Power System Measurements – An Overview of Techniques & Applications

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

Abstract

Accurate measurement of power system quantities plays a vital role in ensuring the stable and reliable operation of the electrical power grid. These measurements can range from basic quantities such as voltage, current & frequency to complex ones including harmonics, flicker, oscillations, etc. While the usage of these measurements in several applications is generally well understood, the impact of their source and measurement techniques employed to estimate them are often overlooked. This can be attributed to several reasons such as application specific measurement techniques, role of compliance standards, signal processing knowledge, etc.

Quantities as simple as the system voltage can be estimated in a variety of ways depending on the end application & the criteria affecting the measurement techniques can include measurement window, system vs nominal frequency, line frequency synchronization, recording interval, reporting rate, etc. Modern IEDs possess the capability to measure and publish such measurements simultaneously, leaving it to the user to decide which ones to use for their specific application.

This paper presents a comparative analysis on the measurement techniques employed for the estimation of several key power system quantities along with an overview of the applications that they're intended for.

1 Power System Measurements – Fundamentals of Windowing

Measurement of power system quantities such as phasors, frequency, harmonics, etc. involves a few fundamental steps –

1. Sampling and acquisition of line voltages and currents.
2. Isolation of a portion of the acquired samples for processing.
3. Signal processing algorithms to estimate the desired quantity.

Step 2 plays a significant role as optimal selection of samples has a major impact on the subsequent processing that's done with the data. In general, this step involves selecting a certain number of samples of the voltage and/or current waveform depending on application requirements & is referred to as windowing.

Consider the following voltage waveform –

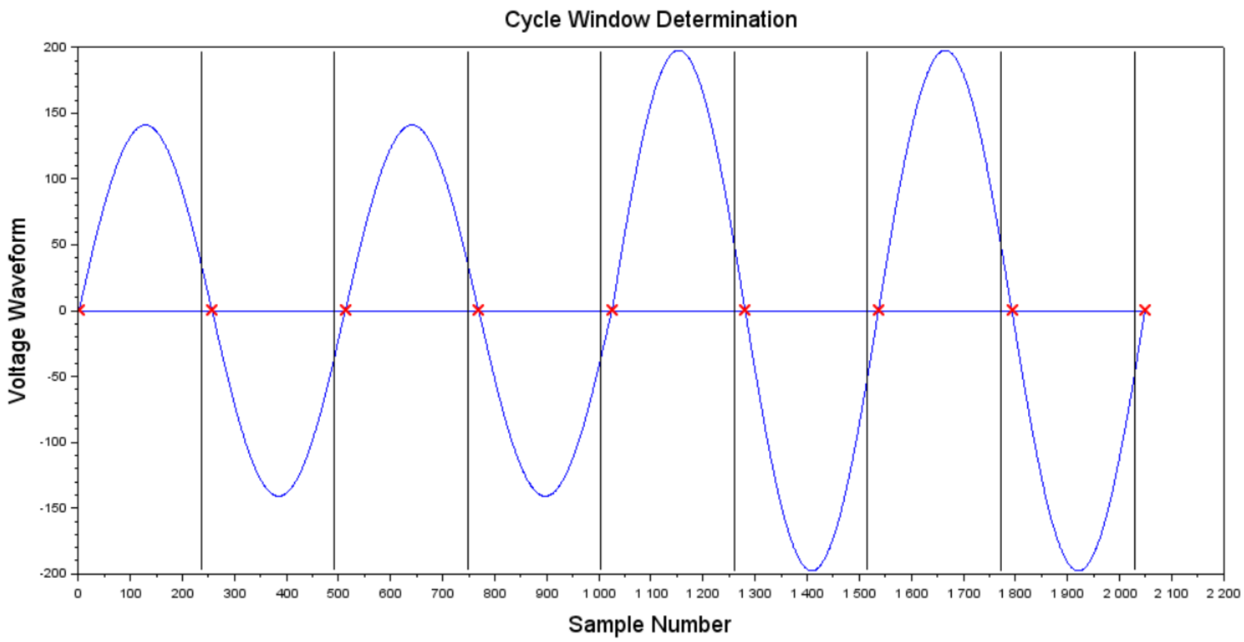

Fig.1: Window determination methods – Zero Crossing and Nominal Frequency Based

A typical example of a window would be 1 cycle of this waveform as highlighted by the red 'x' points. The cycle commences and concludes at zero crossings. Standards such as the IEC 61000-4-30 rely on this definition to classify a cycle for measurements used for sag, swell, interruption and rapid voltage change detection.

However, the duration spanning 3 consecutive vertical lines in the diagram too can be classified as "1 cycle" even though they do not coincide with zero crossings of the waveform. If these lines are always equally spaced, the window would be fixed to the nominal frequency. If they expand/contract according to the line frequency, the window will follow a frequency locked scheme as shown below.

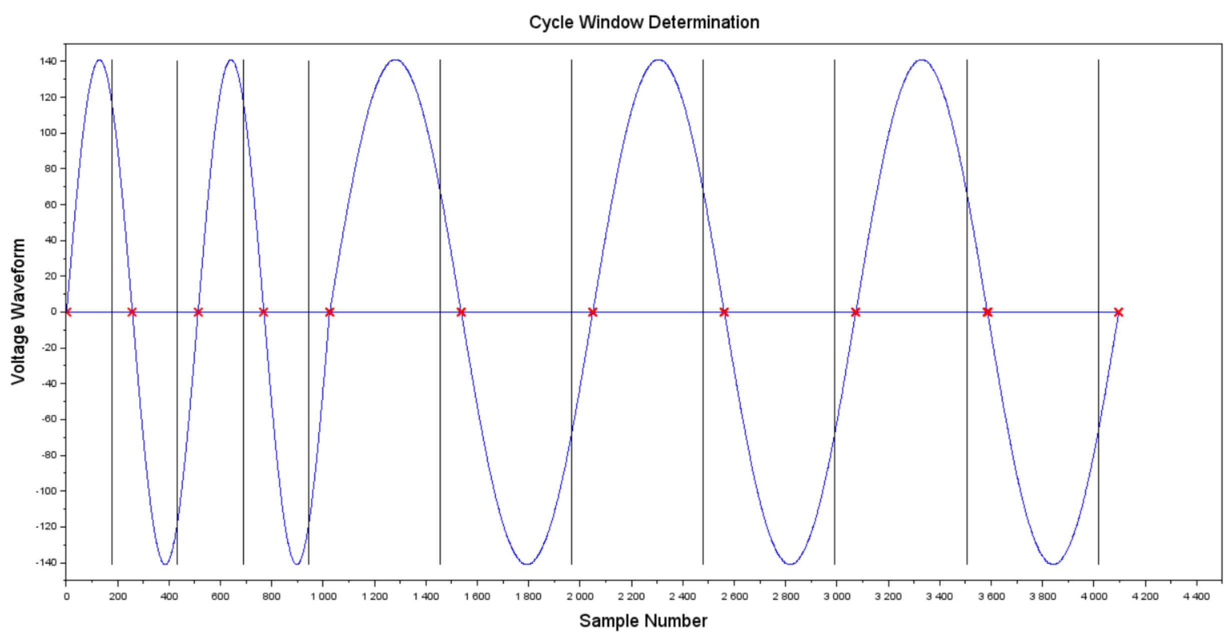

Fig.2: Window determination methods – Line frequency synchronized sampling and windowing

Hence, the definition of a cycle is closely tied to two parameters – Frequency and Phase Angle. While several measuring instruments may utilize a window such as the 1 cycle interval, it's not necessary that they all define a cycle in an identical manner. It's also not mandatory that all instruments compliant with a certain standard based performance class behave the same way under real-world operating conditions which can deviate from the strict confines of the relevant standard/s.

Power quality recording (PQR) and monitoring devices may rely on the zero-crossing synchronized method of windowing while instruments such as digital fault records (DFR), protection relays & phasor measurement units (PMU) may rely on fixed length windowing & fixed frequency sampling. Metering devices may make use of line frequency synchronous sampling and windowing suitable for revenue and billing applications. Several of these instruments can be compliant to the same standards such as the IEEE/IEC 60255-118-1, IEC 61000-4-30, etc. but aren't guaranteed to behave the same way under anomalistic conditions in the power grid that are different in nature from the criteria defined by these standards. Multi-function instruments such as modern DFRs tend to be capable of supporting several such functions within a single device and users need to be aware of the implications of how the system architecture and core application of both multi-function and standalone devices can impact their ancillary functions.

In addition to the core/fundamental intervals such as the 1 cycle window, some of these instruments also utilize longer intervals such as 10/12 cycles. Some measurements such as the power frequency can be estimated over an even longer interval such as 10s defined by the IEC 61000-4-30. These are further used to generate aggregated intervals such as 3s, 10 minutes, 2 hours, etc.

2 Event Overview

To demonstrate the behaviour and impact of windowing methods and intervals, consider the power system anomaly incident below consisting of the following key sequence of events –

1. Steady state pre-fault on all three voltage phases.
2. Dip in the system frequency.
3. Three-phase fault leading to a power swing and subsequent oscillation of both the amplitude and frequency of the phase voltages.

State	Line voltage (L-N)	System Frequency (Hz)
Pre-fault	Nominal (Vnom) = 120 V	Nominal (Fnom) = 60 Hz
Fault	Vnom +/- 19V at 4 Hz	(Fnom – 1 Hz) +/- 0.64 Hz

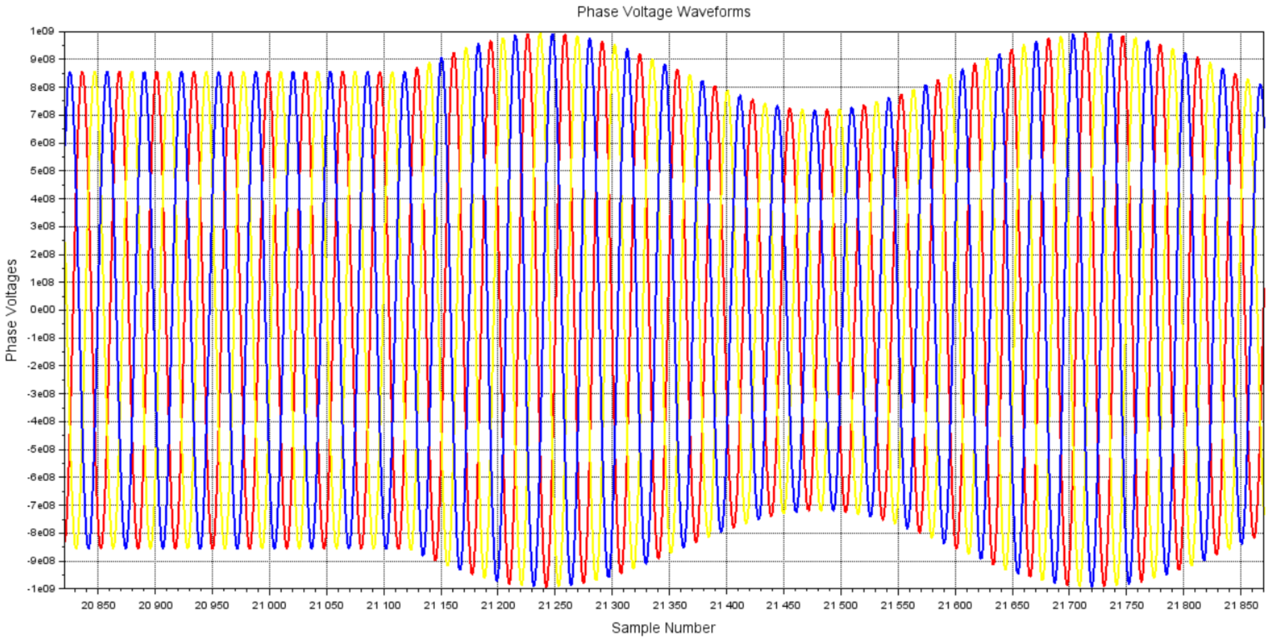

Fig.3: Three Phase Voltage Waveforms

These signals are fed to a multi-function DFR via a secondary injection test set and the measurements mentioned below are collected for analysis.

1. DFR half cycle phasors – RMS value of the phase voltage phasors refreshed every nominal half cycle.
2. IEC 61000-4-30 1 cycle RMS Urms(1/2) – RMS value of the phase voltages refreshed every fundamental half cycle synchronized to waveform zero crossings.
3. IEC 61000-4-30 10/12 cycle RMS – Estimated over an interval of 10 cycles (50 Hz) or 12 cycles (60 Hz) and resynchronized at 10-minute boundaries.
4. DFR half cycle frequency – Frequency value estimated on a frequency channel and updated every nominal half cycle.
5. IEC 61000-4-30 10s power frequency - Frequency value estimated on a frequency channel and updated every 10 seconds.

All these modules function in parallel and measurements are estimated by the instrument simultaneously facilitating a time synchronized view and analysis.

3 Event Analysis

During the event, several power system parameters exhibit variations, and the ones of particular interest are the magnitude and frequency of the voltage phases as these are used for many calculations, derived measurements, and analytical purposes. Each module estimates these using different windows and measurement techniques and the nature of variations observed strongly depends on these.

3.1 Voltage Magnitude

3.1.1 10/12 cycle window

The voltage magnitude measured over a 12-cycle interval according to the IEC 61000-4-30 is shown below.

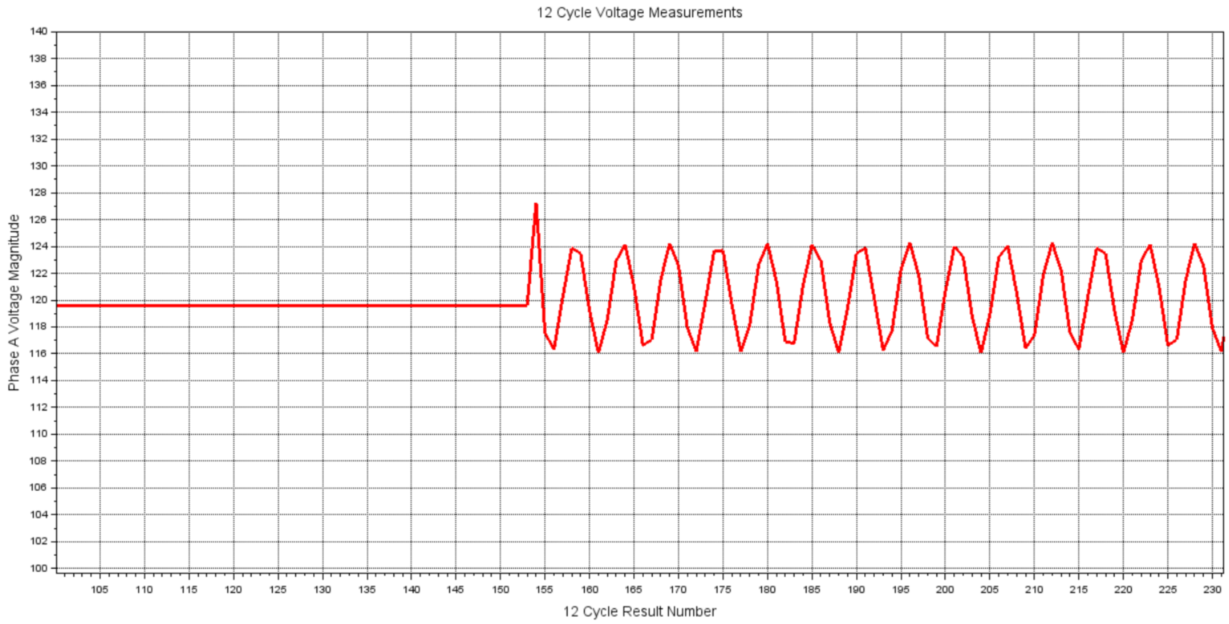

Fig.4: Phase A 12 Cycle IEC 61000-4-30 Class A Voltage Measurements

It is immediately obvious that the extent of fluctuation is lesser than the expected value of +/-19 V. This is because the 12-cycle window suppresses periodic fluctuations due to its averaging nature. It's also seen that the frequency of the variation is about 1 Hz as opposed to the expected value of 4 Hz. The lack of resolution can be attributed to the longer interval and thereby fewer measurements, but the accuracy of these measurements is also compromised under fault conditions.

3.1.2 1 cycle Urms(1/2) window

The 1 cycle window as defined by the IEC 61000-4-30 involves the RMS value computed over 1 cycle beginning at a fundamental zero crossing and refreshed every half cycle. The multiple ways of defining a cycle as described in section 1 plays a key role here. The standard specifies the following in this context –

"The cycle duration for Urms(½) depends on the frequency. The frequency might be determined by the last non-flagged power frequency measurement (see 4.7 and 5.1), or by any other method that yields the uncertainty requirements of Clause 6."

This allows manufacturers to choose amongst a variety of options to both estimate the frequency as well as decide how to use it to determine the bounds of what consists of a cycle. Often, this depends on the primary application of the instrument and the architectural constraints associated with it. For instance, a dedicated power quality monitoring device might rely on the 10s power frequency measurement referred to by the standard. However, multi-functional devices such as DFRs and protection class devices typically possess the capability to estimate frequency at a significantly higher rate. Also, they may have the ability to perform better in the presence of system anomalies such as transients, faults, etc.

The plot below shows the Urms(1/2) for the event with the instrument possessing capabilities such as –

1. Estimation of frequency at a half cycle rate & associated validation ability.
2. Transient detection & determination of reliability for frequency estimation.
3. Out of phase/permanent phase shift detection & fast resync ability.

Both the amplitude and the frequency of the fluctuations are captured correctly & the above abilities play a vital role in this process.

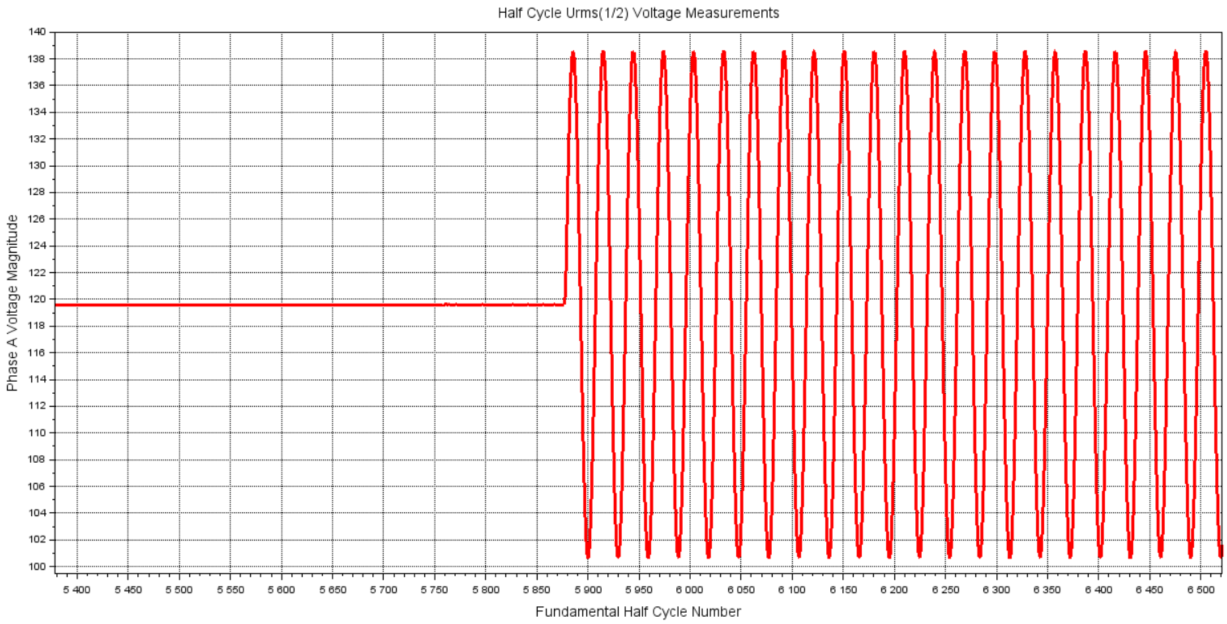

Fig.5: Phase A 1 Cycle IEC 61000-4-30 Class A Urms(1/2) Voltage Measurements

3.1.3 DFR Half Cycle Phasor Estimates

Unlike dedicated power quality monitoring devices or metering instruments, digital fault recorders (DFR), phasor measurement units (PMU) and protection relays have more real time constraints & the need for predictable performance. The key implication of such requirements is that measurements must be made in consistent & often statically defined intervals instead of ones which can vary according to the inputs. When frequency is used in the determination of such windows, it's typical to rely on the nominal value, i.e., 50/60 Hz rather than the fundamental which deviates according to system conditions.

The half cycle phasor magnitude values shown below are estimated at a rate of once per nominal half cycle, i.e., 100 or 120 times per second regardless of the frequency of the inputs to the instrument.

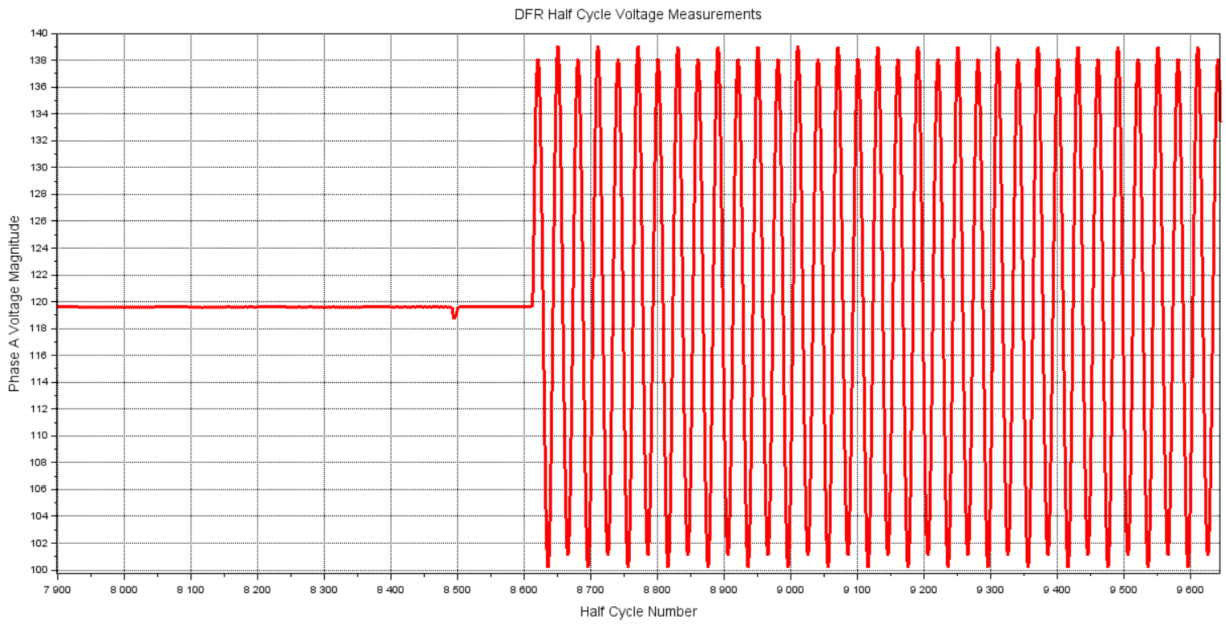

Fig.6: Phase A DFR Half Cycle Voltage Phasor Measurements

The amplitude and frequency accuracy are significantly better than the 12 cycle measurements and only slightly less accurate than the 1 cycle Urms(1/2) from the same instrument. However, the use of a fixed window with associated processing means that the measurements are usable under a lot more scenarios and are inherently more reliable under system anomalies where voltage/current waveforms may have several artifacts.

3.2 Frequency Measurement

Aside of the basic need to record system frequency, estimation of power system frequency aids several functions within instruments and has a major impact on the accuracy of measured values. As discussed in the above sections, magnitude estimation typically relies on system frequency and the intervals/windows used for frequency measurement itself can make a significant difference.

The example event discussed in this paper involves oscillations in the frequency values & measurement methods would need to be able to adapt to such scenarios. This may be atypical for instruments targeted towards applications where frequency is traditionally known to not vary in such a manner.

3.2.1 IEC 61000-4-30 10s Power Frequency

This method involves counting the total number of integral cycles within a 10s interval divided by the cumulative duration of the integer cycles. Unsurprisingly, this method results in significant loss of resolution and short-term fluctuations cannot be captured. The long duration also implies that any changes in the frequency would require at least 10 seconds before it can be noticed.

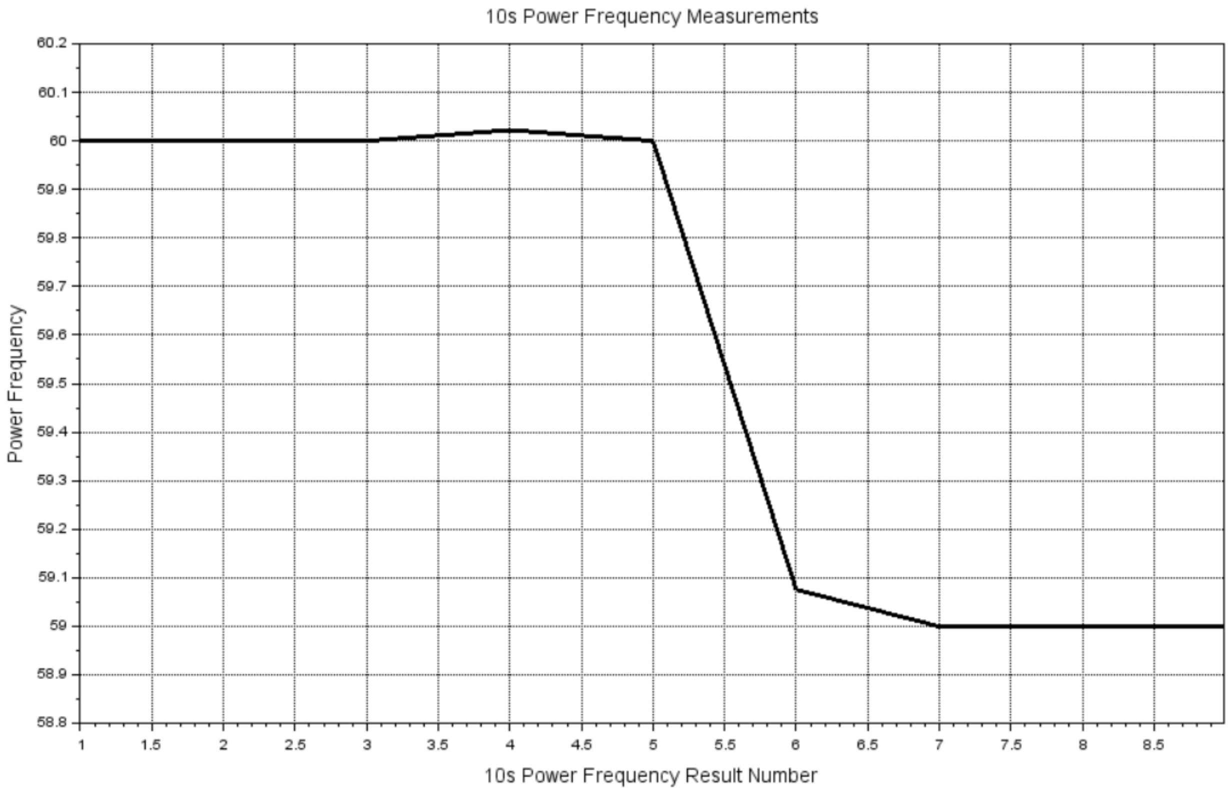

Fig.7: IEC 61000-4-30 Class A Power Frequency Measurements

3.2.2 DFR Half Cycle Frequency

Similar to the constraints on half cycle phasor measurements, instruments such as digital fault recorders, PMUs and protection relays need to estimate frequency within a deterministic interval and due to their inherent nature and targeted applications, this would be done at rates much higher than devices not belonging to such performance classes.

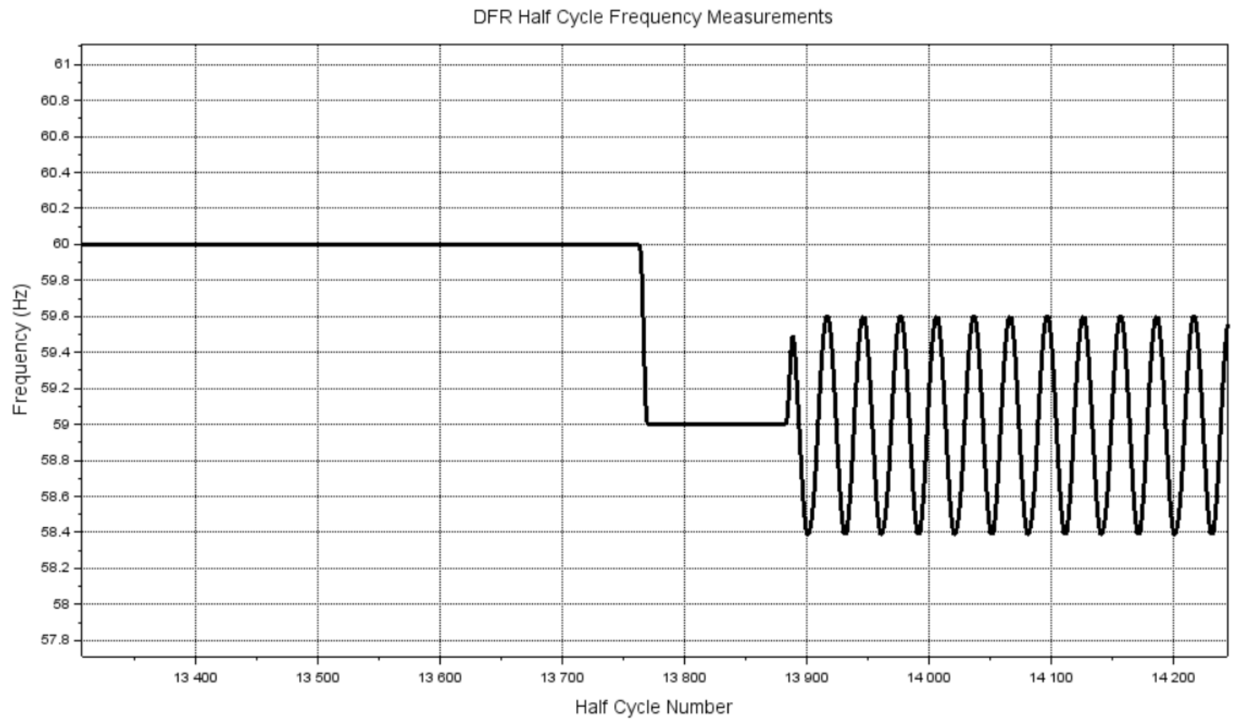

Fig.8: DFR Half Cycle Frequency Measurements

As a result, the changes in frequency are captured with excellent resolution and accuracy owing to the algorithms in use. The range and frequency of oscillation are represented accurately along with timely response to rapid changes in the value.

4 Conclusion

This paper highlights some of the key measurement techniques employed for estimation of power system quantities along with the analysis to understand their behaviour and suitability during system anomalies. The following are some of the key takeaways from this study –

1. Several measuring instruments belonging to different measurement classes may claim compliance to the same standards such as the IEC 61000-4-30, IEEE/IEC 60255-118-1, etc. but their behaviour during conditions not covered by these standards can vary substantially.
2. With every instrument type, it's useful to understand the targeted core application/functionality and the supported ancillary functions. Architectural and application specific constraints can play an important role in determining their performance during various anomalistic conditions.
3. Definition of even fundamental parameters such as a cycle need not be consistent across instruments despite being compliant to the same standards. Sampling and windowing techniques are crucial for accurate measurement but can be constrained by application specific limitations which can particularly be the case with standalone devices providing add-on functions.
4. Dedicated multifunction instruments such as modern DFRs can estimate several power system parameters in a variety of ways targeting specific applications without such constraints. Each measurement module can be tuned to function optimally & in an independent manner.
5. Advanced processing capabilities in such instruments aid in ensuring superior performance during power system events which can deviate from the typical test conditions indicated by standards.

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] IEC 61000-4-30: Testing and measurement techniques – Power quality measurement methods.

[3] IEC 62586-2: Power quality measurement in power supply systems –Part 2: Functional tests and uncertainty requirements