IEEE PES PSDP/PSSC Forced Oscillations Task Force
Monthly Meeting

Using Interharmonic Power for Power System Oscillation Source Location

Presentation by
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Objective and Outline

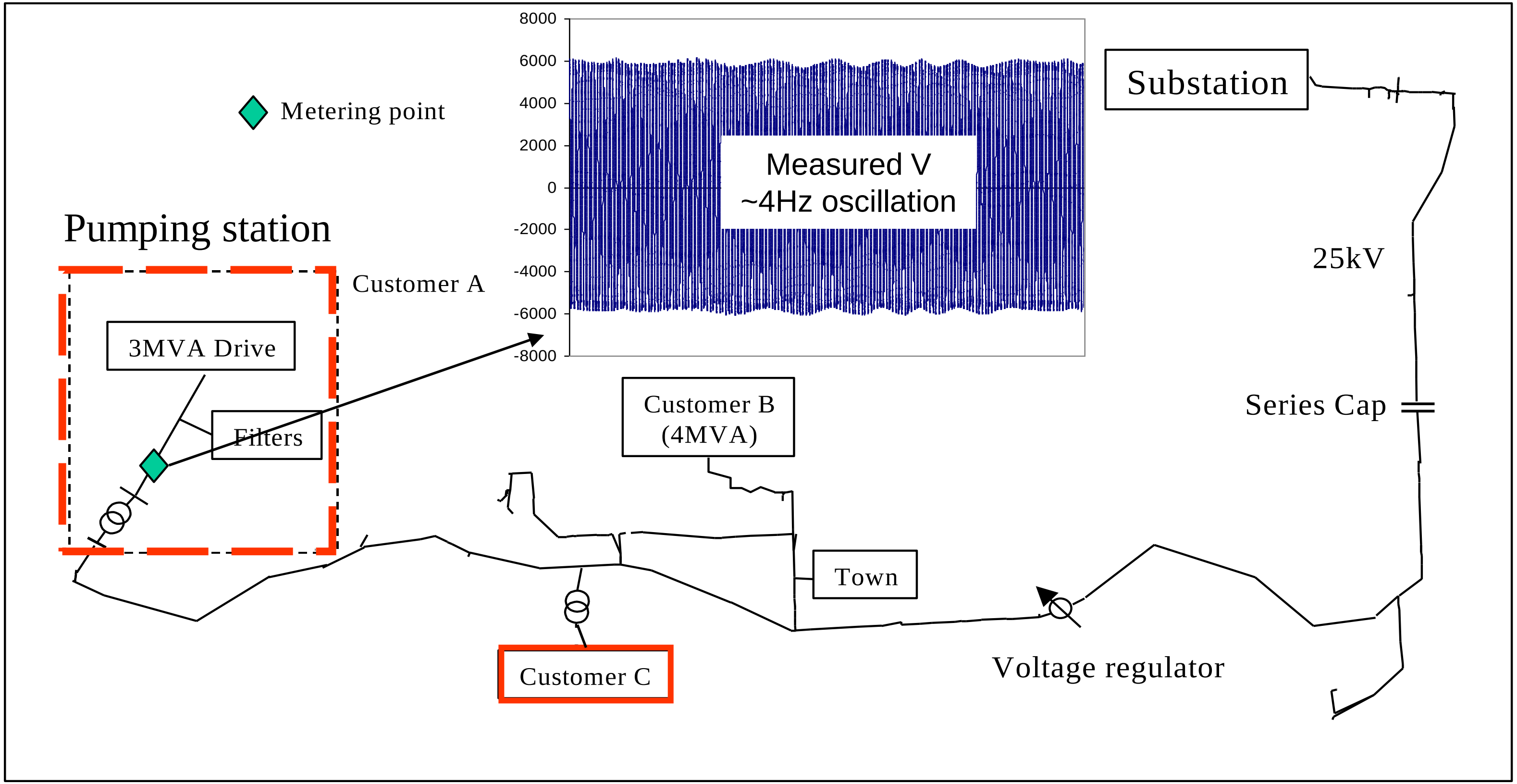
This presentation is to share latest findings on power system oscillations based on the voltage flicker investigation presented in Nov. 2024

1. **Background: from voltage flicker to voltage oscillation**
2. **Relationship between interharmonics and phasor oscillations**
3. **An interharmonic power-based method for oscillation source location and field measurement results**
4. **Additional interesting findings**
5. **Summary and research needs**

1. Background

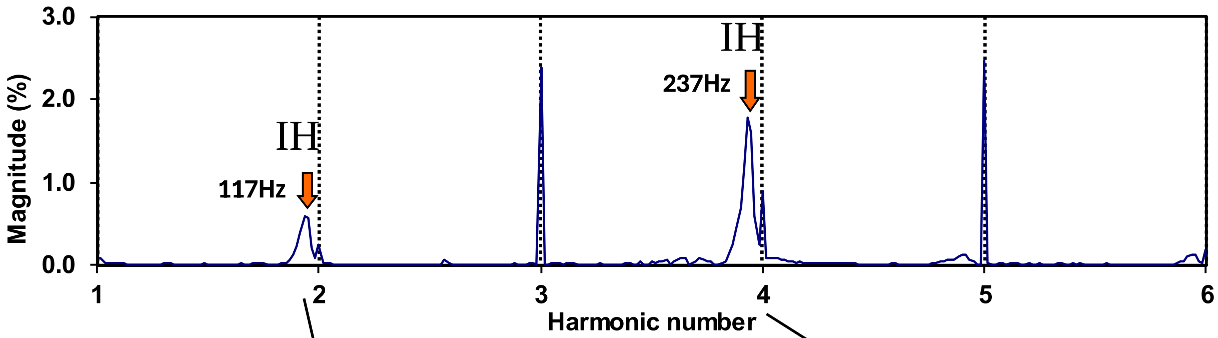
1. Background – a voltage flicker case

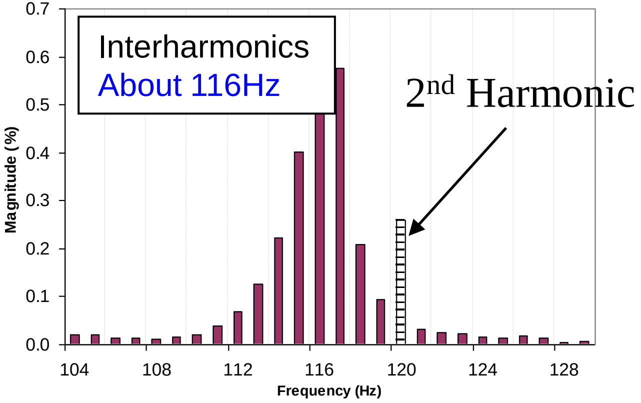
Voltage flicker or fluctuation caused by a variable frequency drive (VFD)

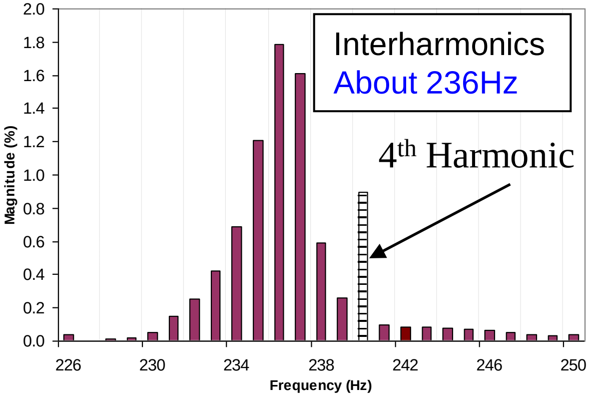


1. Background – a voltage flicker case

Spectrum of voltage waveforms (IH = interharmonics)







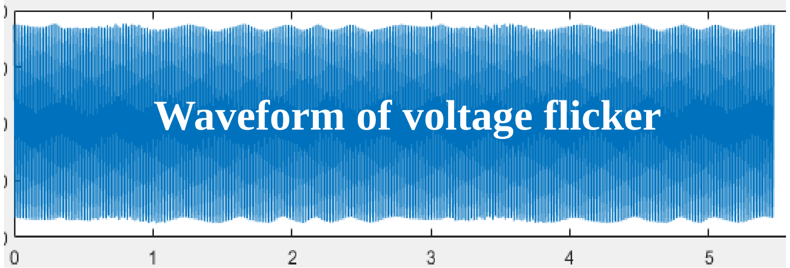
IEC 61000-4-30 definition:

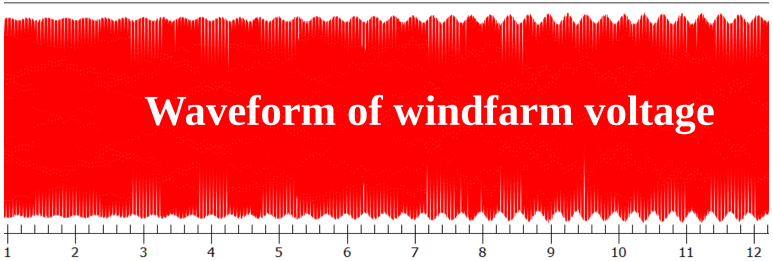
Interharmonics are spectral components whose frequencies are not integer multiple of f_1, ie. $f_{IH}/f_1 \neq$ integer

For convenience, IH here refers to both spectral components below and above f_1

Direction of 116Hz and 237Hz active powers were used to locate the source successfully

1. Background – can we extend it to oscillation phenomena?





To convince stability and phasor researchers, the following must be done:

- Prove the existence of interharmonics is the necessary and sufficient condition for any phasor oscillations
- Show that synchronous generator oscillation can be explained using interharmonics
- Demonstrate that IBR oscillations are also caused by interharmonics
- There are convincing field measurement data to support the above claims

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.

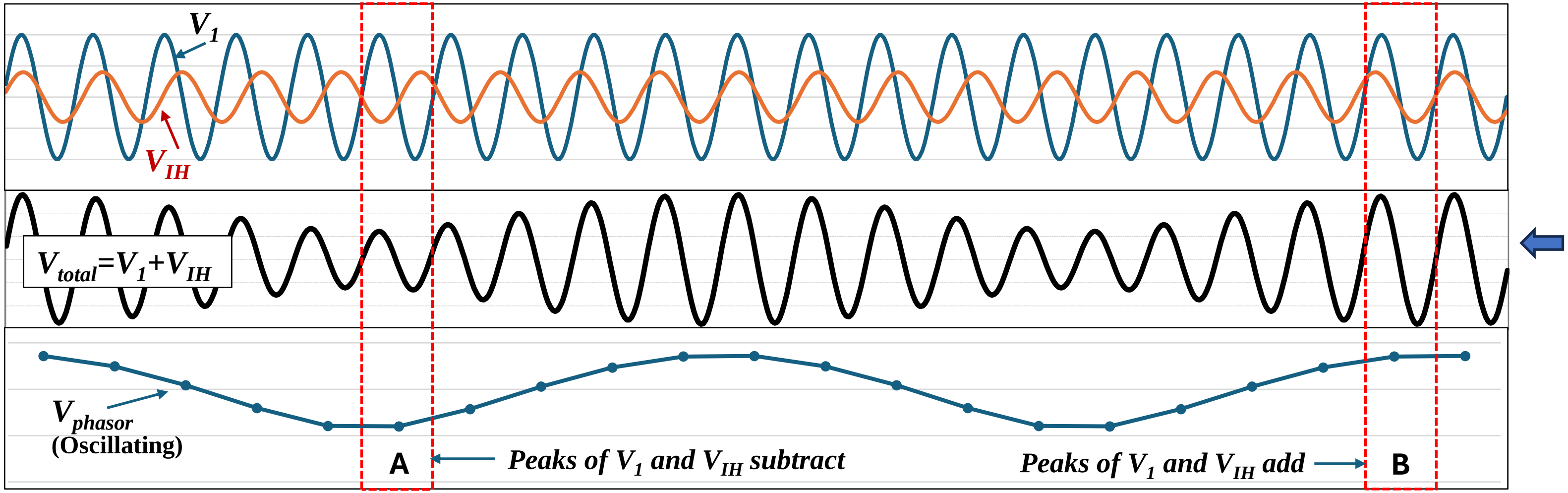
2. Relationship between Interharmonics and phasor oscillations

2.1 First Evidence – the phenomenon of beating wave

Theorem 1: The existence of interharmonic components is the necessary and sufficient condition of phasor oscillations

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



This is the well-known wave beating phenomenon

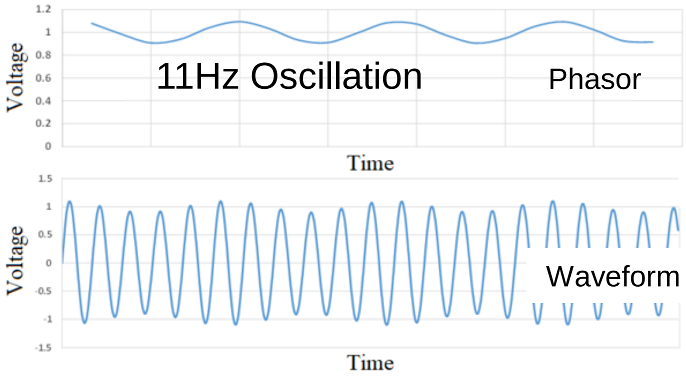
2.1 First Evidence – the phenomenon of beating wave

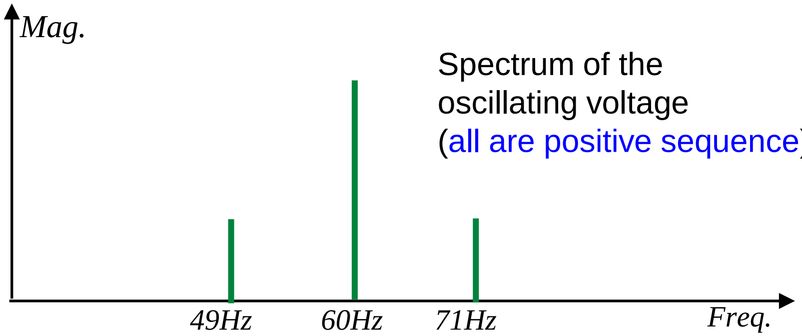
Important takeaway

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

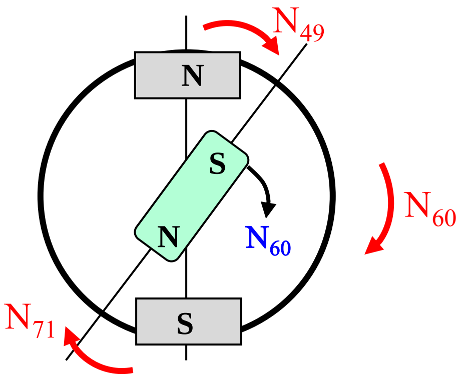
General cause means the following: Each oscillation event has its own specific cause such as mechanical vibration. However, all events manifest as beating voltage and current waveforms from electrical perspective. The beating waveforms are caused by the existence of IH components. This interpretation applies all type phasor oscillation phenomenon regardless their physical mechanisms.

2.2 Second Evidence – Synchronous generator oscillation





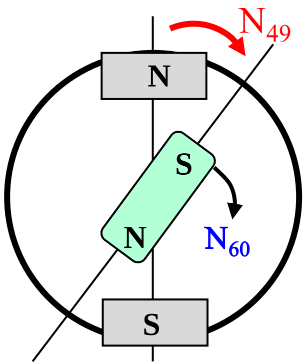
The above results indicate that the SG airgap actually experiences three rotating magnetic fields:



- 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 $N_{49} = 120 f_{49} / p$

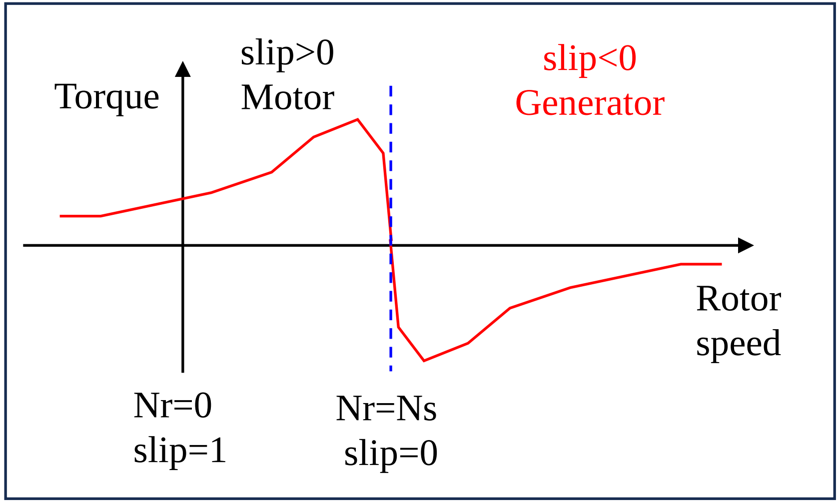
N_s=synchronous speed=rotor speed, p=number of poles

2.2 Second Evidence – Synchronous generator oscillation



Examine the 49Hz magnetic field further:

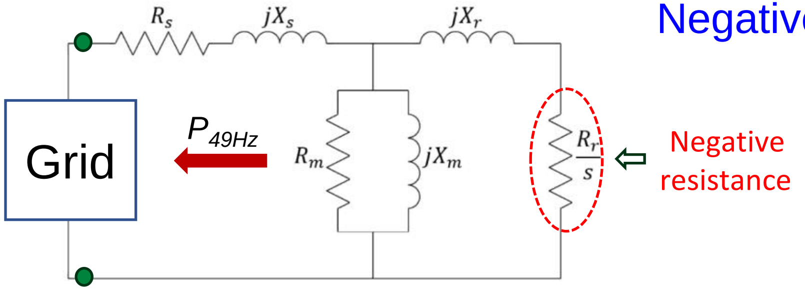
- The 49Hz M-field rotates at N_{49} speed
- The rotator rotates at N_{60} (i.e. synchronous) speed
- Therefore, the rotor rotates faster than the 49Hz m-field
- Thus, the SG behaves as an induction generator w.r.t. to the 49Hz field



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

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

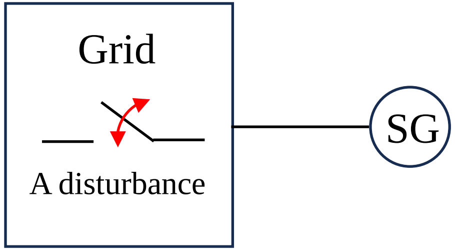
Negative



Equivalent circuit at 49Hz – induction generator

2.2 Second Evidence – Synchronous generator oscillation

Interharmonic interpretation of SG oscillation:

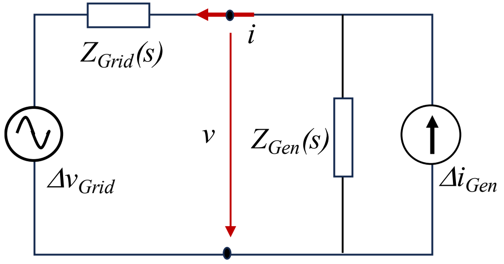


- A disturbance introduces various spectral components in V&I,
- One spectral component is, say, 49Hz,
- This component causes multiple SGs to produce power at 49Hz like an induction generator,
- This power enters the grid. If it cannot be consumed by the grid (due to, for example, resonance at this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

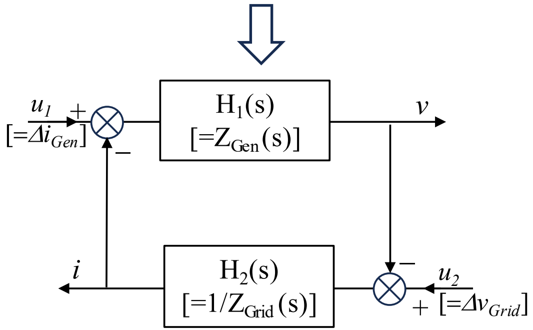
The paper also shows that rotor angle oscillation produces interharmonic voltages at SG terminal

2.3 Third Evidence – Inverter oscillation

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

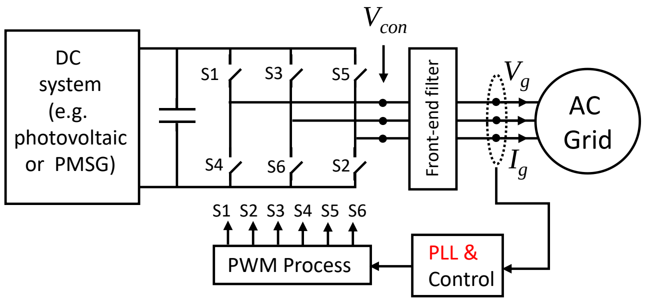


a) Circuit model (linearized system)



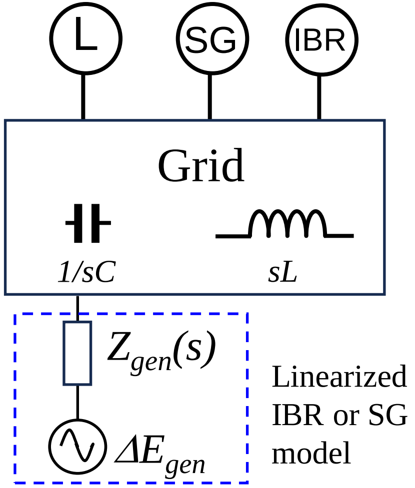
b) Feedback model

Interharmonic (IH) explanation of PLL causing inverter oscillatory instability:



1. The grid running at 60Hz experiences a disturbance
2. PLL detects a 60.5Hz grid frequency instead
3. PLL lets inverter inject a 60.5Hz AC (i.e. an IH) into the grid
4. If this IH is amplified due to high grid impedance,
5. It could make PLL see a 62.2Hz “grid” frequency …
6. This process ends at, say, 74Hz PLL frequency, leading to 14Hz (=74-60) sustained or increasing phasor oscillation

2.4 Fourth Evidence – Eigenvalues of system dynamic models



System dynamic model

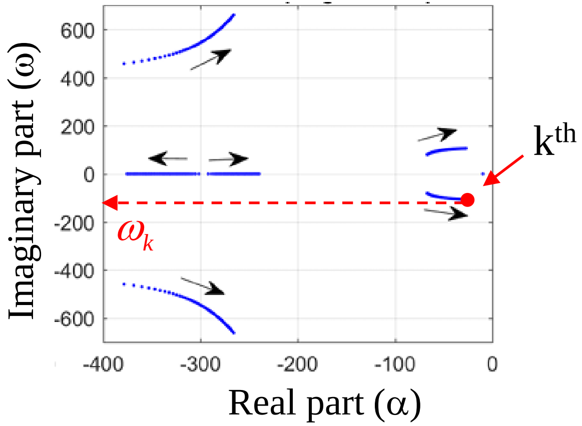
$$[\Delta \dot{x}] = A[\Delta x]$$

or

$$[Y(s)][\Delta V] = [\Delta I]$$

Must be EMT type model

Eigenvalue plot



One of the eigenvalues: $\lambda_k = \alpha_k + j2\pi f_k$ ← Interharmonic frequency

In fact, stability researchers know well that system eigenvalues have frequencies. These frequencies are the interharmonic frequencies we are talking about here.

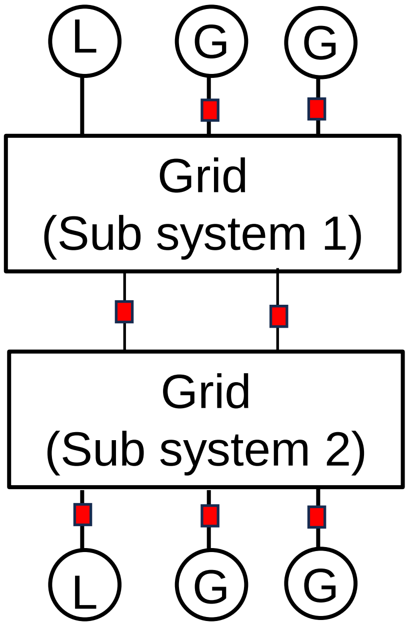
~~**Harmonic instability? Interharmonic instability?**~~ **This is just small-signal stability in wave domain**

3. An interharmonic power-based method for oscillation source location
&
Field measurement results

3.1 The logic of IH based 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;**
- **It is, therefore, reasonable to call the interharmonic power producing components (SG and IBR) as 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 Method of IH based source location – simplest implementation



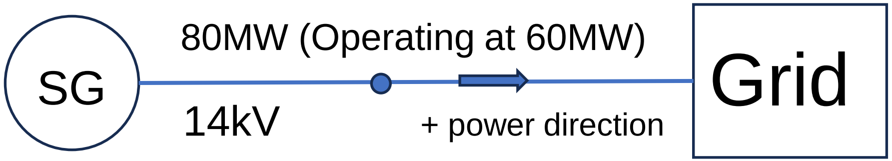
■ – monitors
G – power plants
L – load facilities

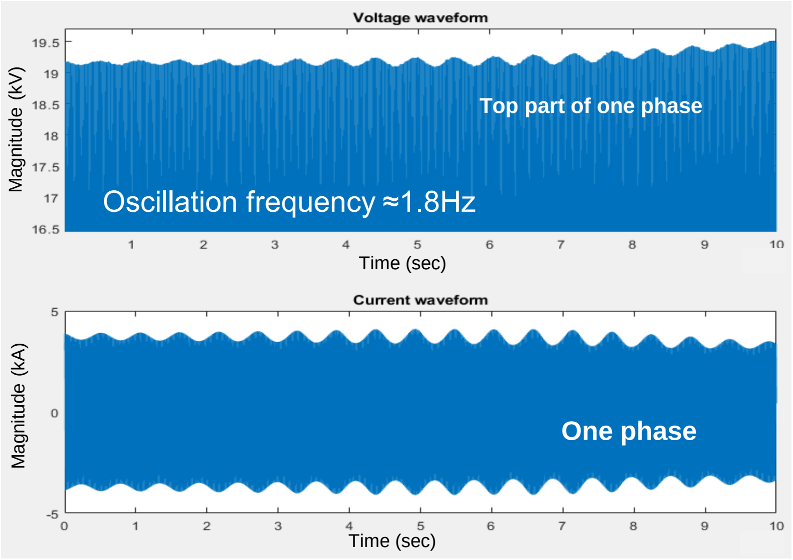
1. **Perform DFT on V&I waveform data of the monitored generator or load, using a moving window;**
2. **Determine and extract key IH components from the results;**
3. **Calculate three-phase IH active powers generated, one data window by one data window, for the IH components;**
4. **Compute the average powers (or accumulated energies) over the period of interest;**
5. **Compare the IH powers (or energies) of all monitored generators or loads, identify and rank the sources**

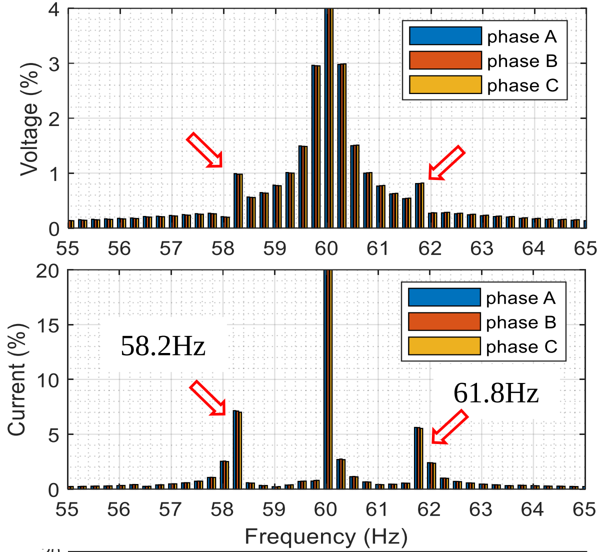
- Networked waveform monitors (such as PQ monitors) are already deployed. Their software needs to be modified for this specific task
- IH powers at key interties can be monitored to determine if an oscillation event is local or system wide

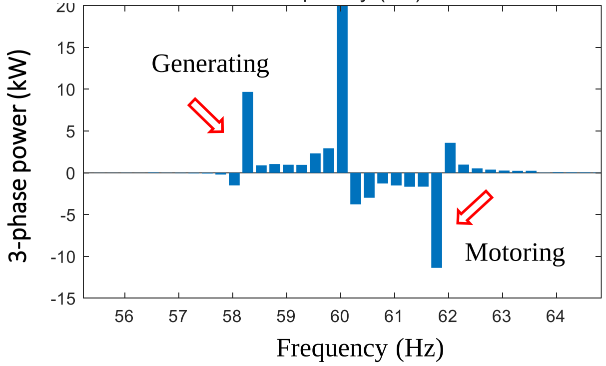
3.3 – Field measurement results

Case 1: Synchronous generator (SG)









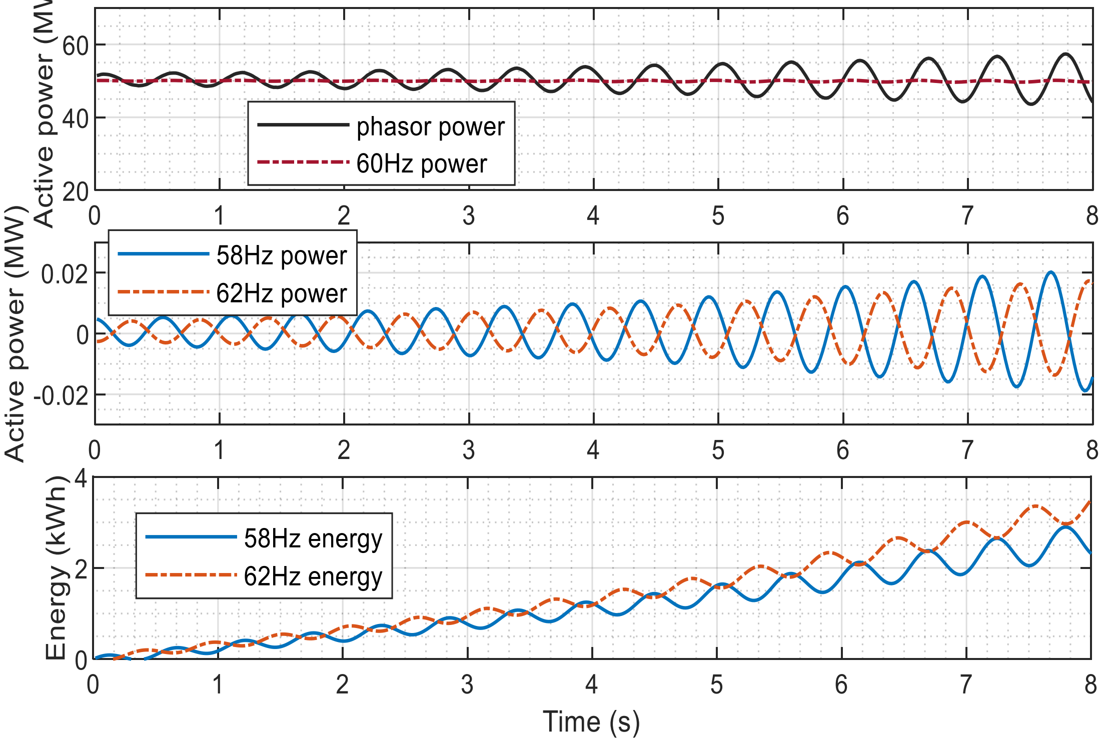
3.3 – Field measurement results

Case 1: Synchronous generator (SG)

$$P_{total} = \frac{1}{T_{os}} \int_{t_0}^{t_0+T_{os}} v(t) \times i(t) dt = P_1 + P_2 + \ldots + P_k + \ldots$$

$$P_k = V_k I_k \cos(\theta_k)$$

Trend of phasor, 60Hz and interharmonic powers

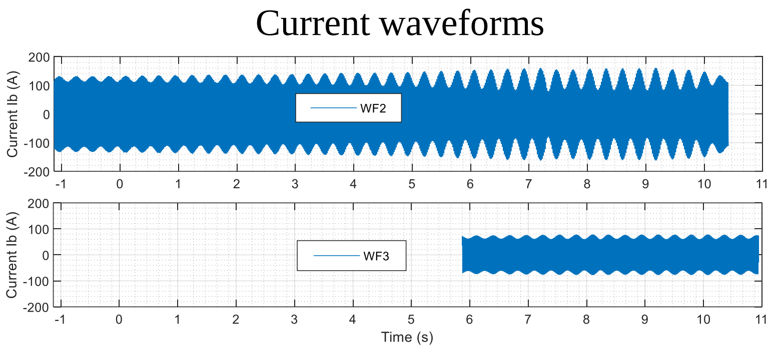


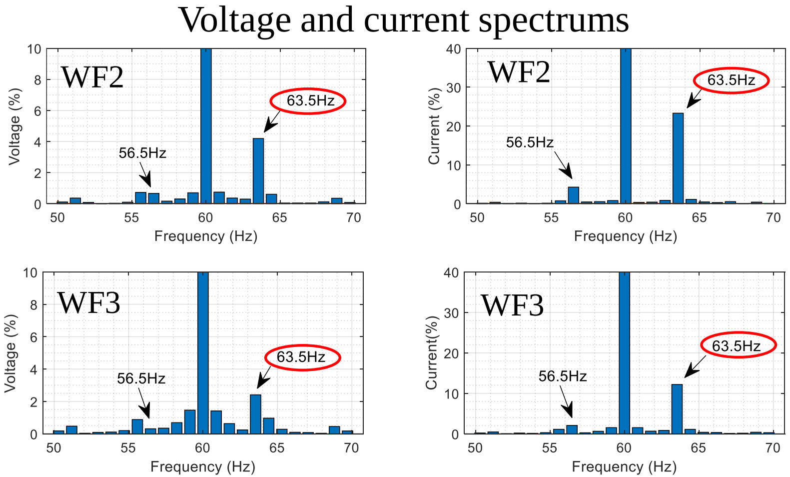
Unexpected but important findings:

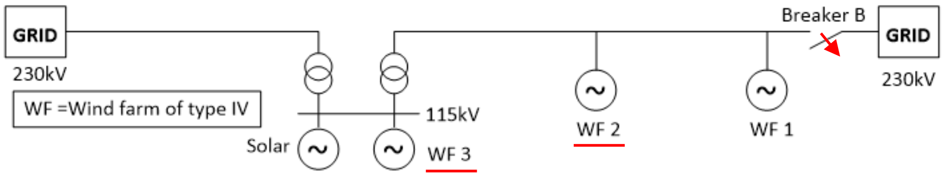
- Fundamental frequency (60Hz) power does not have noticeable oscillation;
- Phasor power oscillates. But it is supposed to represent 60Hz power;
- The oscillation is caused by the beating effect of the interharmonics (Theorem 1)

3.3 – Field measurement results

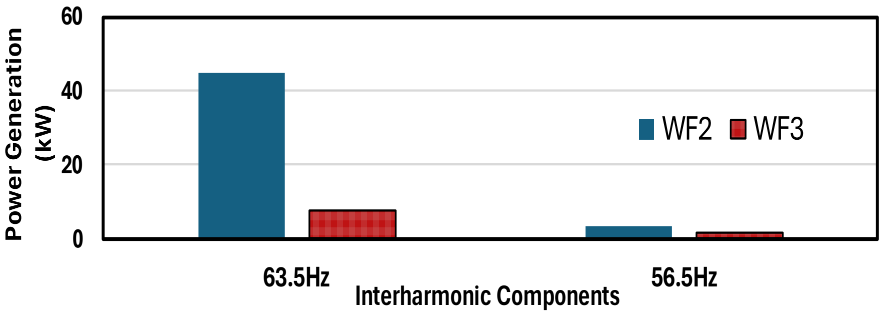
Case 2: Wind farms (WF)







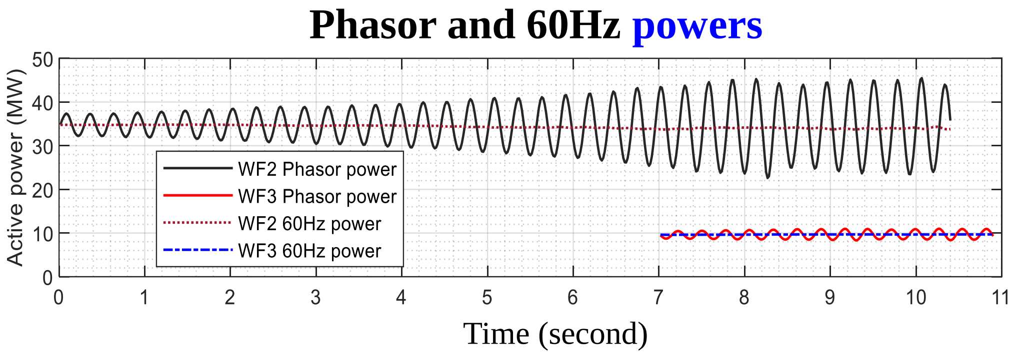
Comparing average IH powers of two WFs:

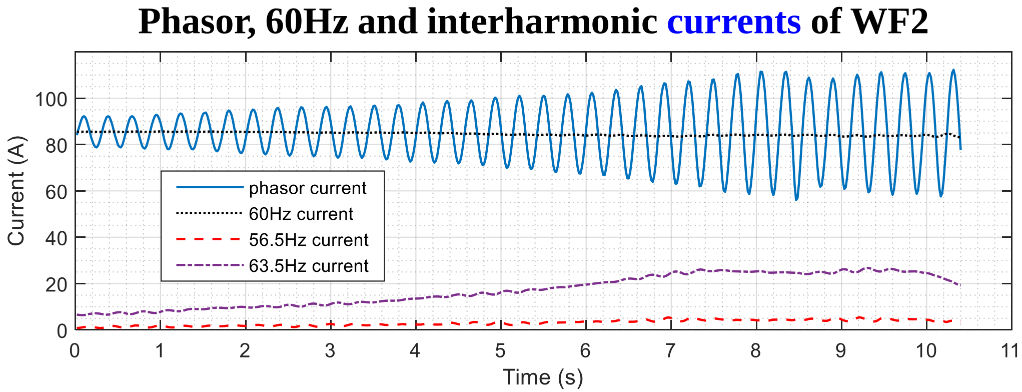


- **Both WFs contribute to the oscillation**
- **WF2 is the main contributor among the two**

3.3 – Field measurement results

Case 2: Wind farms (WF)



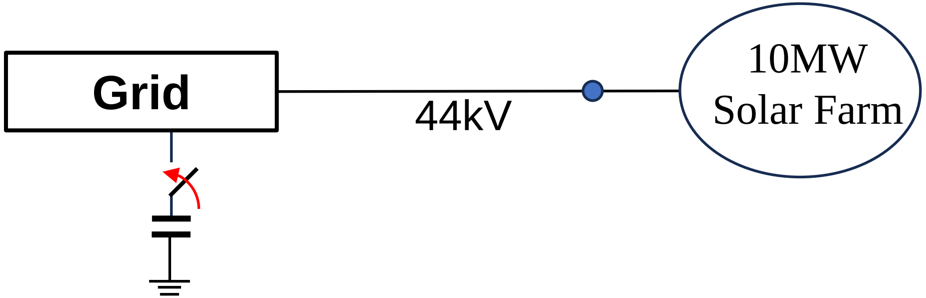


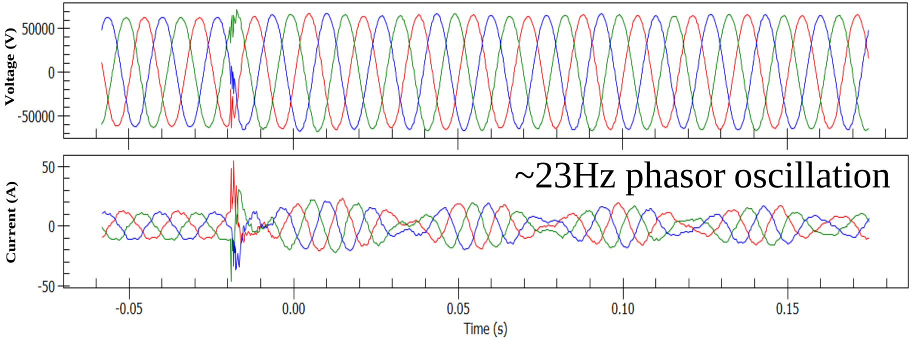
- Again, we can see 60Hz power and current have little oscillations
- The phasor power and current oscillate, so they don't represent the 60Hz behavior of the system

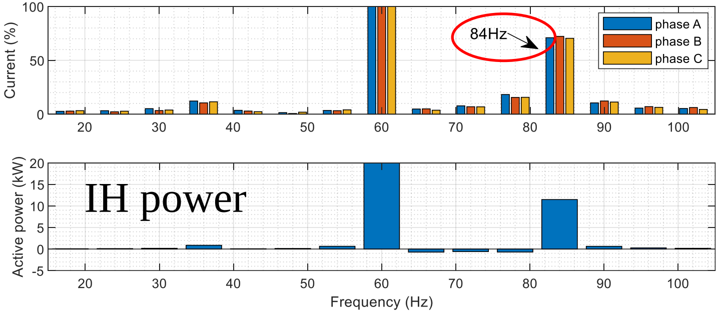
Possible explanation: phasor is a human created concept. It cannot represent what is experienced by power system elements R, L and C here. Such elements determine system behavior.

3.3 – Field measurement results

Case 3: Solar Farm

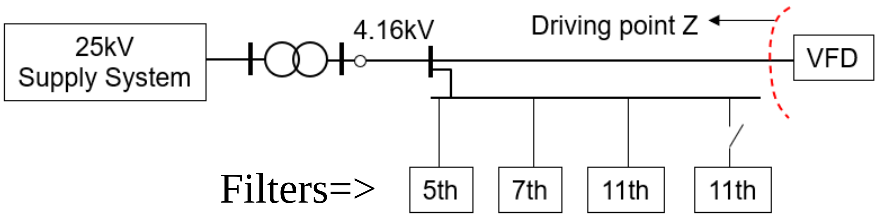


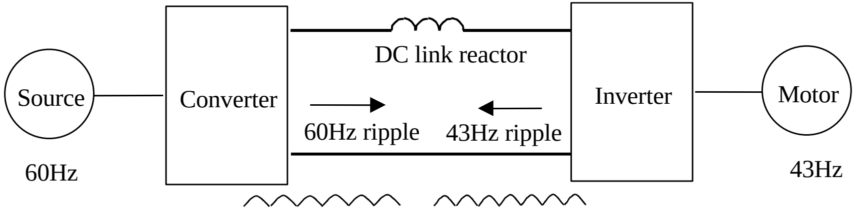


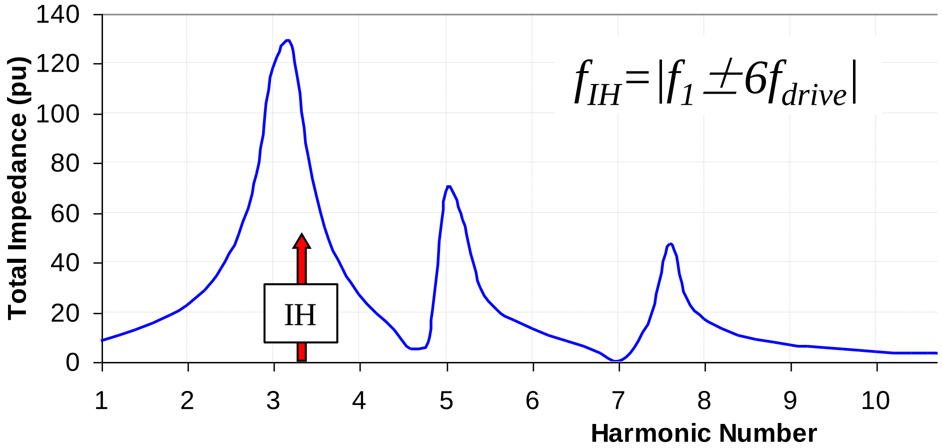


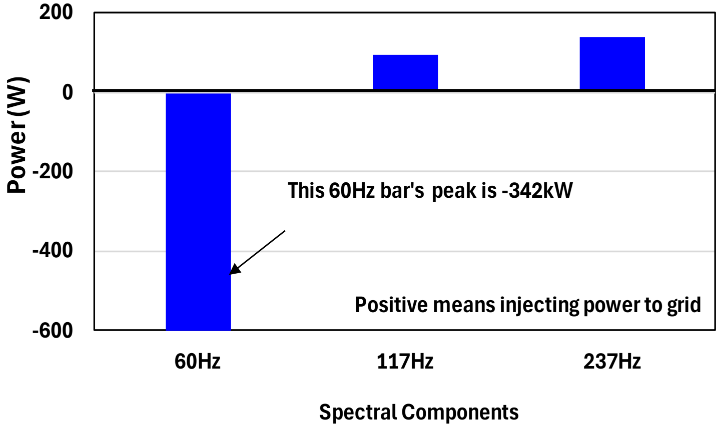
3.3 – Field measurement results

Case 4: Load facility with a variable frequency drive









3.3 – Field measurement results

Summary

- It makes sense to use interharmonic power as oscillation source locator, which is based on the law of energy conservation;
- The interharmonic power can be determined using simple DFT analysis, and the method can be easily implemented based on PQ monitor experiences;
- Four field measurement cases have demonstrated that 1) interharmonics are indeed involved in oscillations, 2) the IH power method can locate the sources.

4. Additional interesting findings

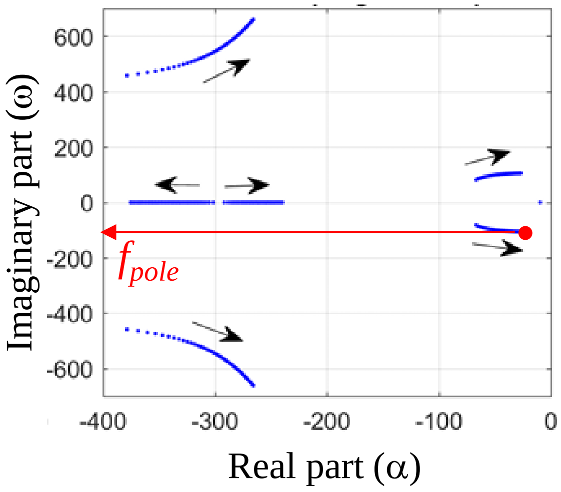
4.1 – Clarifying three frequencies

- **Frequency of (phasor) oscillation, f_{os}**
- **Frequency of critical mode or pole, f_{pole}**
- **Frequency of interharmonic, f_{ih}**

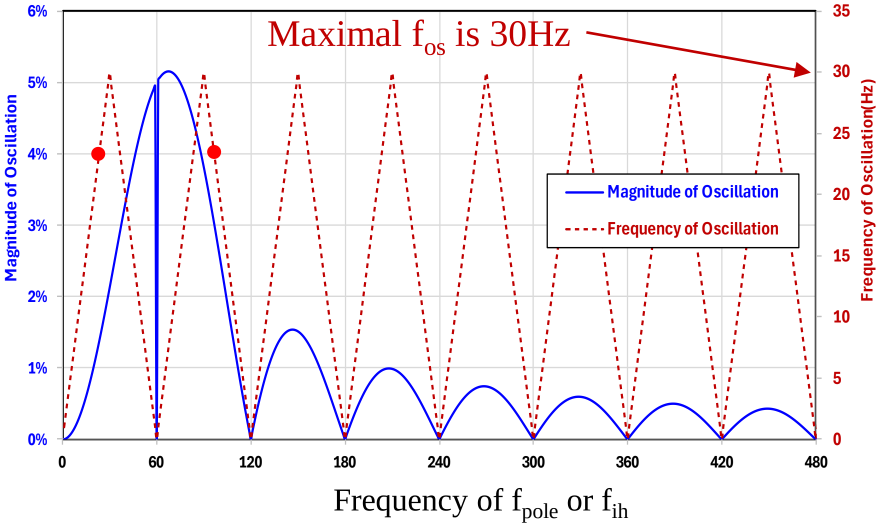
$$f_{ih} = f_{pole}$$ ⟸ frequency of interfering wave

$$f_{os} = | f_{pole} - hf_1 |$$ ⟸ frequency of beating

Example eigen-mode profile

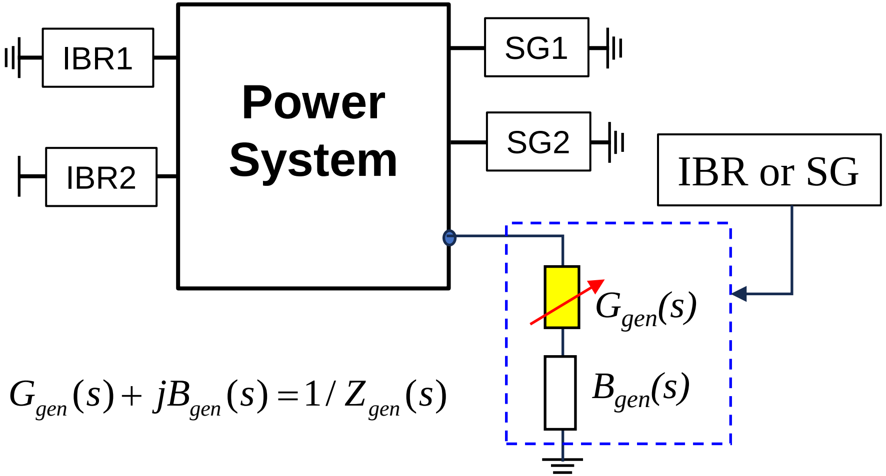


Interharmonic versus phasor oscillation curve



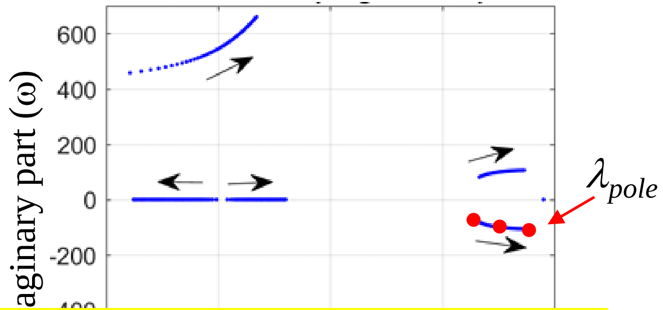
4.2 – IH active power and eigen-sensitivity

S-domain system dynamic model $[Y(s)][\Delta V(s)]=[\Delta I(s)]$



$$G_{gen}(s)+jB_{gen}(s)=1/Z_{gen}(s)$$

Example eigen-mode profile



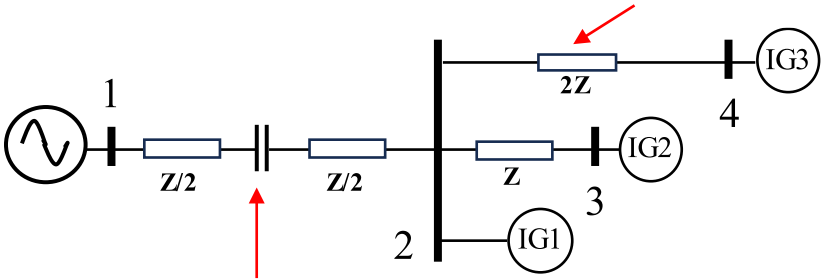
$$Eigenvalue\ Sensitivity=\frac{d\,|\lambda_{pole}|}{dG_{gen}(s_{pole})}$$

Real part (α)

- **It is found that eigenvalue sensitivity is proportional to IH active power of the generator**
- **Therefore, measuring IH power is equivalent to measuring modal (or eigenvalue) sensitivity**
- **This finding also provides a theoretical support to the use of IH power for source location**

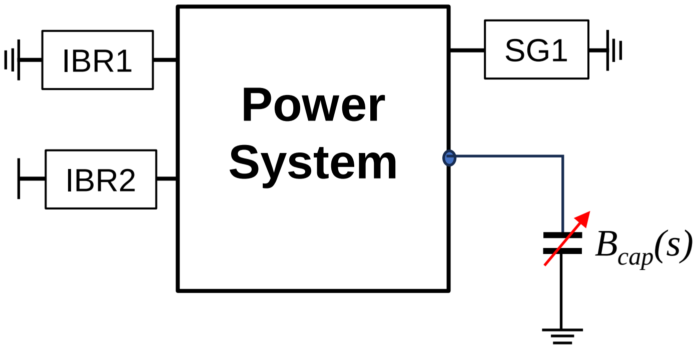
4.3 – Identifying resonant components

Which components cause resonance which in turn leads to oscillation?



Solution:

Use interharmonic reactive power to identify and rank these components



$$Eigenvalue\ Sensitivity = \frac{d\,|\lambda_{pole}|}{dB_{Cap}(s_{pole})}$$

Theoretical support: the above eigenvalue sensitivity is proportional to IH reactive power

4.4 – Extracting participation information from EMT simulation

There are two types of tools for power system small-signal stability studies:

EMT simulation:
widely used but it does not offer stability characteristics of the system, such as participation factors and critical generators etc.

Eigen-analysis ([A] matrix or [Y(s)] matrix based):
Can offer participation factors, but a new tool (eigen-analysis tool) is needed

The findings of this work make the following efficient stability studies possible:

- Perform EMT simulation for a system using PSCAD (or similar tools) as usual
- "Measure" IH active powers from simulated results ➔ generator participation factors
- "Measure" IH reactive powers from simulated results ➔ resonance participation factors
- Thus, there is no need to use eigen-analysis tool for practical engineering studies

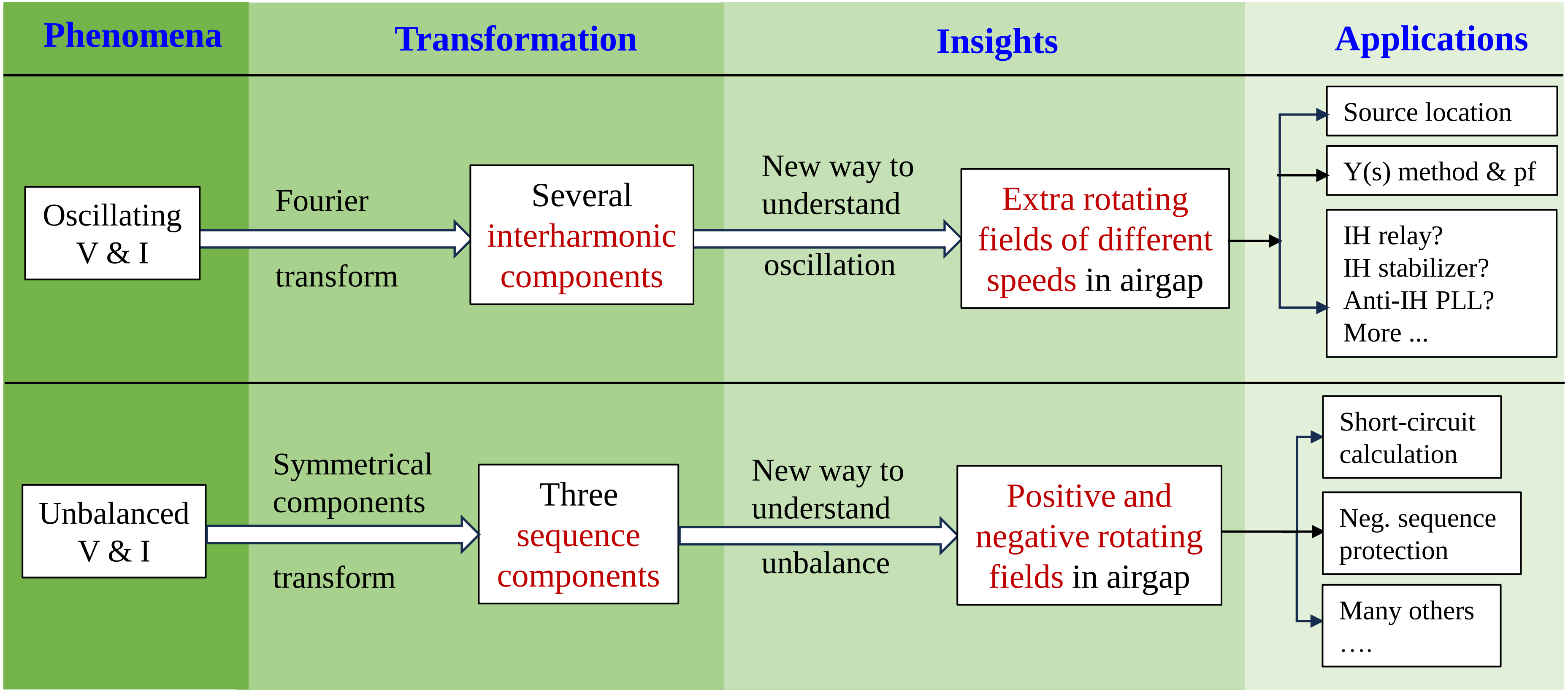
5. Summary and research needs

5.1 Main takeaways

- **The propagation of interharmonics in a system is the general cause of power system oscillations**
- **Interharmonics need power to drive their propagation, so the generation of interharmonic active power can be used to locate and rank oscillation sources**
- **The IH frequencies are determined by the energy exchanges among reactive elements. Thus, interharmonic reactive power can help identifying resonate components in a system**
- **The above concepts can be extended to EMT simulation results, supporting model-based power system stability studies**

5.2 New opportunities for Innovation

Comparing Interharmonic Component Analysis with Symmetric Component Analysis



5.3 Follow Up Research needs

Immediate (for oscillation source location)

- More accurate interharmonic determination (window size, shape, spectral leakage etc.)
- Interharmonic determination for non-stationary (i.e. short-duration) waveforms
- Improve understanding of the SG&IBR behaviors from the interharmonic perspective

Intermediate and Futuristic

- Further improve [Y(s)] matrix-based stability analysis, such as indices to characterize the propagation and coherency of oscillations
- Interharmonic relay for IBR (unit or plant) shedding
- Active interharmonic filter or active interharmonic energy absorber

Thank you

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.

An interesting topic for discussion

Which comes first, oscillating phasors or interharmonics?

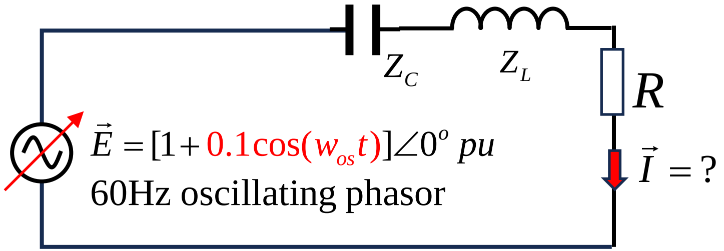
Oscillating phasors result in interharmonics:

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

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

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

- Phasor is a human created concept;
- R,L,&C elements experience waveforms. They don’t “see” phasors;
- Power system response is determined by how R, L&C element behaves, not by indices created to characterize the response



$$\vec{I} = \frac{\vec{E}}{Z_L + Z_C + R}$$

Is this solution correct?