Power Oscillation Detection and the Impact of Phasor Measurement Techniques

Abhishek Madhyastha
AMETEK Power Instruments
abhishek.madhyastha@ametek.com
India

Abstract

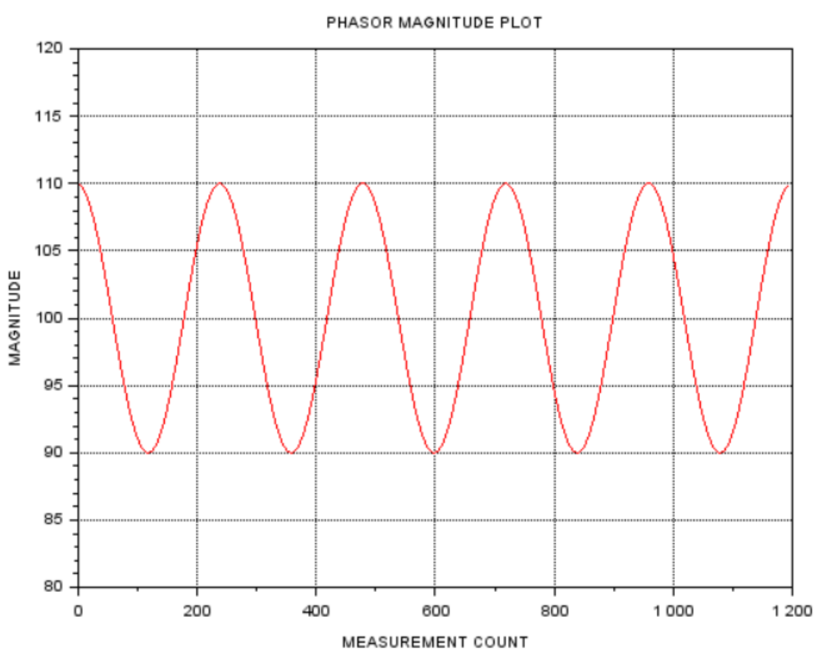
With the increased deployment of phasor measurement units (PMU) in the power grid, oscillation detection techniques that rely on phasors have gained popularity over the years. The availability of voltage, current, frequency and subsequently power measurements at data rates that can easily reach as high as 100/120 frames per second make phasors an attractive option for this purpose.

While oscillation detection algorithms play a key role in determining the efficacy of the monitoring and analysis system, accuracy of the measured phasors which serve as source data can have a significant impact particularly during such system anomalies. Since they act as the foundation for detection algorithms, it's crucial to understand and ensure that phasor measurement techniques are well adapted for such scenarios.

Standards such as the IEEE/IEC 60255-118-1 [1] & the IEEE Synchrophasor Measurement Test Suite Specification [2] set the requirements & testing specifications for phasor measurement units and the dynamic compliance requirements are of particular interest for oscillation detection. This paper looks at various factors which impact the quality of phasor measurements in the presence of oscillatory content in the grid while using these standards as reference.

1 Oscillations & Phasors – A Signal Processing Perspective

Detection of oscillations using phasors typically involves some form of analysis of the variation in the magnitude of the phasor and associating that with a frequency characteristic. This aids in determining the severity of the oscillation at various frequencies. Although the base data used by equipment that rely on this technique for oscillation detection are phasors, it's worth looking at how these phasors themselves are measured in the presence of oscillatory content in the voltage/current waveforms. Consider the following magnitude plot of the system voltage –



The magnitude oscillates above and below a certain level. In this case, the magnitude oscillates +/-10V around the nominal value of 100V at a frequency of 0.5 Hz. The mathematical approach of amplitude modulation can be employed to associate this type of fluctuation in the magnitude with the actual waveform of the signal. In the above scenario, a nominal voltage signal can be amplitude modulated with a signal at a particular amplitude and frequency to obtain an oscillatory waveform that emulates oscillations in the power system. From a signal processing perspective, the nominal voltage would be the "carrier" while the oscillatory component would be the equivalent of a message or modulating signal.

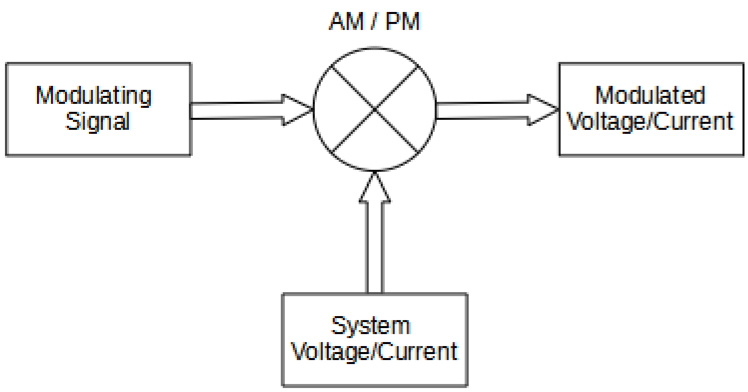


Fig.1: Amplitude/Phase modulation (AM/PM) to emulate power system oscillations

Phasor measurement units (PMU) typically estimate the magnitude and angle (or real and imaginary components) of a signal by selecting a window & subjecting it to a certain form of Fourier analysis. The behaviour of such a system in the presence of oscillatory components in the signal is of utmost importance since this decides the accuracy of the measured phasor and thereby the efficiency of the entire oscillation monitoring system.

2 Standards and Requirements for Phasor Measurement

Numerous methods exist for phasor measurement & these vary from vendor to vendor. However, a common ground is achieved using standards and test procedures that all vendors must comply with. Two major standards are of particular importance –

1. IEEE/IEC 60255-118-1: Supersedes the IEEE C37-118-1 [3] standard and details the synchrophasor measurement requirements and the compliance requirements.

2. IEEE Synchrophasor Measurement Test Suite Specification: Specifies the testing requirements to verify compliance with the IEEE/IEC 60255-118-1.

Section 5.5.6 "Dynamic compliance—measurement bandwidth" of the IEEE/IEC 60255-118-1 outlines the requirements that PMUs must meet when the inputs are subjected to sinusoidal amplitude and phase modulation. Mathematically, the input signals are represented as -

$$X_a = X_m [1 + k_x \cos(\omega t)] \text{ X } \cos[\omega_0 t + k_a \cos(\omega t - \pi)]$$

$$X_b = X_m [1 + k_x \cos(\omega t)] \text{ X } \cos[\omega_0 t - 2\pi/3 + k_a \cos(\omega t - \pi)]$$

$$X_c = X_m [1 + k_x \cos(\omega t)] \text{ X } \cos[\omega_0 t + 2\pi/3 + k_a \cos(\omega t - \pi)]$$

where,

X_m = Peak amplitude of the input signal

ω_0 = Nominal power system frequency in radians/second ($2\pi F_0$)

ω = Modulation frequency in radians/second

k_x = Amplitude modulation index

k_a = Phase angle modulation index

t = Time

Table 5 summarizes the overall compliance requirements –

Modulation level	**Reference condition**	**Minimum range of influence quantity over which PMU must be within given TVE limit**	
		P class	
		Range	**Max TVE**
$k_x = 0.1$, $k_a = 0$ radian	100% rated signal magnitude, $f_{nominal}$	Modulation frequency 0.1 to lesser of $F_s/10$ or 2 Hz	3%
$k_x = 0$, $k_a = 0.1$ radian	100% rated signal magnitude, $f_{nominal}$		3%

3 Influence of System Parameters

For the most part, the above requirements cover a subset of what's observed with real world anomalies but it's not uncommon for PMUs to be used under conditions that surpass these. Some of the key areas of interest include –

3.1 Modulation Frequency Range

The dynamic compliance requirements specified in section 5.5.6 of the IEEE/IEC 60255-118-1 state that the modulation frequency should be limited to 0.1 to lesser of $F_s/10$ or 2 Hz for P class PMUs.

The following plot shows the TVE vs modulation frequency obtained for the reference design mentioned in the standard for this range –

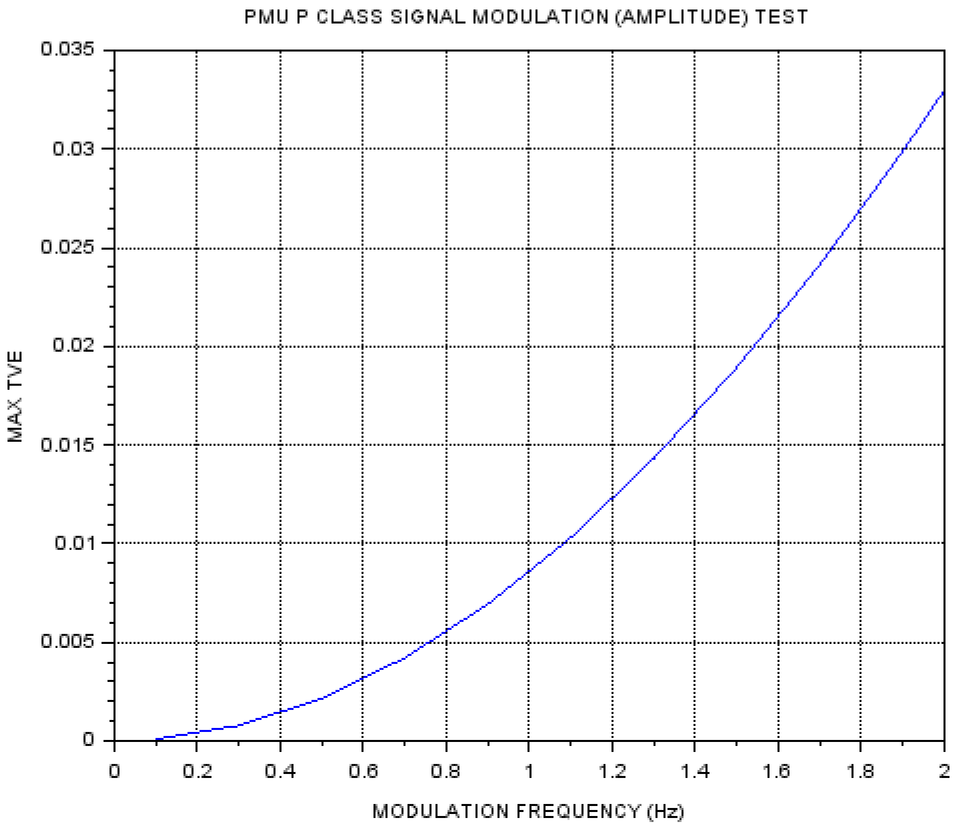


Fig.2: TVE vs Modulation frequency plot for the P class reference design (0.1 – 2 Hz)

The TVE values are well below the 3% limit imposed by the standard within the 0.1 – 2 Hz range. However, practical applications involve oscillation frequencies which can easily go beyond this range. The plot below shows the TVE vs modulation frequency up to the Nyquist limit –

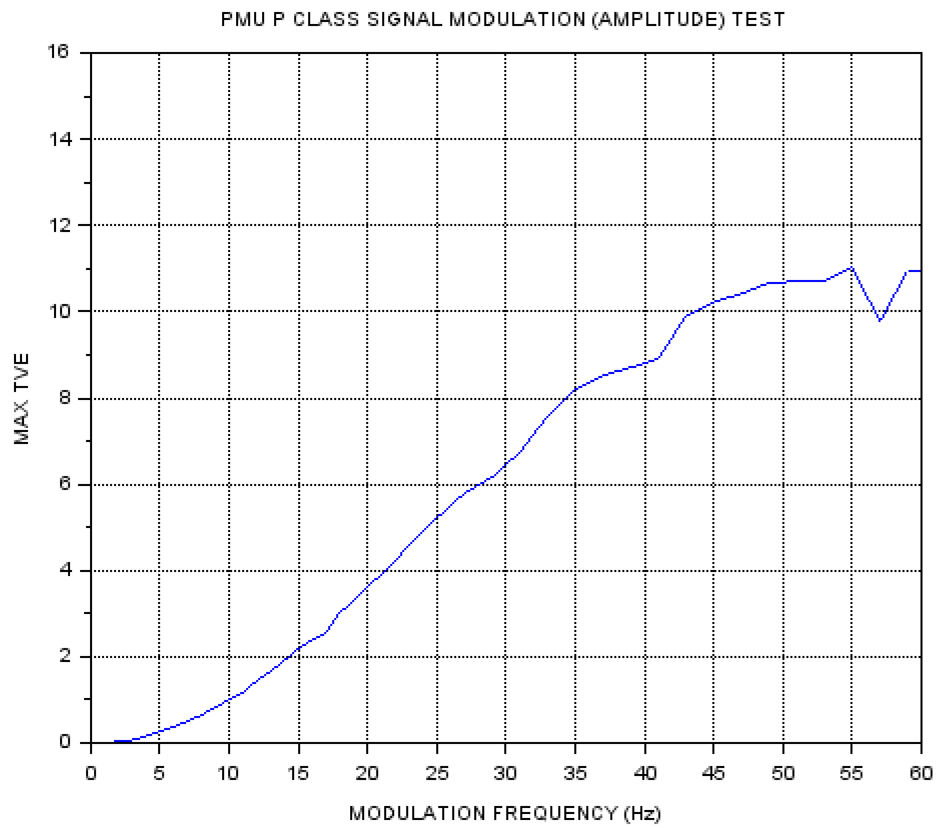


Fig.3: TVE vs Modulation frequency plot for the P class reference design (0 – 60 Hz)

It can be seen quite clearly that the TVE increases substantially as the modulation frequency is increased. This implies that the measured phasors do not capture the oscillatory content accurately at higher oscillation frequencies. As such, it's useful to analyse the behaviour of the phasor measurement system, particularly the filtering mechanisms, under scenarios involving the presence of high frequency modulation on the inputs.

3.2 Modulation Level

As an extension to 2.1, the amount of observable oscillation in the phasor measurements is a function of the modulating frequency & the attenuation. This represents the ability of the PMU to faithfully capture oscillatory components in the waveform. The following plot shows the attenuation of the modulating component at different frequencies with the P class reference filter –

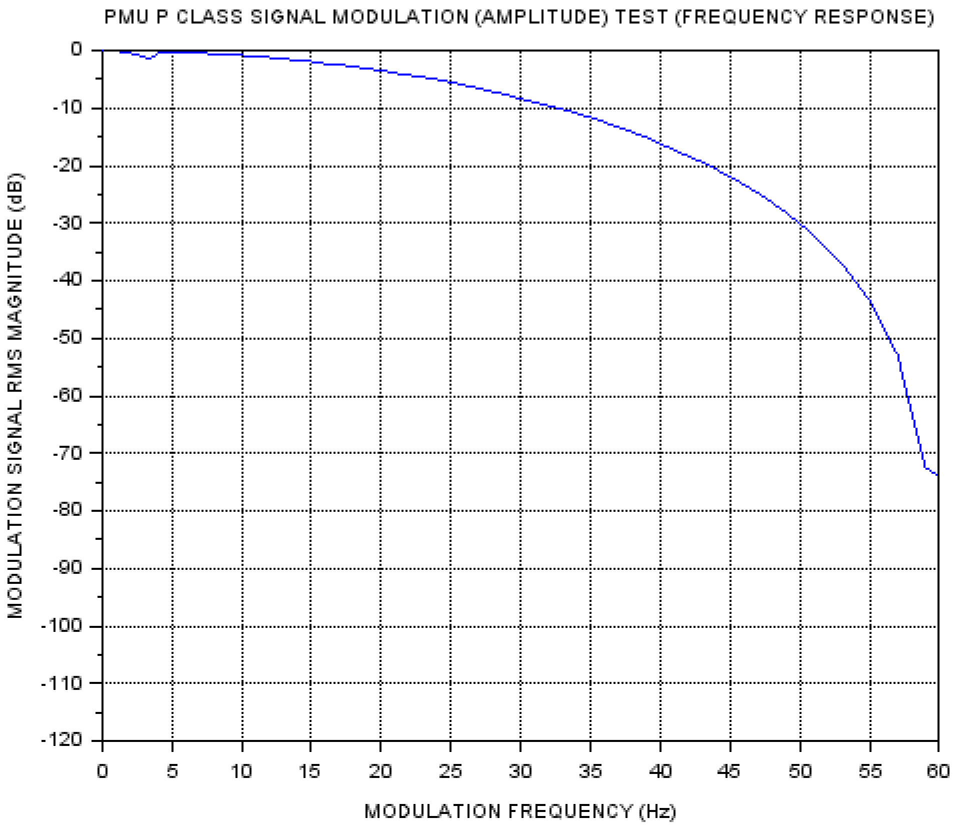


Fig.4: Modulation signal magnitude vs modulation frequency for the P class reference design

High frequency oscillations are attenuated considerably by the filter meaning that high levels of oscillation at such frequencies could be misrepresented (reported with a magnitude that's lower than expected) in the measured phasors. Therefore, the magnitude-frequency response is an important characteristic to study when determining the suitability of a phasor measurement system for oscillation monitoring.

3.3 Harmonic Content

Fourier based filtering techniques are typically known to provide excellent immunity to harmonic content. This can be seen in the plot below of the TVE computed in the presence of harmonics with frequencies that're multiples of the fundamental component (at a nominal frequency of 50 or 60 Hz).

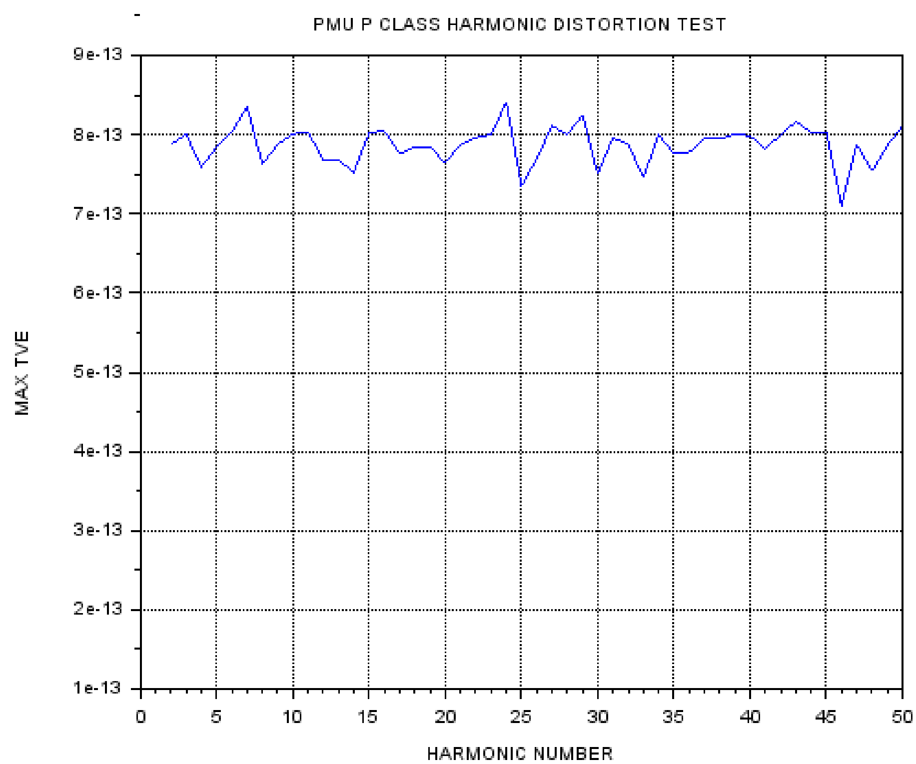


Fig.5: TVE vs Harmonics

However, the same level of attenuation isn't imposed on frequencies below the fundamental, i.e., sub-harmonic frequencies. The magnitude response plot for the P class reference filter highlights this –

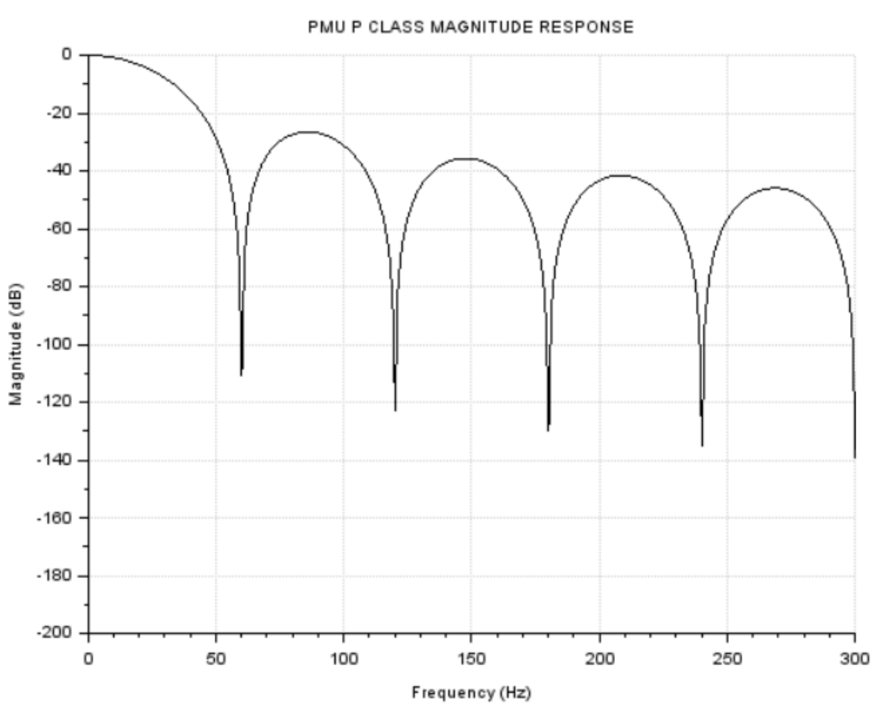


Fig.6: Magnitude response of the P class reference filter

This has an adverse impact as sub-harmonic components tend to manifest themselves in a similar fashion to oscillatory components which makes it difficult to distinguish between the two. The figure below is a plot of the phasor magnitude of a 100V, 60 Hz voltage phasor superimposed with a 10%, 30 Hz sub-harmonic.

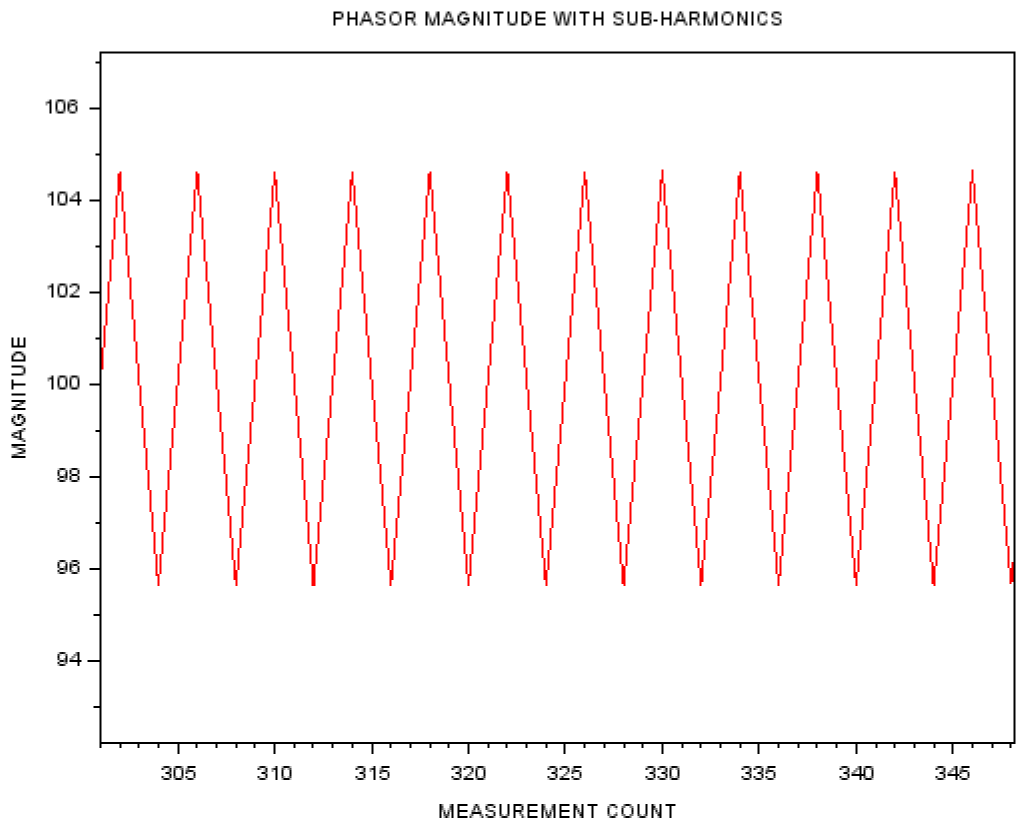


Fig.7: P class reference filter phasor magnitude in the presence of sub-harmonics

The magnitude exhibits an oscillatory pattern reminiscent of true oscillations emulated using amplitude modulation. This imposes a significant challenge for oscillation detection mechanisms to distinguish between true oscillations and oscillatory patterns in the magnitude due to inadequate filtering at sub-harmonic frequencies.

3.4 System Disturbances

In a typical power system, it's likely that several system anomalies occur at the same time in the event of a disturbance. Under such circumstances, the effects described above would have a combined impact on the quality & accuracy of the measurements. The following is an example of such an event – A simulated system anomaly involving oscillations at 25 Hz (simultaneous magnitude and phase modulation), a sub-harmonic signal at 30 Hz and the system voltage at an off-nominal frequency of 60.1 Hz.

Some key observations include –

1. The presence of the oscillatory component at 25 Hz is heavily masked by the 30 Hz sub-harmonic. The complex interaction between the two makes it difficult to reliably detect the oscillation frequency. This could potentially masquerade the true oscillation frequency to an extent where a monitoring system tuned to cover a certain range of frequencies may not even detect the oscillations.

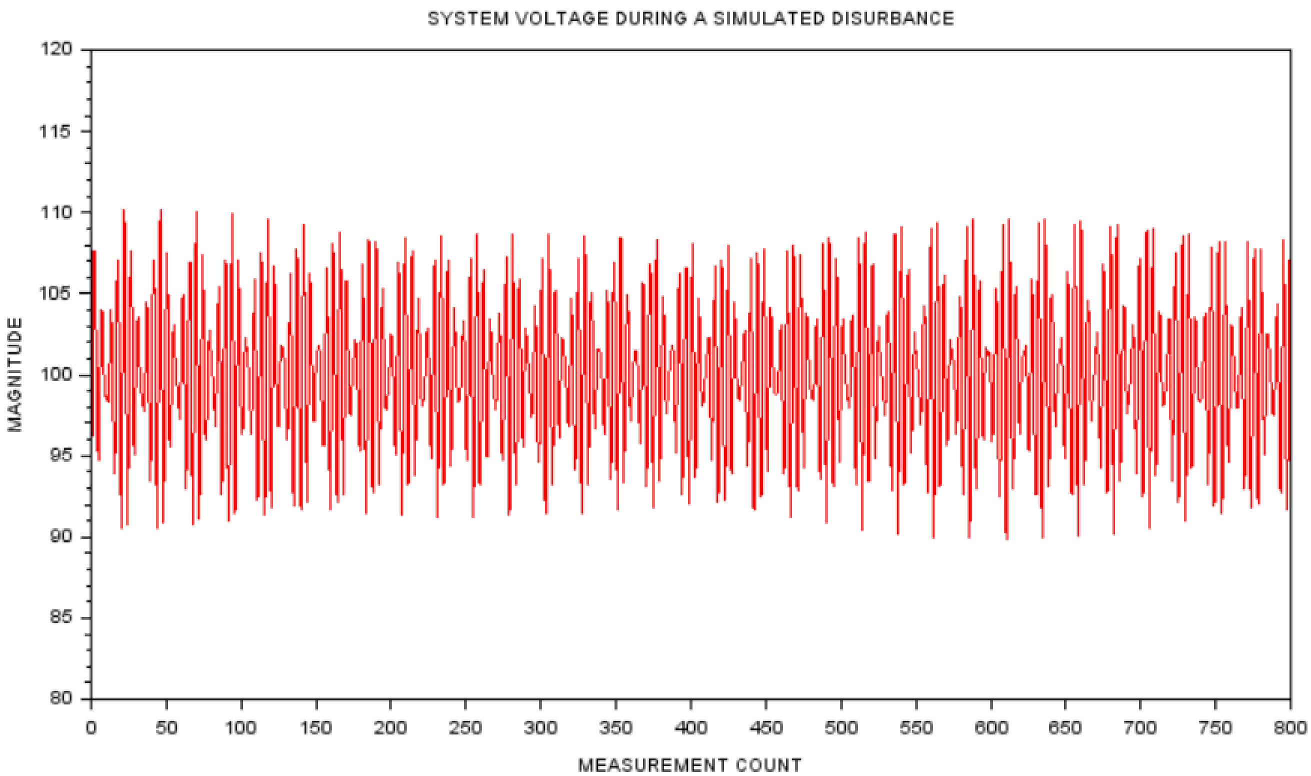


Fig.8: Phasor magnitude of the system voltage during a simulated disturbance

2. In addition to the 25 Hz oscillation, a faint oscillatory envelope can also be seen around the magnitude plot. This is due to the off-nominal frequency of 60.1 Hz & the subtle fluctuation can also manifest itself when trying to estimate the magnitude of the oscillation, as shown below –

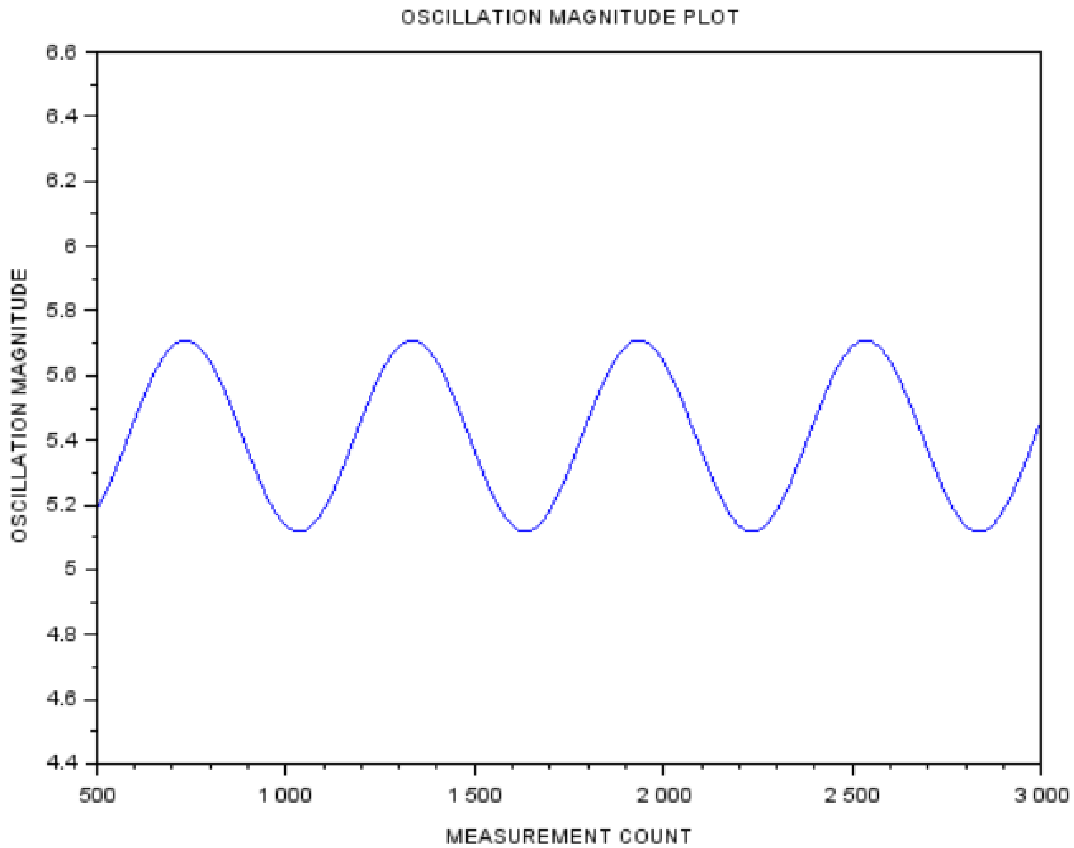


Fig.9: Magnitude of the oscillatory component during a simulated system disturbance

3. It can also be seen from the above figure that the estimated oscillation level is less than the expected value of 10% of nominal. The key reason for this is the attenuation offered by the P class reference filter which suppresses oscillations of higher frequencies. The presence of sub-harmonics further increases the error levels while the off-nominal system frequency causes the oscillation magnitude to fluctuate.

4. Phase modulation causes the estimated frequency value to oscillate, and this too is heavily affected by the presence of inter-harmonics and errors in the phase angle estimates due to the various system anomalies.

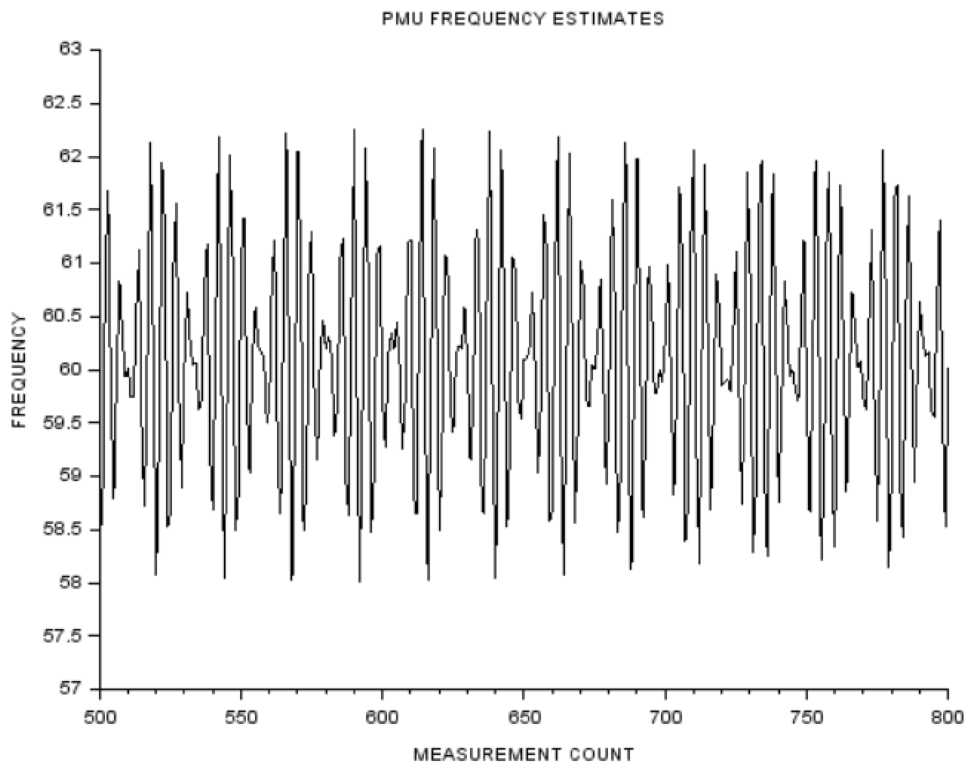


Fig.10: Frequency estimated by the P class reference filter during a simulated system disturbance

4 Conclusion

This paper highlights the impact that phasor measurement techniques can have on power oscillation detection and analysis. The challenges associated with the usage of synchrophasor measurements for such applications rely heavily on the employed measurement methods & their resilience towards system anomalies. The following are some of the key takeaways from this study –

1. Phasor measurement systems compliant with standards such as the IEEE/IEC 60255-118-1 need not necessarily exhibit the same levels of accuracy and reliability during system disturbances which may exceed the compliance limits imposed by the standards.
2. With the ever-increasing adoption of renewable energy sources, distributed energy generation schemes, etc. & the use of non-conventional systems such as power electronic devices, presence of sub-harmonic frequencies and high frequency oscillations are not as uncommon as it used to be. Measurement techniques capable of functioning in the presence of such anomalies can produce more accurate results and improve the overall efficiency and reliability of oscillation monitoring systems.
3. “Not all phasors are created equal” – Multi-vendor PMUs, despite being compliant with the IEEE/IEC 60255-118-1, don’t necessarily produce similar results when subjected to such system disturbances. As a result, oscillation monitoring systems might produce different results for a single disturbance depending on the source of the phasor data.
4. Dedicated oscillation monitoring equipment may employ phasor measurement techniques specifically geared to work reliably during such system anomalies with reduced emphasis on being compliant with the IEEE/IEC 60255-118-1.
5. Accuracy and reliability of oscillation monitoring systems that rely on PMU data are constrained by the accuracy of the phasors they use.

References

[1] IEEE/IEC International Standard - Measuring relays and protection equipment - Part 118-1: Synchrophasor for power systems – Measurements, IEEE/IEC 60255-118-1, 2018

[2] Test Suite Specification: Synchrophasor - IEEE Synchrophasor Measurement Test Suite Specification--Version 3

[3] IEEE Standard for Synchrophasor Measurements for Power Systems, IEEE Standard C37.118.1-2011/2014, 2011/2014