IEEE PES PSDP/PSSC Forced Oscillations Task Force
Monthly Meeting

Disturbance Source Location Research and Practice in Power Quality Monitoring

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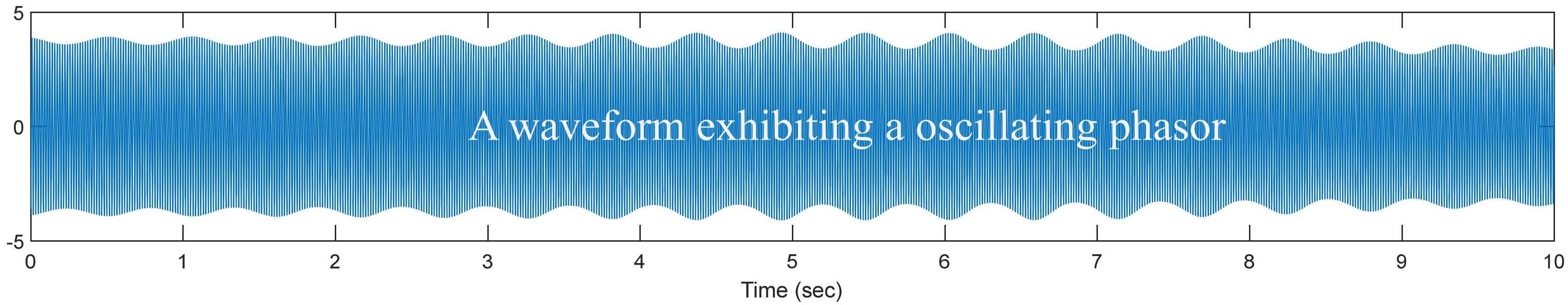
Objective and Outline

This presentation is to share experiences on disturbance source location from PQ perspectives. It is hoped that such information can stimulate new ideas for oscillation source location research.

1. **Key PQ disturbances and the need for source location**
2. **Example source location problems and solutions**
3. **Locating voltage flicker source – a real-life example**
4. **Summary: what useful information can we extract from PQ research?**

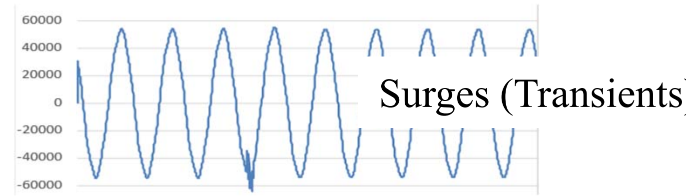


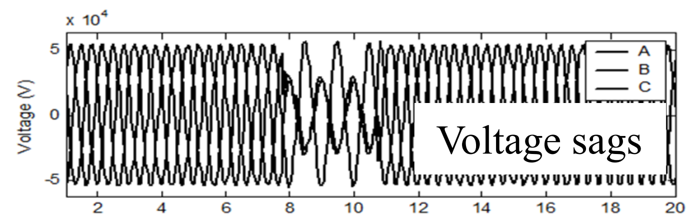
1. PQ Disturbances and the need for source location

PQ is concerned with the impact of electrical disturbances on utility customers

1. Transient disturbances

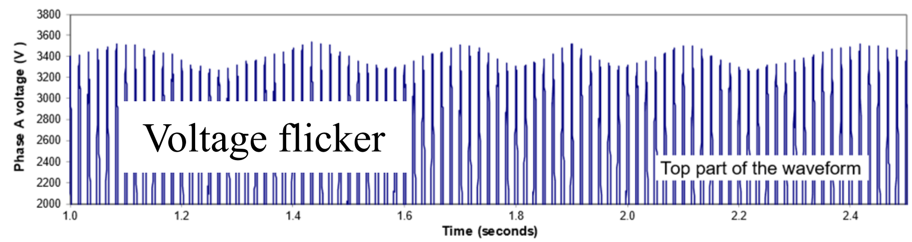
- Voltage surges (formally called voltage transients)
- Voltage dips (formally called sags) and swells





2. Steady-state (sustained) disturbances

- Harmonics
- Three-phase voltage imbalance
- Voltage flicker



Power system oscillations are essentially a type of electrical disturbances. Since the main victim is utility system and equipment, it has not been labeled as a PQ concern.

1A. The need for source location

PCC (Point of Common Coupling) – Metering or interfacing Point

1. **If a disturbance damages customer equipment, who is responsible?**

   Example: is the damaging voltage surge created by the customer facility itself?

2. **If a PQ limit is exceeded, which party is responsible to mitigate limit violation?**

   Example: is the excessive harmonic voltage at the PCC caused by the utility?

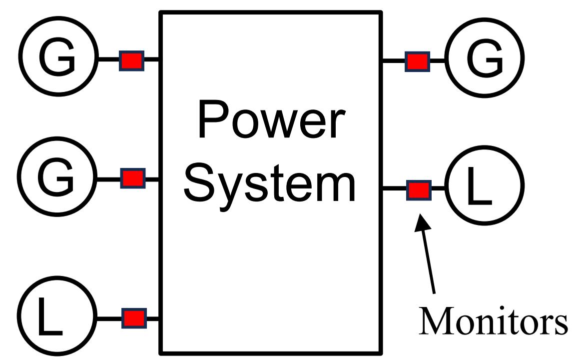
There are two types of source location (or responsibility determination) problems:

- Qualitative (Yes/No? for transient disturbance): Is the disturbance from the utility or customer?
- Quantitative (How much? for steady-state disturbance): What is utility system's contribution to the limit violation?

1B. Infrastructures of PQ monitoring

Disturbance monitors (i.e. PQ monitors) are widely deployed these days:

- PCC points of all transmission-connected customers
- PCC points of many distribution-connected industrial customers
- PCC points of all generators selling power to the grid
- Sending ends of many distribution feeders in a substation



G–Generator, L–Load (substation)

Capabilities of current disturbance monitors:

- Voltage and current waveforms of transient disturbances (typically 128 samples/cycle)
- Voltage and current waveform snapshots of steady-state disturbances and their indices such as harmonic voltage and negative sequence current (example: 1 set of outputs per 15 minute)
- Continuous non-gap waveform recording (latest development)
- The data are stored locally in the monitors and can be downloaded on demand
- The data are stamped using GPS clock (i.e. can be synchronized precisely) or monitor's clock

1C. Mode of operation

From PQ management perspective, there is no need for real-time or online disturbance source location, because:

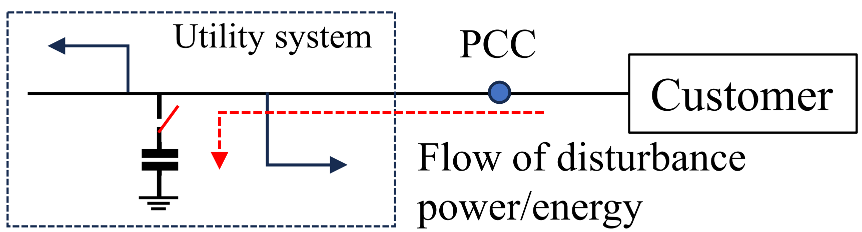
- The first line of defence is protection. It operates regardless the location of a disturbance;
- Thus, location information is not needed to trigger immediate action even though some location results are available immediately;
- Location information is used main for post-mortem investigation such as troubleshooting and dispute resolution;
- Location determination is typically done through off-line analysis by PQ engineers. Some PQ monitors can provide qualitative location information;
- In some cases, multi-monitor data are analyzed together to reach a conclusion if multiple sources are suspected.

2. Example source location problems and solutions – transient disturbances

Example 1: Locating source of voltage transients and sags:

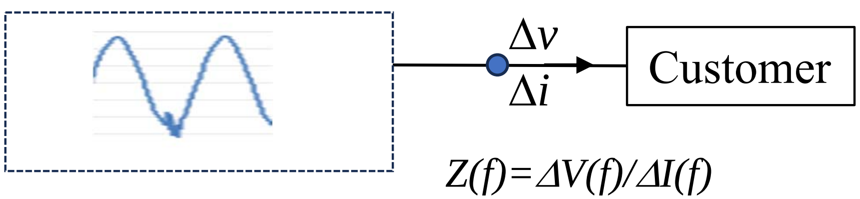
- Monitor location: PCC of utility-customer
- Form of results: Qualitative - is the disturbance from the utility side or the customer side?
- Application status: Some PQ monitor has implemented one of the following two methods.

Method A: disturbance power/energy-based method:



- Power/energy is needed to charge the capacitor
- The direction of power flow indicates location
- Waveform data is needed for P and E calculation

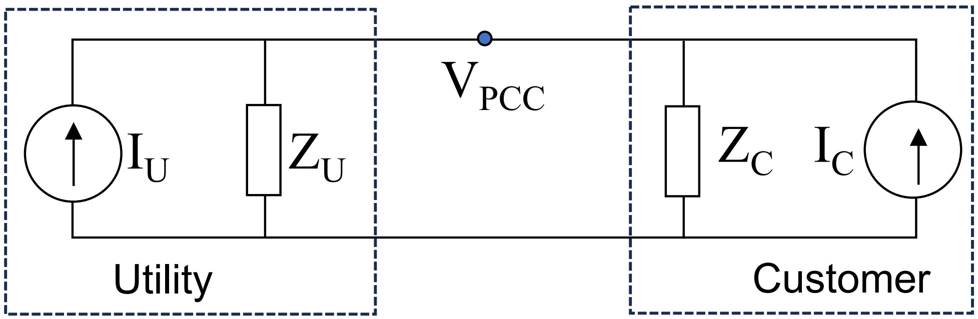
Method B: impedance estimation-based method:



- The disturbance injects a perturbation to one side
- System identification method is used to estimate Z
- The sign of R can indicate the location of disturbance
- Again, waveform data is needed for Z estimation

Example 2: Determine respective contributions to harmonic voltage at PCC

- Monitor location: PCC of utility-customer
- Form of results: Quantitative - what is the harmonic contribution of customer at the PCC?
- Application status: Unsolved problem



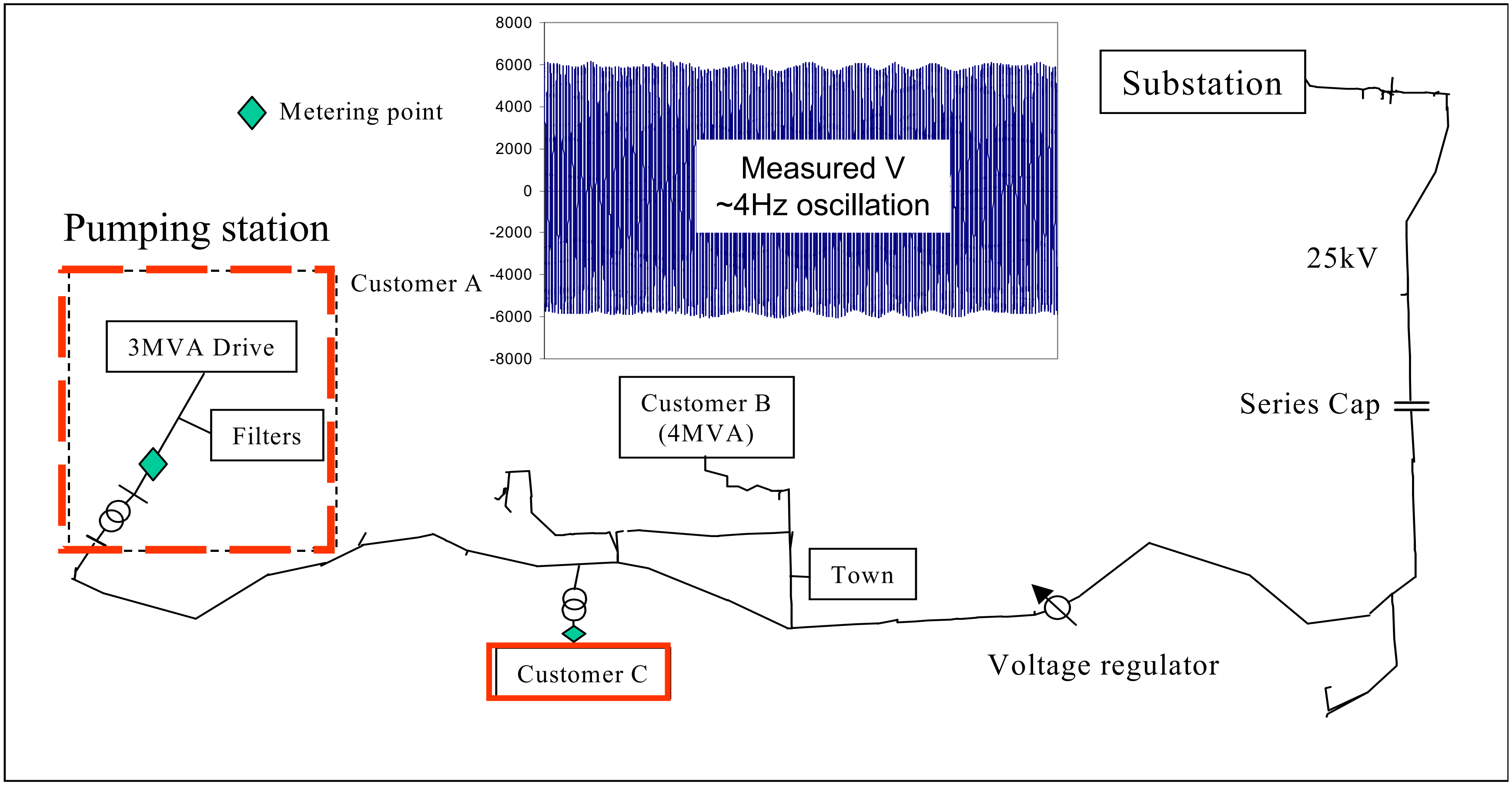
Equivalent circuit at the h^th harmonic

- Both sides contain harmonic sources;
- Norton circuits can represent both sides;
- V_{PCC} is caused by both I_U and I_C
- Thus, the task is to determine the respective contributions of I_U and I_C

- The problem can be solved in theory by using the principle of superposition
- However, it is very difficult to implement in practice since I_U, Z_U, I_C and Z_C all need to be estimated
- Statistical correlation over a long period is often used to determine responsibility in practice
- Energy/power-based method does not work in this case even qualitatively

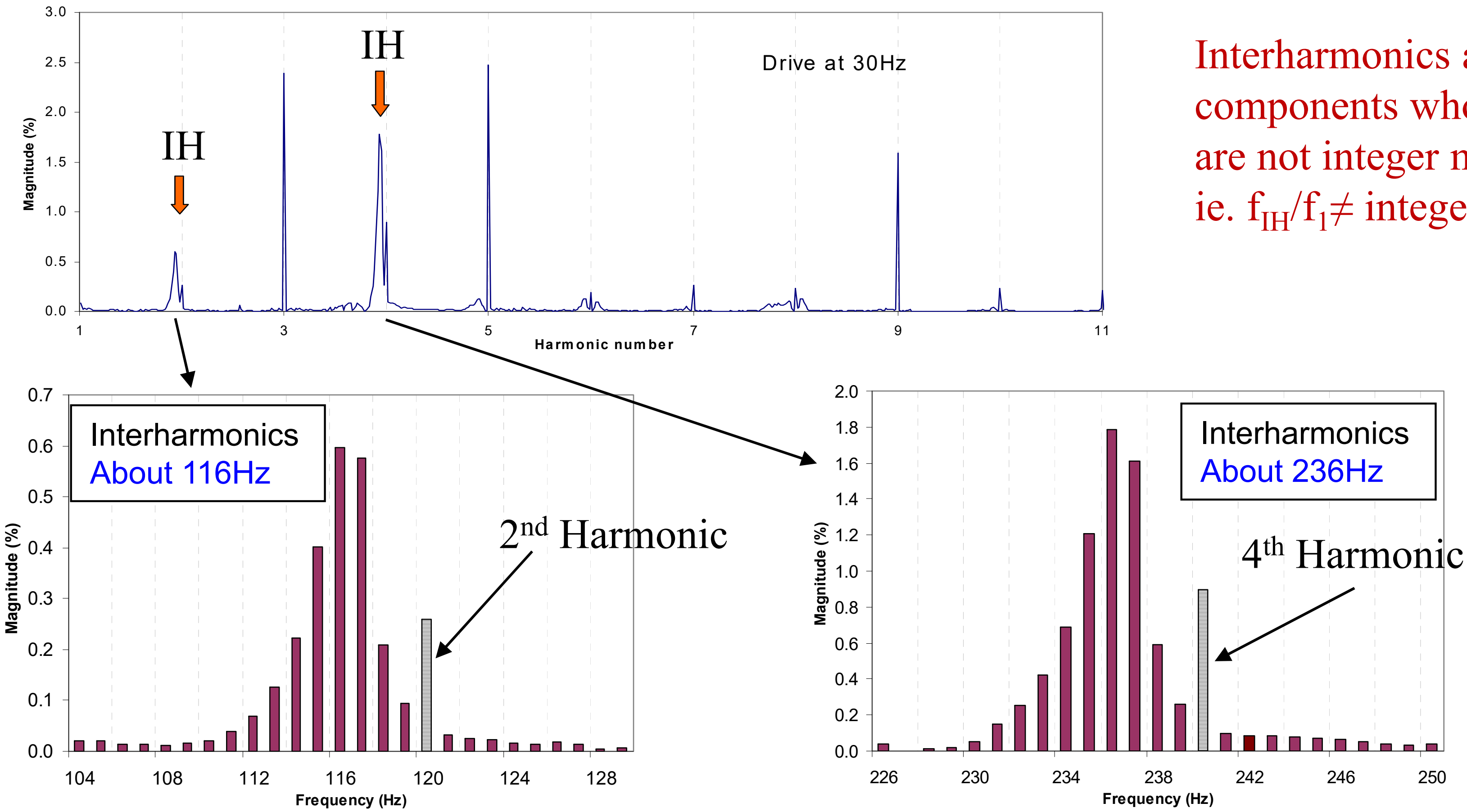
3. Locating sources of voltage flicker – a case study

Forced oscillation (voltage flicker) caused by a variable frequency drive (VFD)



3. Locating sources of voltage flicker

Spectrum of voltage waveforms (IH = interharmonics)



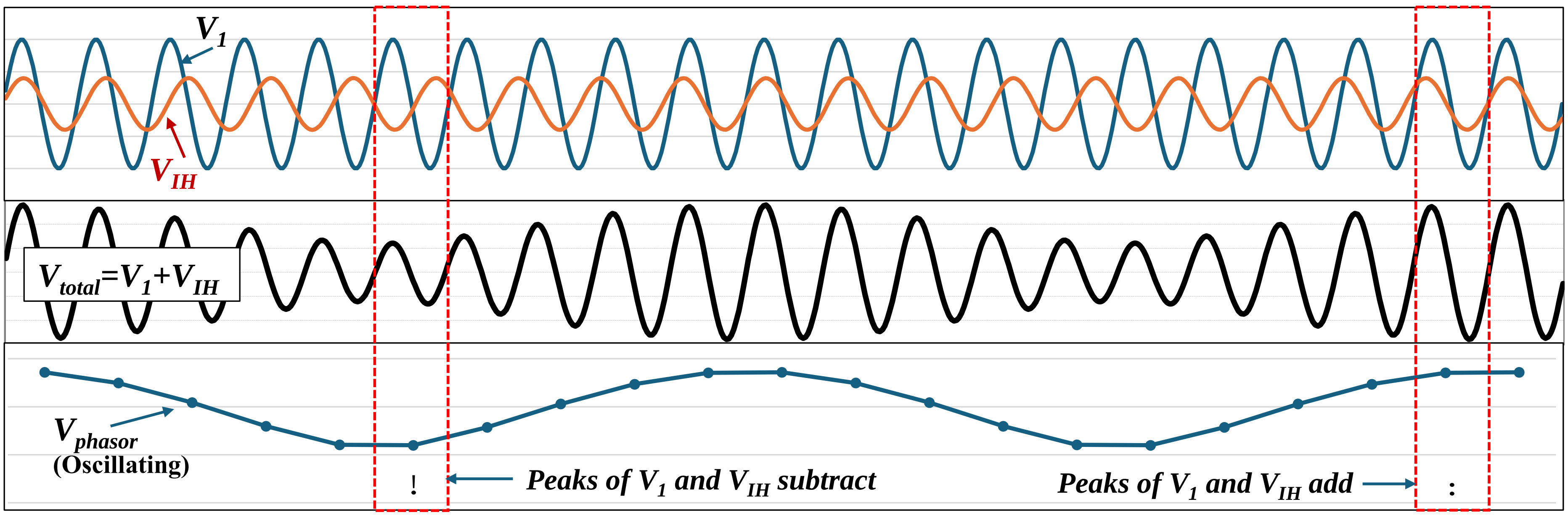
Interharmonics are spectra components whose frequencies are not integer multiple of f_1, ie. $f_{IH}/f_1 \neq$ integer

3. Locating sources of voltage flicker

How does an interharmonic cause voltage flicker (or oscillating phasor)?

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

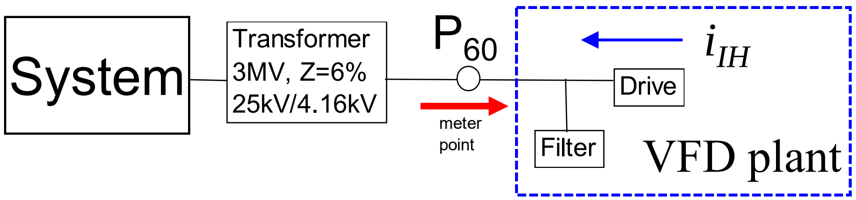
PMU definition of (measured) 60Hz phasor: $\vec{V}_{phasor}(k) = \frac{1}{\sqrt{2}T_1} \int_{(k-1)T_1}^{kT_1} v(t) e^{-j2\pi f_1 t} dt$

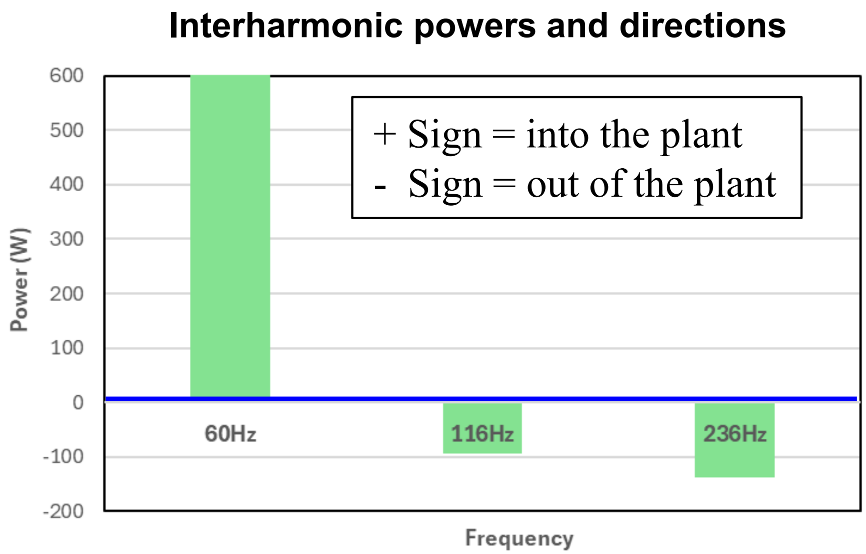


3. Locating sources of voltage flicker

Where do the interharmonics come from?

- It is extremely rare that there are multiple sources in the grid that produce the same 116Hz and 236Hz interharmonics
- It is, therefore, logical to conclude there is only one source producing these interharmonics
- This source must inject IH power into the grid to cause voltage flicker
- Therefore, the direction of IH power can be used to locate the IH or flicker source



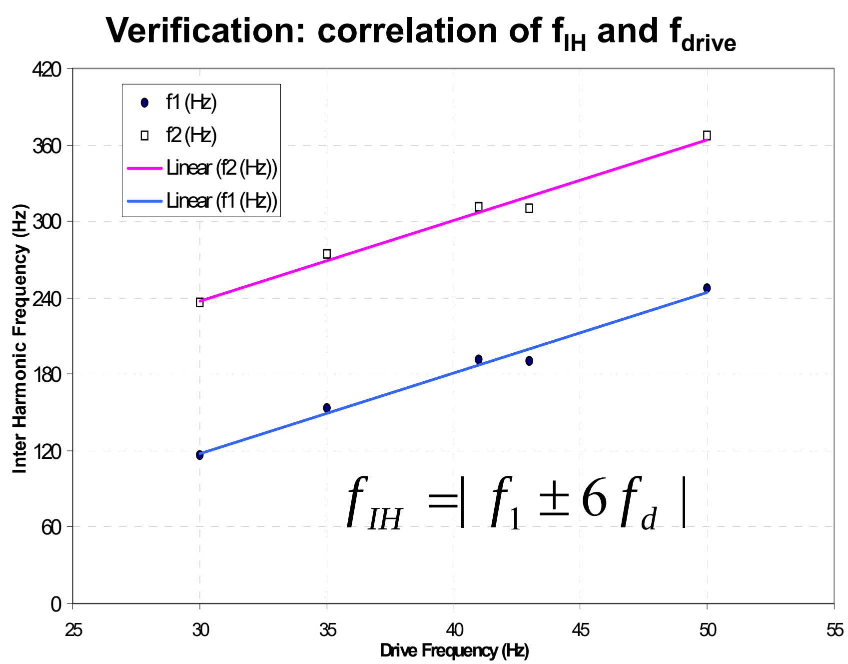


Finding: The pumping station is the source since it injects both IH powers into the system

3. Locating sources of voltage flicker

Further confirmation of the finding:

- VFD does produce interharmonics in theory
- The IH frequencies are related to the motor speed
- Correlation of IH frequencies and motor speed further confirms that the VFD is indeed the source of voltage flicker
- The problem was solved by using a novel re-configurable harmonic filter for the plant

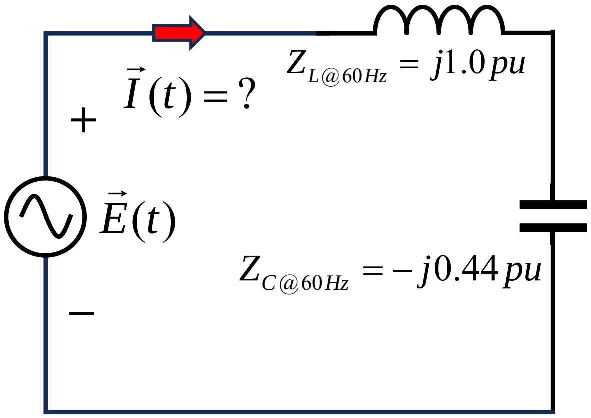


An important question:

Can we solve this flicker source location problem using dynamic phasors?

3A. Can we solve the problem using dynamic phasors instead of interharmonics?

Discussion 1: Theoretical perspective - a circuit example



a) Dynamic phasor-based solution

- **E is a 60Hz voltage source**
- **It has an oscillating magnitude with, say, f_{os}=20Hz**
- **The source can be modelled using a dynamic phasor:**

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

Task: what is the solution for phasor current I?

Standard method to solve the problem:

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

$\vec{I}(t)$ is also a dynamic phasor

3A. Can we solve the problem using dynamic phasors instead of interharmonics?

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

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

It actually means the following voltage:

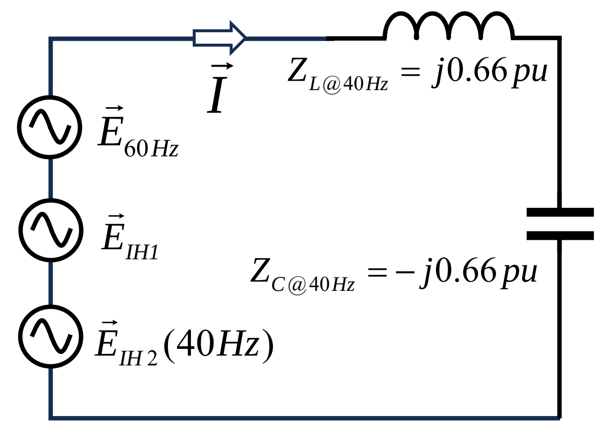
$$e(t) = \sqrt{2}[1 + 0.1\cos(2\pi f_{os} t)]\cos(2\pi f_1 t + 0)$$
$$= 1.414\underline{\cos(2\pi f_1 t)} + 0.071\underline{\cos(2\pi f_{IH1} t)} + 0.071\underline{\cos(2\pi f_{IH2} t)}$$

The above reveals

1) E is composed of three static phasors

2) Their frequencies are f_1=60Hz, f_{IH1}=80Hz, f_{IH2}=60Hz
IH1 and IH2 are interharmonic components

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



b) Interharmonics-based solution

Solution of current caused by E_{IH2}:

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

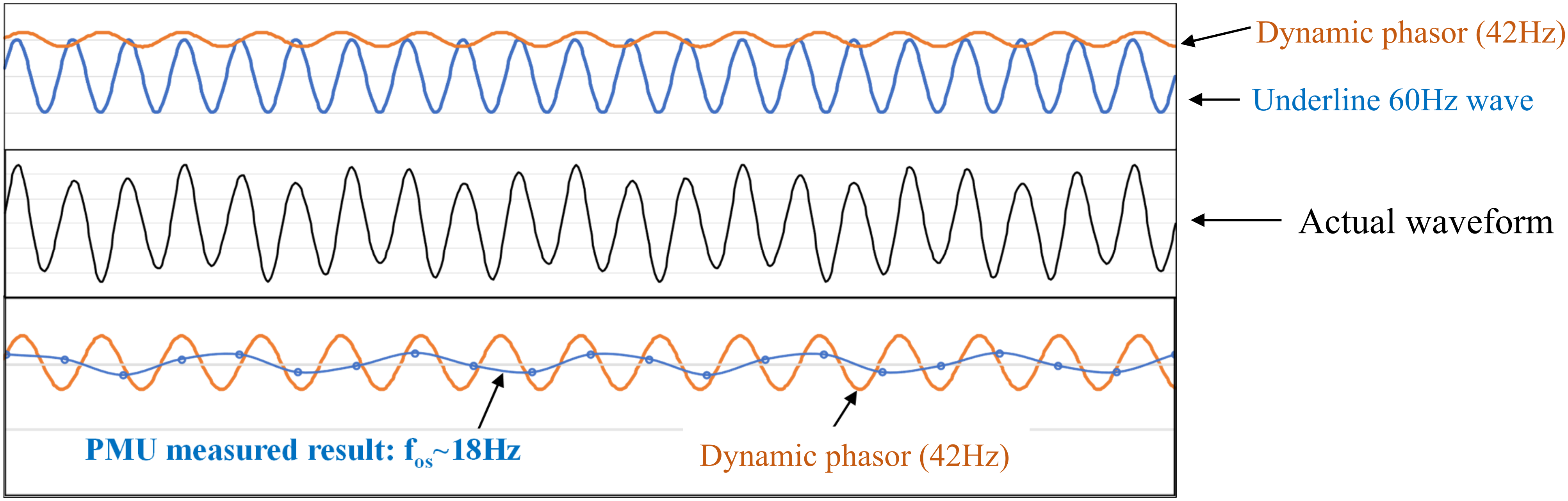
h=40/60

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

3A. Can we solve the problem using dynamic phasors instead of interharmonics?

Discussion 2: Practical perspective - a measurement example

Measure the dynamic phasor of $\vec{E}(t) = [1 + 0.4\cos(2\pi f_{os} t)]\angle 0^o \quad pu$



- According to Nyquist theorem, a PMU phasor can only report up to 30Hz oscillation frequency
- If the real oscillation frequency > 30Hz, the phasor result is corrupted by the aliasing effect

3B. Demonstration using Excel

1. Impact of interharmonic and harmonic:

$$v_{total}(t) = v_1(t) + v_{IH}(t) = \sin(2\pi f_1 t) + a \times \sin(2\pi f_{IH} t + \theta_{IH})$$

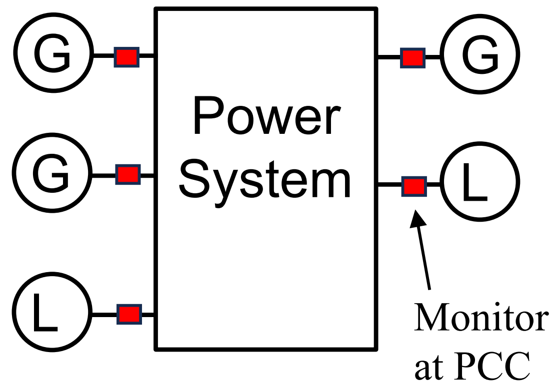
2. Measuring a waveform with dynamic phasor characteristic:

$$\vec{E}(t) = [1 + 0.4\cos(2\pi f_{os} t)]\angle 0^o \quad pu$$

4. Summary - What useful information can we extract from PQ research?

Re-formulate the problem?

- Forced oscillation is very likely associated with a single disturbance source
- Thus, qualitative answer may be sufficient, i.e. is the source up- or down-stream of the monitor?
- Therefore, independent monitors installed at the PCCs of interests are sufficient, leading to a simpler, distributed source location scheme
- There is no need for combined analysis of data from multiple locations since there is only one source
- Not a real-time process (i.e. similar to PQ)?



G – Generator
L – Load

4. Summary - What useful information can we extract from PQ research?

Consider alternative, waveform data-based approaches?

- Waveform data are the most authentic data, and it is widely available nowadays
- Waveform data can give interharmonic information
- Interharmonics are related to the modal frequencies of the (EMT-model based) state equation
- IBR units/plants can oscillate at high modal (i.e. interharmonic) frequencies
- A 60Hz PMU phasor has limited bandwidth (up to 30Hz) due to Nyquist constraint

Portable PQ monitor

Stationary PQ monitor

Gapless WMU

Relay-based WMU

Merging Unit

I have done some research on interharmonics-based method for both forced and natural oscillation source location. If there is an interest, I can share the findings with TF members in a future meeting

Appendix – determination of active (average) 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 fundamental frequency phasor

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

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

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