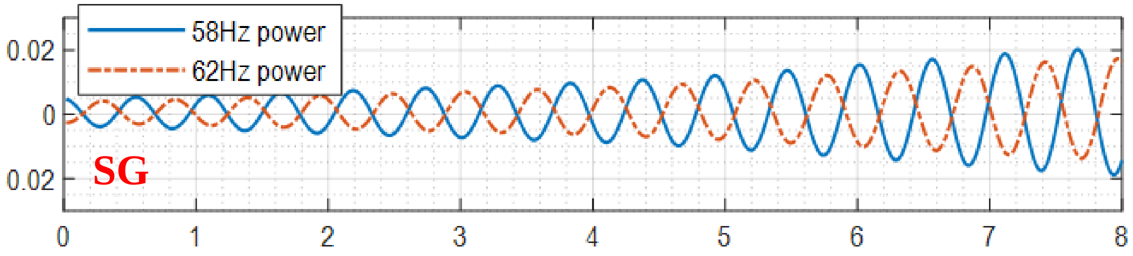


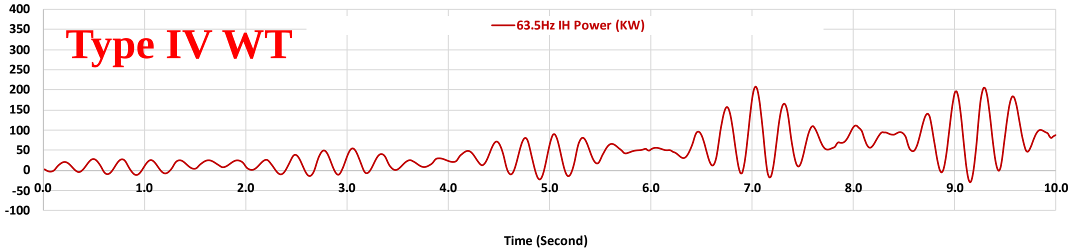


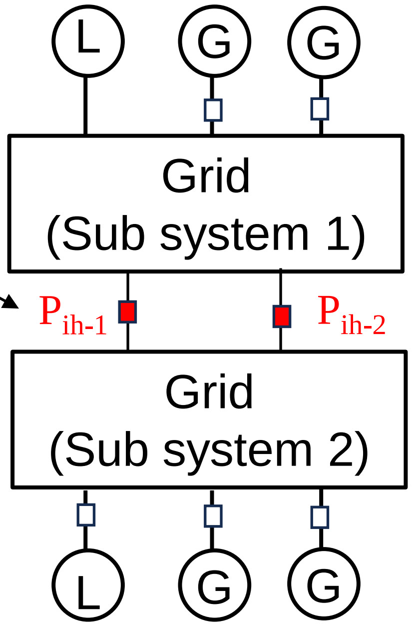
A.2 – The role of synchronized waveforms

System wide pattern of oscillation:

- **Areas containing sources of oscillations:**
- **Coherency of oscillations among the generators:**





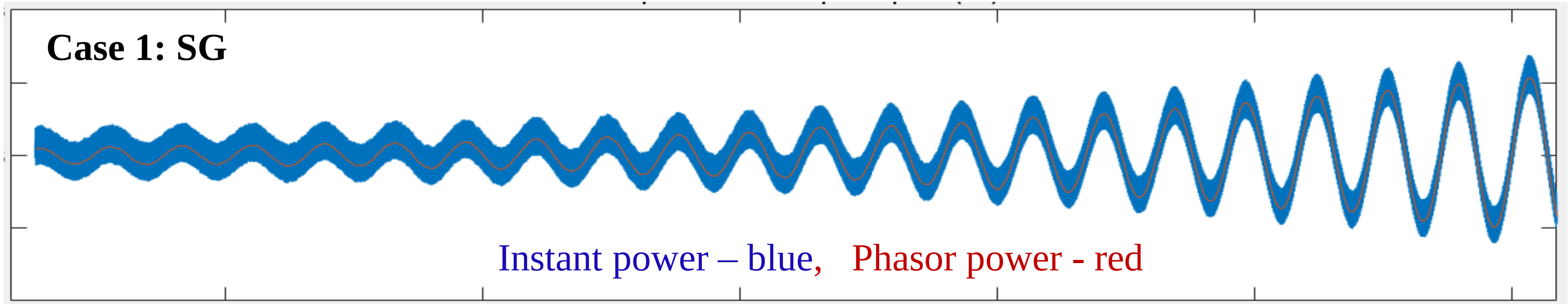


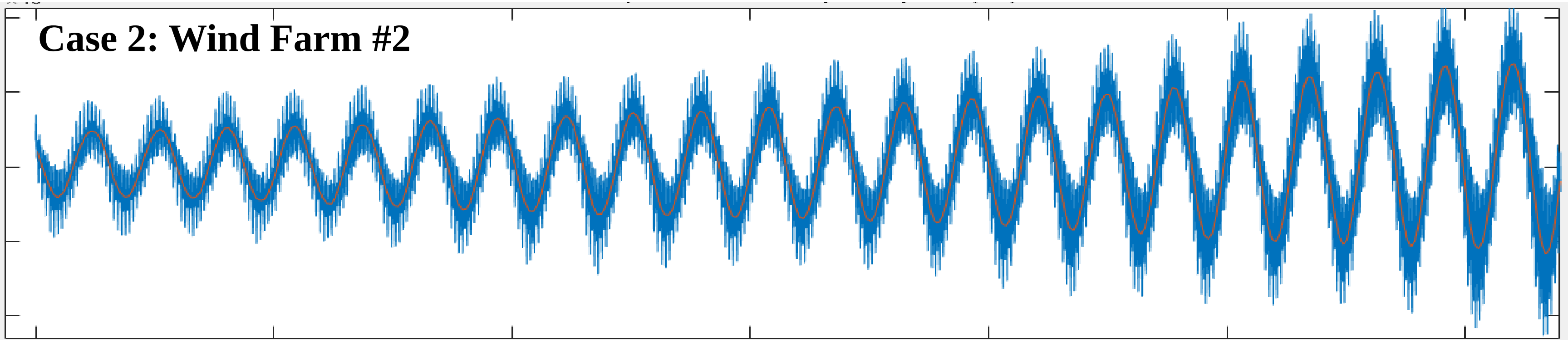
🟥 – monitors
G – power plants
L – load facilities

A.3 Three-phase phasor power versus instant power

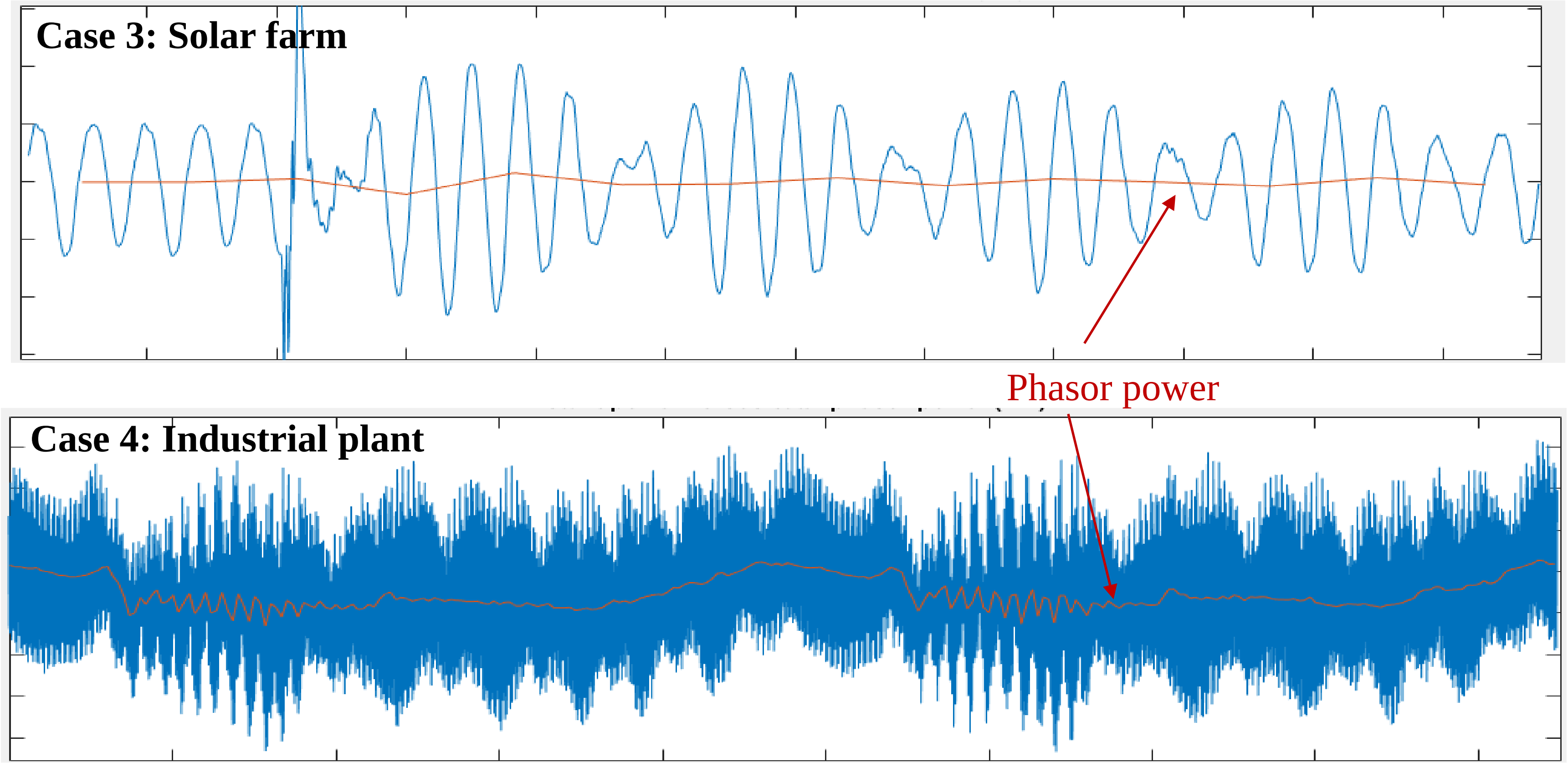
$$P_{instant} = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t)$$

(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

A.4 Inspiration from symmetrical component analysis

Comparing Interharmonic Component Analysis with Symmetric Component Analysis

Phenomena	Transformation		Insights		Applications
Oscillating V & I	Fourier transform	Several interharmonic components	New way to understand oscillation	Extra rotating fields of different speeds in airgap	Source location Y(s) method & pf IH relay? IH stabilizer? Anti-IH PLL? More ...
Unbalanced V & I	Symmetrical components transform	Three sequence components	New way to understand unbalance	Positive and negative rotating fields in airgap	Short-circuit calculation Neg. sequence protection Many others ….