# Study of P Class Phasor Measurements during Fault Conditions and Impact on Analysis Applications

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**Abstract**

Several power system fault analysis techniques and applications that use synchrophasor measurements have emerged over the years. As PMUs can be strategically placed at different parts of the power grid which are spread over a wide geographical area, measurements obtained from them during system anomalies such as faults have proven to be useful for both real-time and post-fault analysis. Specifically, PMU data facilitates root cause analysis and validation of protection equipment behaviour during faults. The IEEE C37.118.1 standard and its successor, the IEEE/IEC 60255.118.1 - 2018, are widely accepted as benchmarking sources for the performance of a PMU and provide reference models for both P and M class variants. While the standard specifies performance limits under steady and dynamic conditions, behaviour under practical scenarios can be vastly different due to several factors such as the presence of harmonics, deviation of the fundamental frequency from its nominal value, sub and inter-harmonics, loss of phases, phase unbalance, oscillations, etc. A typical fault may involve a combination of these occurring simultaneously and the performance of PMUs during these conditions would be important for analysis applications. This paper presents a study on the nature of P class phasor measurements captured during such power system conditions and the impact they have on post-fault analysis. A power system model is designed and subjected to faults under the mentioned conditions. The captured signals are used to obtain P class phasor measurements which are further employed in the computation of fault specific data. A critical analysis is presented between data obtained from the IEEE/IEC P class PMU model and dedicated fault recording and analysis equipment. The study highlights the expected challenges associated with the usage of these measurements for analysis applications and the considerations that need to be made.

## 1 Introduction – Usage of PMUs for post fault analysis

Post-fault analysis involves the use of data captured across the power grid to determine the root cause of the incident/s, verify operation and performance of protection schemes and evaluate the stability of the system after the occurrence of a disturbance. Faults in a three-phase system are generally diagnosed using sequence components [1] which simplify the analysis of an unbalanced system by converting it into a balanced set of phasors. The typical quantities that support fault analysis are measurements pertaining to voltage/current magnitude and angle, frequency, rate of change of frequency (ROCOF), impedance and other derived quantities such power, etc.

These are the measurements that are readily available from phasor measurement units which can report them at a variety of rates ranging from as low as 1 frame per second to as high as 100 frames per second (for a 50 Hz system) and beyond. PMUs carry out these measurements with reference to a common time source such as GPS and can typically provide accuracy better than a microsecond. Due to the usage of a common time reference, measurements acquired from PMUs located several hundreds of miles apart can be directly compared with each other, thereby enabling the analysis of a geographically wide system at the same instant of time. Data generated by PMUs across the grid is collected by phasor data concentrators (PDCs) which archive and make it available for analysis in the event of a disturbance.

The measurements acquired from PMUs during fault conditions can be used for both real-time and offline analysis applications. The latter aids in forensic and root cause analysis studies. Typical uses include,

a) Detection of abrupt changes in the magnitude and angle of the phase voltages and currents.
b) Fault classification.

c) Determination of pre-fault and post-fault fault system frequency and rate of change of frequency.
d) Validation of protection equipment and fault clearance times.
e) Post-fault stability analysis
f) Distance to fault estimation

Extensive analysis details have been collected by utilities across the world which provide insight into the performance of PMUs during various anomalies [2].

## 2 Phasor measurement classes and techniques

Phasor measurement involves the estimation of two fundamental quantities of a signal, the magnitude and the phase angle. The IEEE/IEC 60255-118-1 standard specifies two classes of PMUs – protection class (P) and measurement class (M), along with reference measurement algorithms [3][4]. A key factor involved in the design of a PMU compliant to this standard is that measurements must be made available at defined time intervals in a consistent manner. This implies that a constraint is imposed on the selection of the portion of the signal, otherwise known as the window.

Table 1 lists some of the differences between the two PMU classes specified by the standard which impact analysis applications.

**Table 1 :** P Class vs M Class

| P class | M class |
|---|---|
| Short acquisition window and minimal filtering (2 nominal cycles) | Long acquisition window and extensive filtering (several cycles) |
| Low accuracy due to short window | High accuracy due to long window |
| Limited protection against interference signals, especially inter-harmonics | Good attenuation of interference signals including inter-harmonics |
| Fast response to abrupt changes and low settling period | Slow response to abrupt changes and high settling period |

While the P class PMU offers fast response to abrupt changes in the signal, it suffers when off-nominal frequency harmonic content, inter-harmonics close to the nominal frequency and sub-harmonic content are present. The M class PMU offers better immunity to interference signals but at the cost of longer delays and higher response periods.

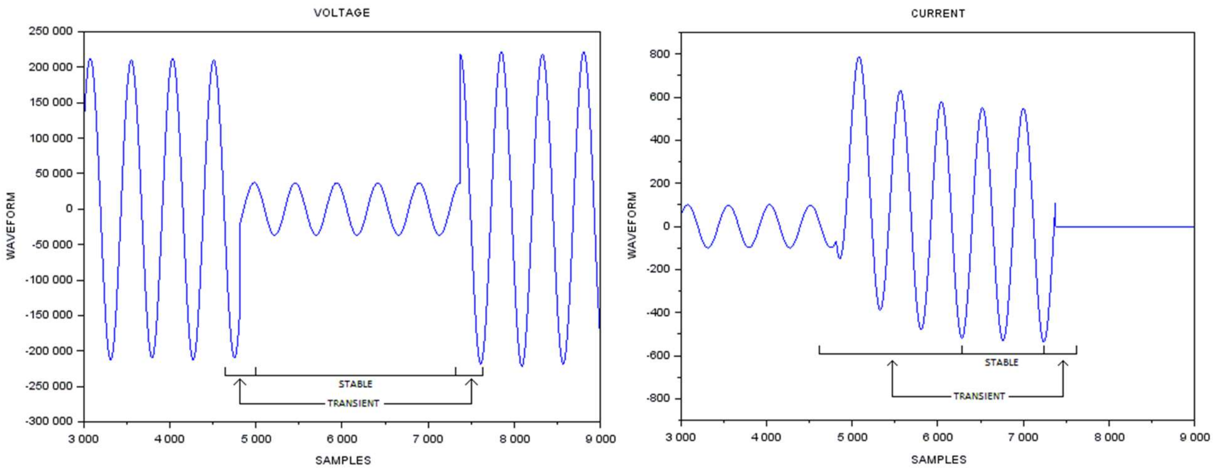
## 3 Phasors for fault analysis – applications and challenges

Applications involving fault analysis may require high levels of accuracy and short response time. Both these qualities are contradictory in nature and fault conditions present unique challenges.

### 3.1 Short time frame for data acquisition

The occurrence of a fault is generally followed by protection relays issuing trip signals to circuit breakers for its isolation. As such, there exists a finite window of time during which the captured data would contain fault components. Fast isolation of faults is a desirable quality among protection relays which implies that this time window might be short and limited.

Hence, it is necessary to obtain the best measurements in this limited time frame while also ensuring fast response and low settling periods.



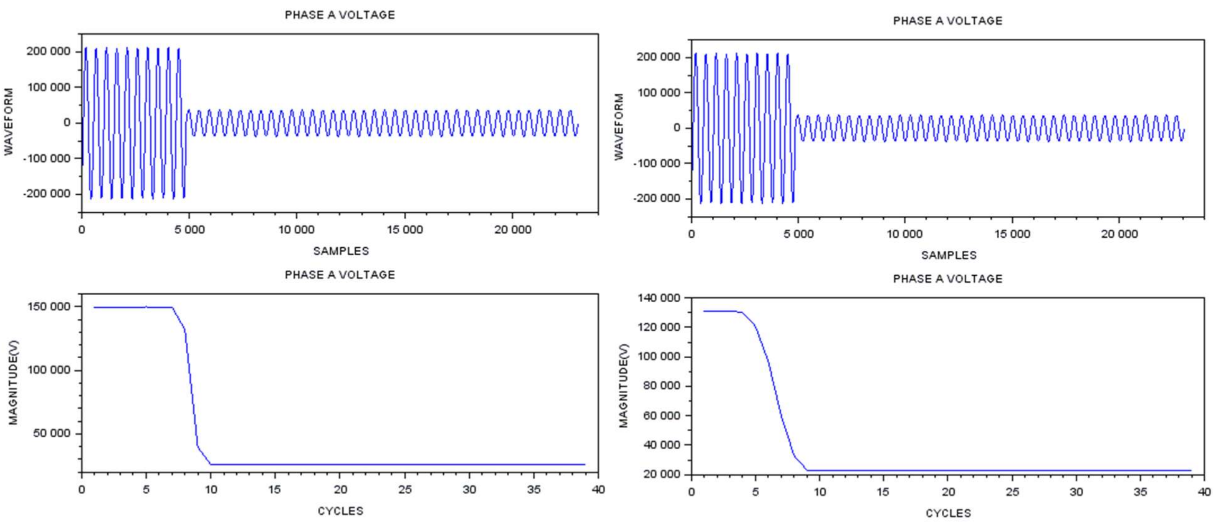

(a) (b)

**Fig.1:** A fault comprising of transient and stable regions. Measurements are valid only in the stable region which can have a short duration. (a) Voltage signal. (b) Current signal

### 3.2 Impact of measurement window length

Usage of a short acquisition window with minimal filtering would ensure that sufficient phasor estimates are obtained before the fault is isolated. However, a short window provides low accuracy and is susceptible to interference signals such as harmonics and inter-harmonics.

On the other hand, a long acquisition window can sufficiently attenuate interference signals but suffers from sluggish response times, higher delays and longer settling periods. All measurements computed over a transient are generally discarded due to the unstable nature of the estimated values [5].




(a) (b)

**Fig.2:** Comparison between short and long windows. (a) Short window with fast response. (b) Long window with sluggish response

### 3.3 Post fault accuracy

The occurrence of a fault pushes the system into an unstable state and this instability would continue to exist until the fault is cleared and a state of normalcy is restored. During this period, measurement algorithms can be subjected to extreme conditions which can have a negative impact on their accuracy. Conditions involving loss of phase/s, severe phase unbalance, off-nominal system frequency, oscillations, etc. are some examples that'd adversely affect the performance of measurement algorithms.

## 4 Measurement during anomalistic conditions

Measurements obtained under such anomalistic conditions can have a variety of undesirable effects on analysis applications and the following sub-sections highlight some of these. For this purpose, a set of power system faults are simulated under a variety of conditions and digital samples for the equivalent phase voltages and currents are obtained. These samples are fed to the IEEE/IEC P class model and its performance is benchmarked against Ametek's expert analysis system whose details are as described below.

(a) IEEE/IEC 60255-118-1 P class PMU reference model

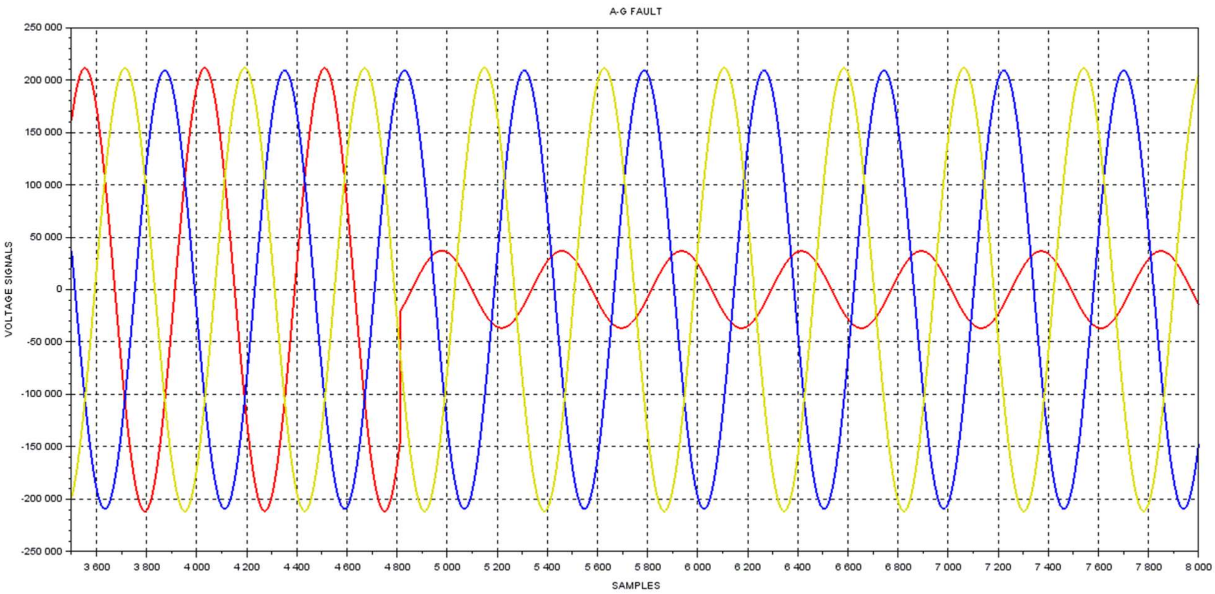
The P class phasor measurement reference algorithm specified by the IEEE/IEC 60255-118-1 standard. Produces phasor estimates with a fixed window length of two nominal cycles and utilizes a fixed fundamental frequency design approach.

(b) Ametek adaptive expert analysis system

Offline analysis system with adaptive window selection, frequency tracking, transient detection and adaptive filtering capabilities. Produces phasor estimates at variable intervals based on the true frequency of the system and utilizes intelligence to obtain measurements with a balance of accuracy and response time.

The results obtained from these are presented in subsequent sections along with their performance relative to one another.

As an example, an A-G fault is chosen whose voltage and current waveforms are shown in fig.3.

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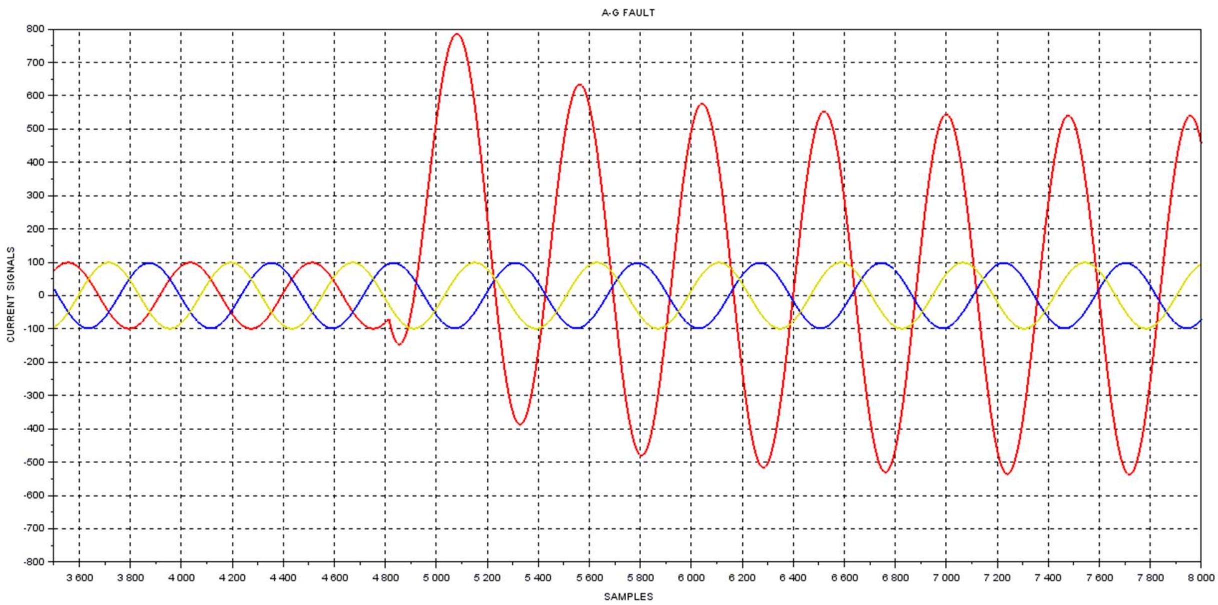


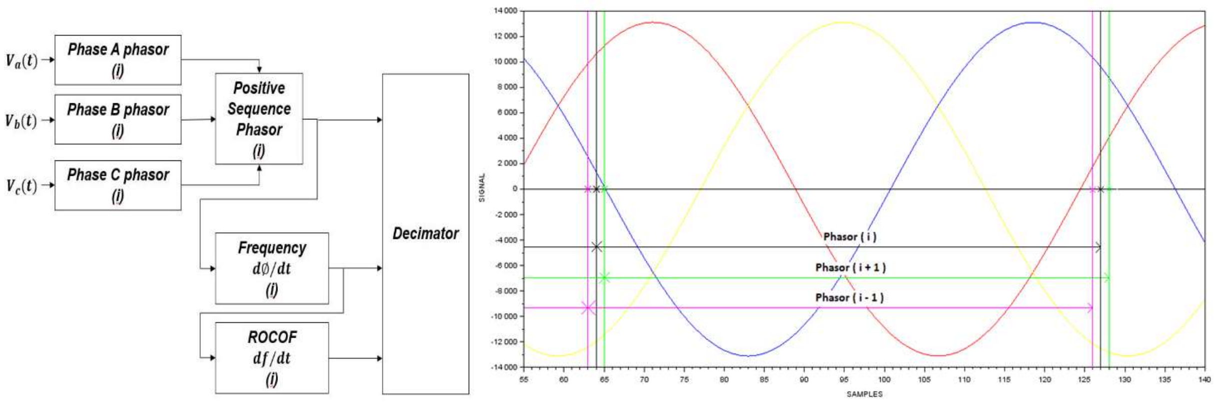

(b)

**Fig.3:** A-G fault waveforms. (a) Voltage signals. (b) Current signals

The frequency is deliberately set to a value of 53.5 Hz to highlight the effect of off-nominal frequency.

### 4.1 Frequency measurement

The IEEE/IEC 60255-118-1 based frequency measurement algorithm uses the rate of change of phase angle of the positive sequence phasor to estimate the frequency.




(a) (b)

**Fig.4:** IEEE/IEC reference phasor model. (a) Estimation algorithm. (b) Phasor windows

$$f = f_0 + [\theta(i+1) - \theta(i-1)]/[4\pi * \Delta t] \quad (1)$$

where,

$f$ = Estimated frequency

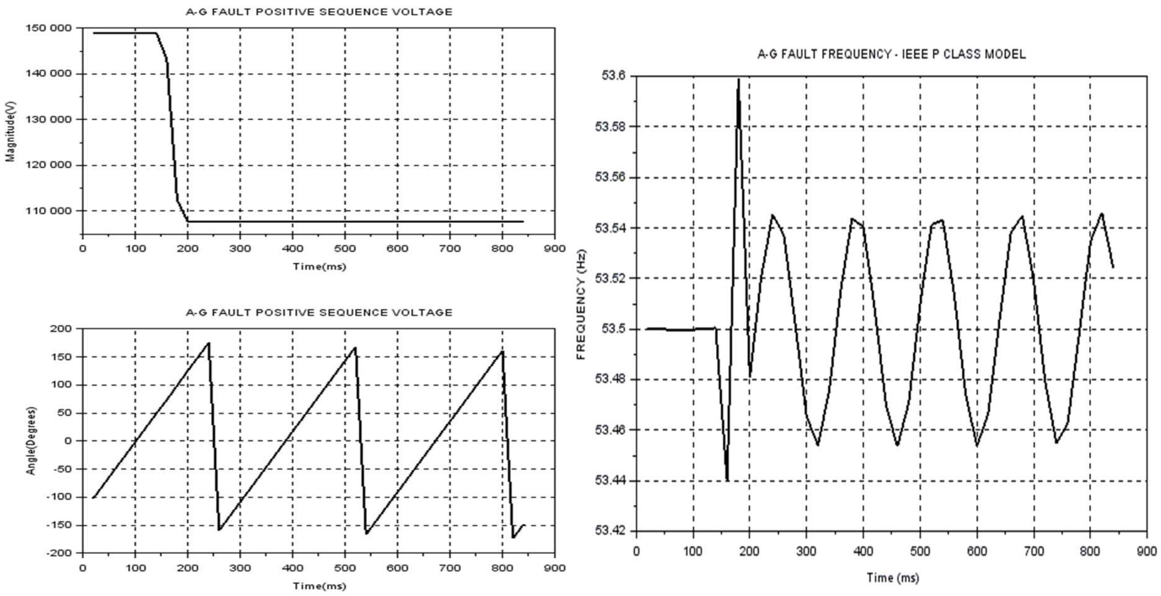
$f_0$ = Nominal frequency (50 Hz or 60 Hz)

$\theta(i+1)$ = Angle of the $i+1^{\text{th}}$ phasor, i.e. the angle following the $i^{\text{th}}$ estimate.

$\theta(i-1)$ = Angle of the $i-1^{\text{th}}$ phasor, i.e. the angle prior to the $i^{\text{th}}$ estimate

$\Delta t$ = Sampling period

The equivalent positive sequence values and the estimated frequency are shown in fig.5.



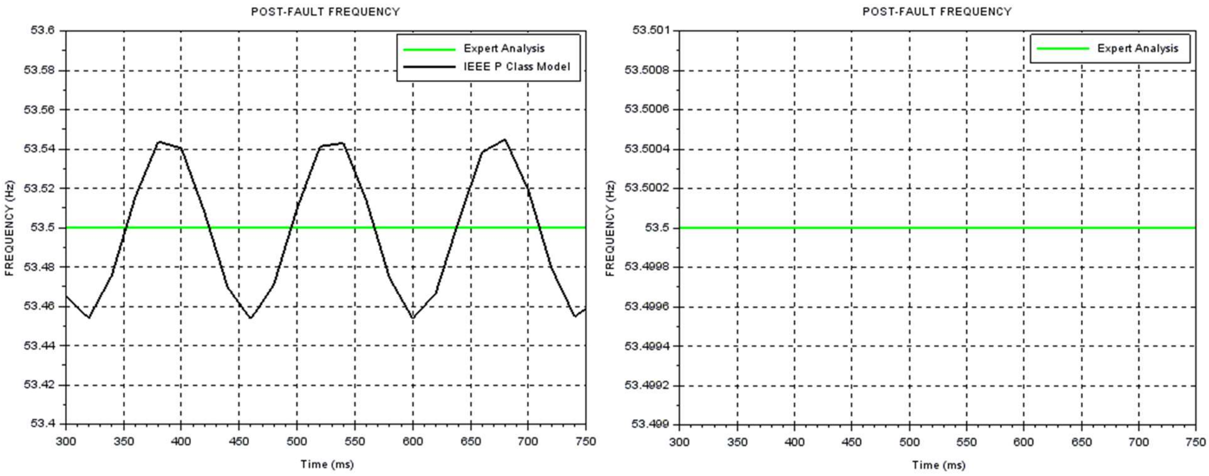

(a) (b)

**Fig.5:** Frequency measurement using the positive sequence. (a) Positive sequence magnitude and angle. (b) Measured frequency

While the magnitude and phase plots of the positive sequence show minimal adverse impacts, the frequency plot shows a spike at the fault instant followed by an oscillation in the value over a range of approximately 100 mHz.

The spike is expected due to the transient effect associated with the sudden drop in the positive sequence magnitude and lasts only for the time-period corresponding to the window length. However, the oscillatory behaviour in the post-fault region is due to the inherent design of the P class algorithm which uses a fixed filter methodology and doesn't adapt its filtering to the actual fundamental frequency. The fault was deliberately retained to highlight that this oscillatory behaviour isn't a transient effect which decays over time.

Fig.6 shows the comparison between the frequency measured by the IEEE/IEC P class algorithm and the expert analysis system in the post-fault region.




(a) (b)

**Fig.6:** Post-fault frequency. (a) IEEE/IEC P class reference model vs expert analysis. (b) Expert analysis frequency measurement highlighted to show error margins

It can be observed that the expert analysis measurement has an error that's below 0.1 mHz. This accuracy can be attributed to the fact that the phasor estimator of the expert analysis system adapts to the line frequency and has the intelligence to select the best window length which allows it to provide maximum attenuation to harmonic and inter-harmonic signals.

### 4.2 Rate of change of frequency

According to the IEEE/IEC 60255-118-1 reference model, the ROCOF estimate is computed as the derivative of the rate of change of phase angle.

$$f = [\theta(i+1) + \theta(i-1) - 2\theta(i)]/[2\pi * \Delta t^2] \quad (2)$$

The estimated ROCOF values using this algorithm for the fault sequence are shown in fig.7.

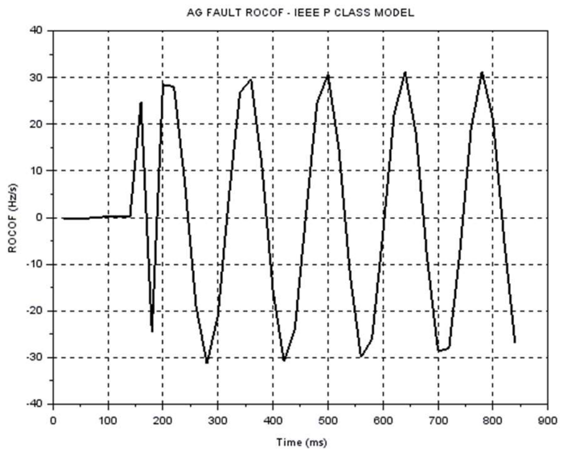
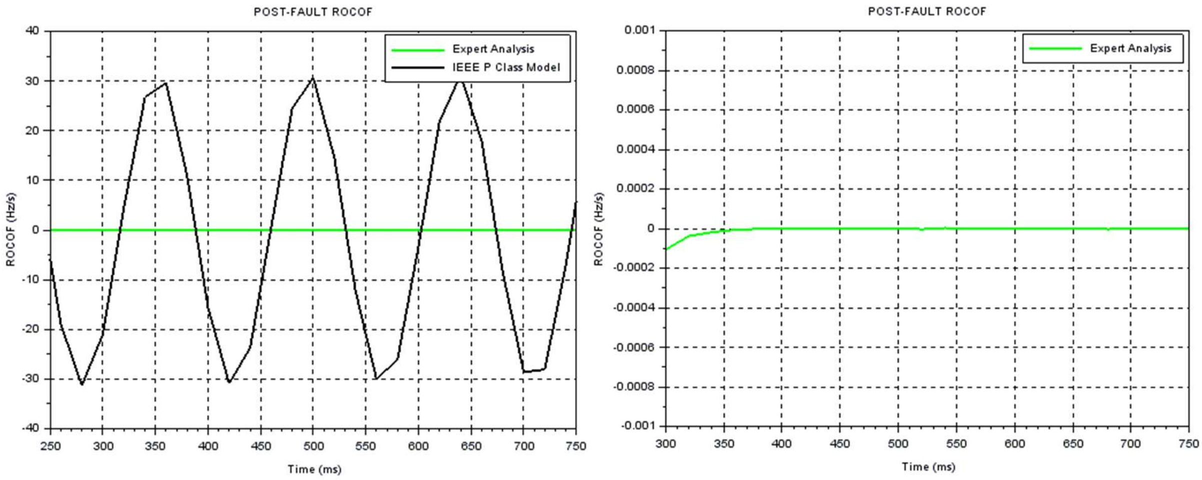



**Fig.7:** ROCOF measurement from the IEEE/IEC P class reference model.

It can be observed that in the post-fault region, the ROCOF values oscillate by a significant amount and its peaks exceed even that of the transient portion. The reason for this behaviour is attributed to the fact that this algorithm is very sensitive in nature and minute errors in the phase angle estimates manifest as significant errors in the ROCOF estimates. A comparison with the expert analysis estimates in the post-fault region is shown in fig.8.



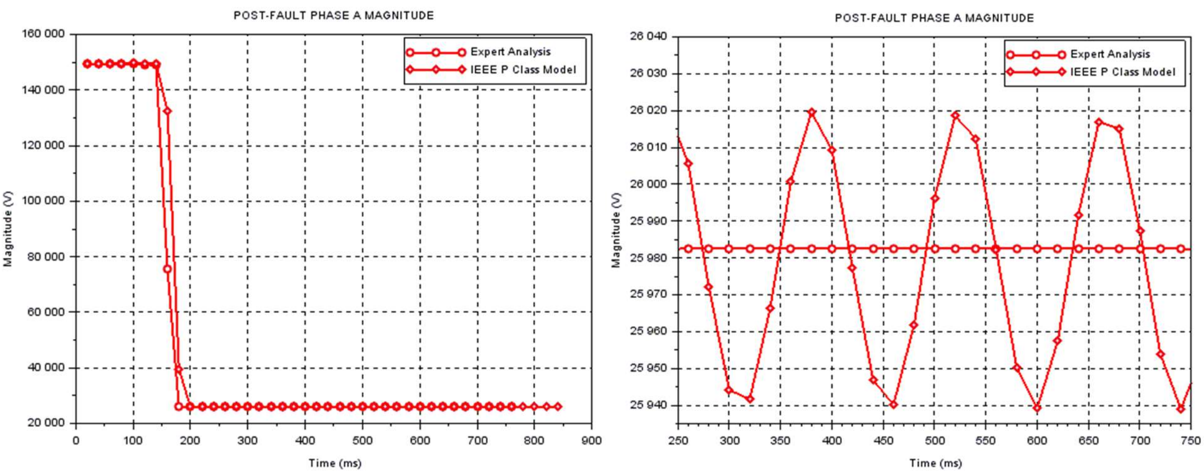

(a) (b)

**Fig.8:** Post-fault ROCOF. (a) IEEE/IEC P class reference model vs expert analysis. (b) Expert analysis ROCOF measurement highlighted to show error margins.

The ROCOF values computed by the expert analysis system show errors below 1 mHz. As in the case of the frequency estimates, this accuracy is due to the line frequency adaptation capability.

### 4.3 Phasor magnitude

Fig.9(a) shows the plot of the voltage phasor magnitude of phase A. As the fault under consideration is an A-G type fault, the magnitude rapidly drops at the fault instance. At first glance, the post-fault region appears to be stable. However, on highlighting the post-fault region in fig.9(b), an oscillatory pattern can be seen in the magnitude.

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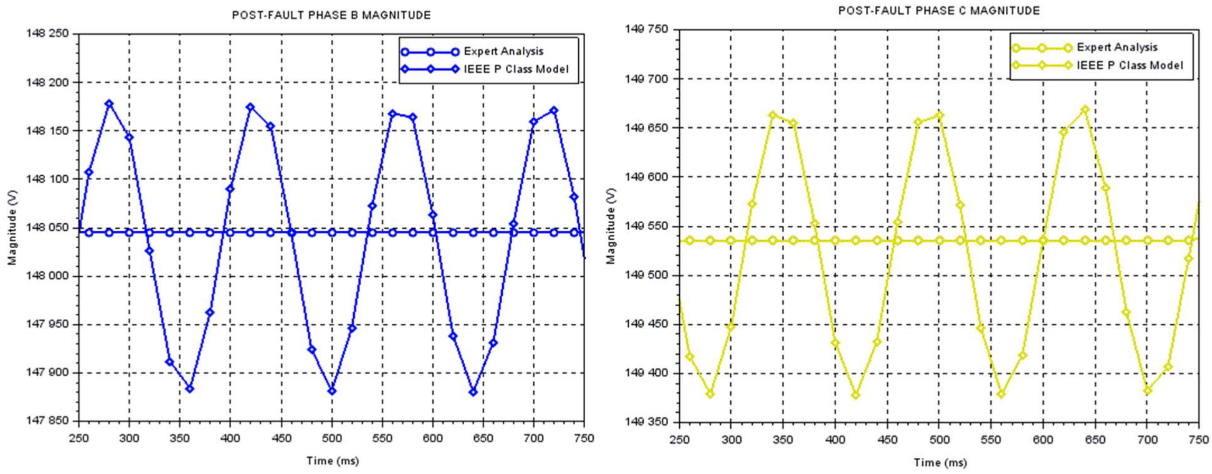



(c) (d)

**Fig.9:** Post-fault phasor magnitudes. (a) Dip in the phase A voltage magnitude. (b) IEEE/IEC P class reference model vs expert analysis for phase A. (c) IEEE/IEC P class reference model vs expert analysis for phase B. (d) IEEE/IEC P class reference model vs expert analysis for phase C.

While the range of oscillation on phase A is small, phases B and C are also seen to exhibit oscillations but to a slightly lower degree (in terms of the error percentage and not the actual range of oscillation) despite being healthy, as seen in fig.9(c)(d). This is primarily due to the behaviour of the IEEE/IEC P class model when subjected to off-nominal frequencies.

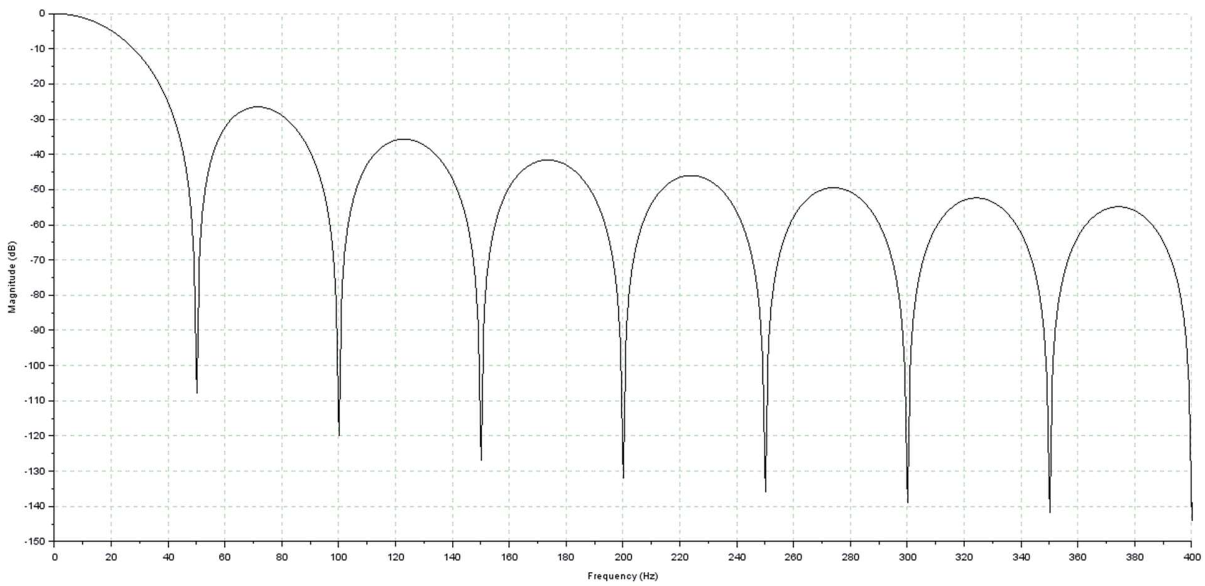



**Fig.10:** Magnitude response of the IEEE/IEC P class reference filter.

As the filter used is a fixed frequency variant (set to 50 Hz or 60 Hz), if the fundamental frequency is not equal to the nominal value, the magnitude of the estimate is attenuated in accordance with the gain response shown in fig.10. This attenuation is compensated using equation 3.

$$\hat{X}(i) = X(i)/[\sin(\pi(f_0 + 1.625\Delta F(i))/2f_0] \quad (3)$$

where,

$\hat{X}(i)$ = Compensated phasor

$X(i)$ = Uncompensated phasor

$\Delta F(i)$ = Frequency deviation from nominal

$f_0$ = Nominal frequency

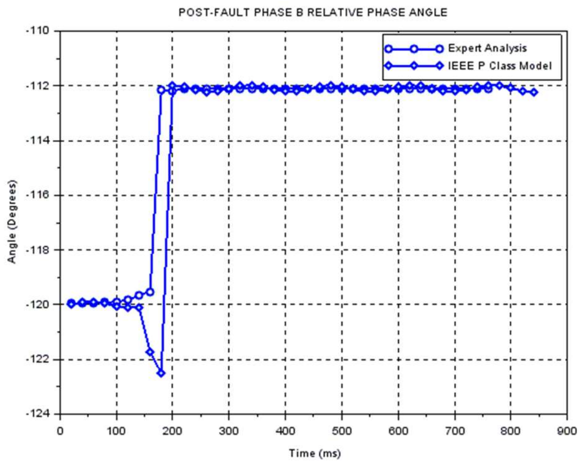
It is worth noting that the effects of harmonics and inter-harmonics have not been considered and the oscillations are purely due to the off-nominal system frequency.

The expert analysis estimates show that the oscillations are indeed due to algorithmic errors and that frequency tracking estimators can provide more stable values.

### 4.4 Phase angle

It can be observed in fig.5(a) that the absolute phase angle varies uniformly over a range of +/- 180 degrees. This is because the IEEE/IEC reference model uses a fixed frequency filter and off-nominal frequencies will cause the phase angle to rotate at a rate of $2\pi(f - f_0)T_0$.

No anomalies are immediately evident from the plot but on calculating the relative phase angles and closely inspecting the values in the post-fault region, oscillating patterns can be observed as shown in fig.11.

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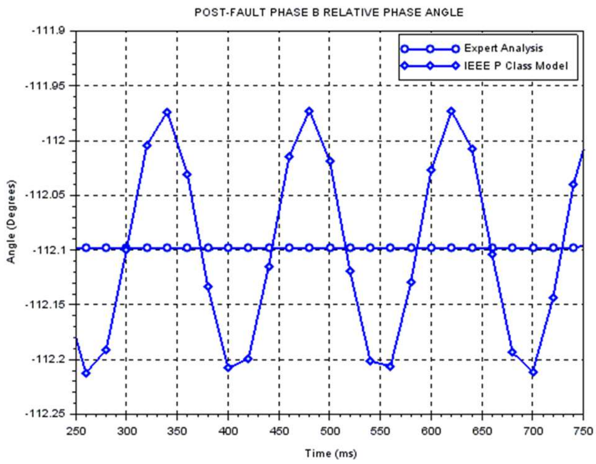


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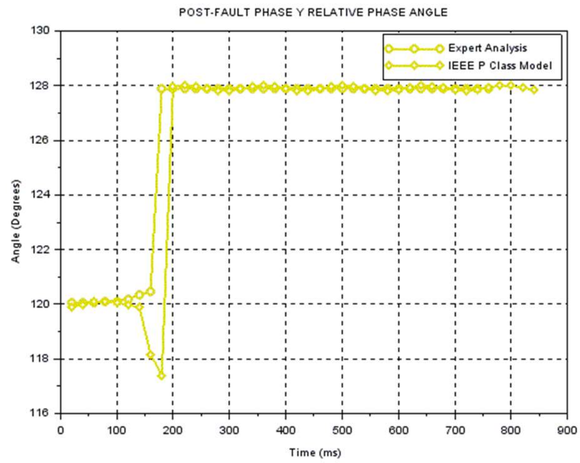


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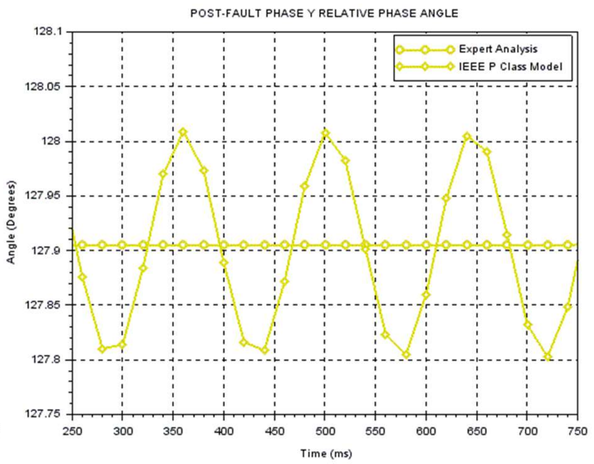



(d)

**Fig.11:** Phasor angles – IEEE/IEC P class reference model vs expert analysis. (a) Phase B relative phase angle. (b) Post-fault phase B relative phase angle (c) Phase C relative phase angle. (d) Post-fault phase C relative phase angle.

The phase angles oscillate over a range of about 0.25 degrees. Equivalent estimates by the expert analysis system show stable values. Despite the frequency compensation in equation 3 being a magnitude specific requirement, even the phase angle measurement exhibits errors.

### 4.5 Impedance

The presence of errors in the magnitude and phase angle measurements imply that the impedance values would also exhibit errors. The combined effect of the errors in the voltage and current measurements are shown in the impedance plot in fig.12.

The simulated fault is at 91.667% of the line length and the ideal phase A fault impedance is 11.1 + 67.23j Ohms. Factors such as the mutual impedances aren't considered to clearly highlight the error introduced just by the measurement algorithms.

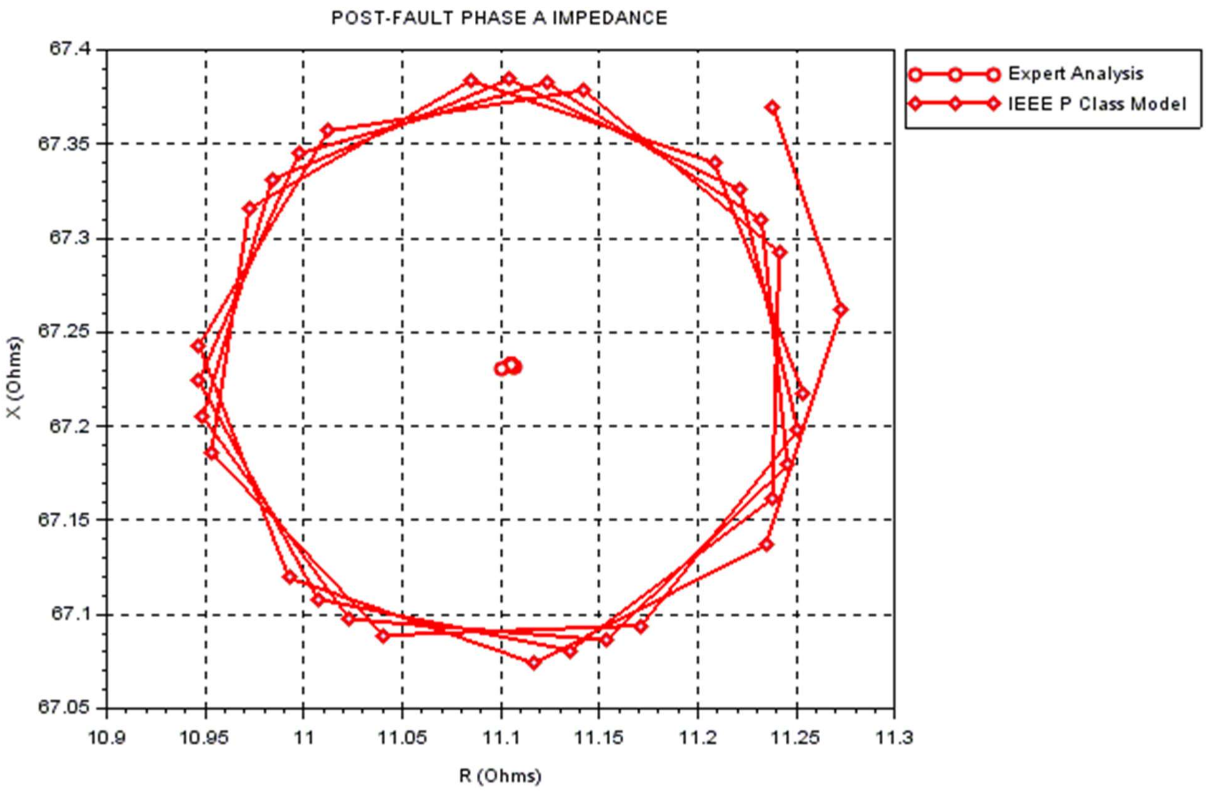



**Fig.12:** Post-fault phase A impedance plot – IEEE/IEC P class reference model vs expert analysis.

Using the basic single ended distance to fault estimation algorithm, the apparent positive sequence fault impedance for the A-G fault is calculated as,

$$Z_1' = V_A \, / \, (I_A + I_0((Z_1 - Z_0)/Z_1)) \quad (4)$$

where,

$Z_1'$ = Apparent positive sequence impedance

$Z_1$ = Positive sequence line impedance

$Z_0$ = Zero sequence line impedance

$V_A$ = Phase A voltage

$I_A$ = Phase A current

$I_0$ = Zero sequence current

With $Z_1 = Z_0$ (due to the mutual impedance values being ignored), the equation is reduced to

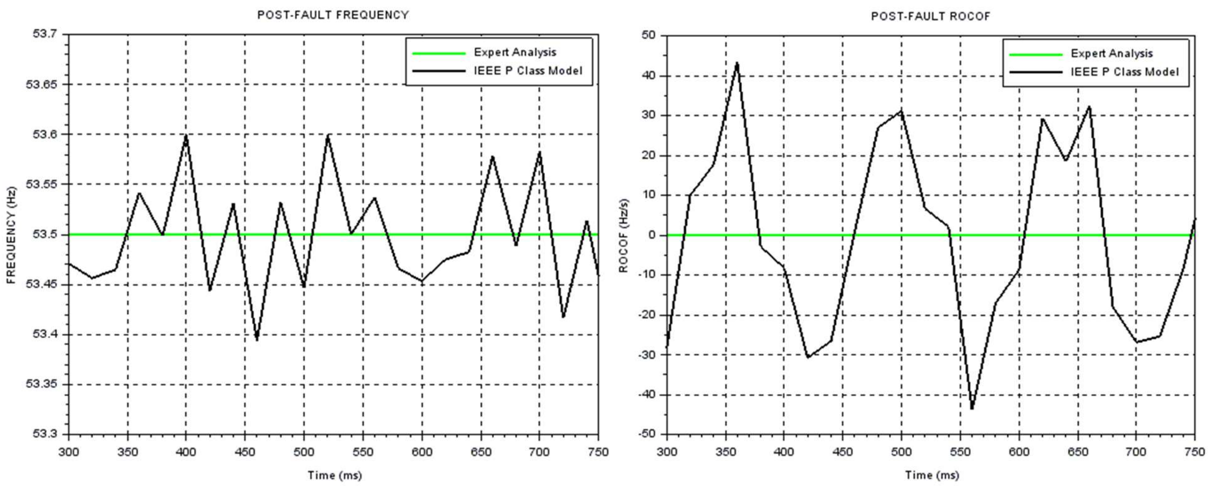
$$Z_1' = V_A / I_A \quad (5)$$

which is the phase A impedance. The impedance values computed using the IEEE/IEC P class model trace a spiral path with the values ranging between R = 10.94 Ohms to 11.26 Ohms and X = 67.06 Ohms to 67.39 Ohms. This constitutes an error of 1.5% even without taking the effects of mutual impedance, fault resistance and other DTF algorithmic factors into consideration.

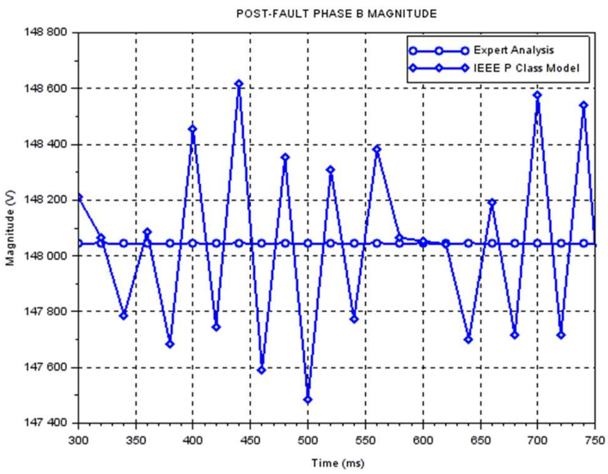
The expert analysis estimates are seen to exhibit higher levels of accuracy attributed to the intelligent window selection, frequency tracking and adaptive filtering capabilities.

### 4.6 Presence of harmonics and inter-harmonics

The previous sections depicted the challenges associated with phasor measurement during anomalistic conditions but in the absence of interference from harmonic and inter-harmonic signals. Fig.13 shows the computed measurements for the same A-G fault presented earlier but with 1% inter-harmonics injected with a frequency of 1.5 times the fundamental frequency.




(a) (b)

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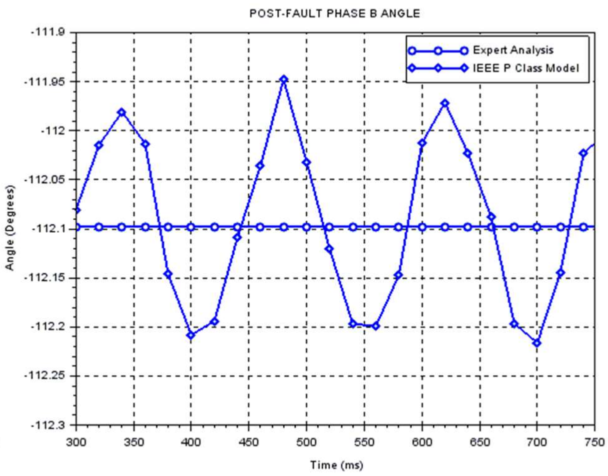


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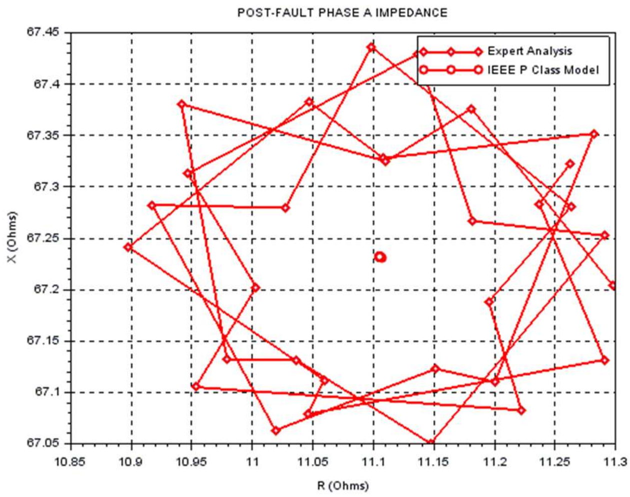


(e)

**Fig.13:** Measurements with the presence of inter-harmonics – IEEE/IEC P class reference model vs expert analysis. (a) Frequency. (b) ROCOF. (c) Post-fault phase B magnitude. (d) Post-fault phase B relative phase angle. (e) Post-fault phase A impedance.

The following observations can be made about the measurements from the IEEE/IEC P class model -

a) The range of oscillations in the frequency measurement is observed to have doubled.
b) The ROCOF errors are higher by 50%.
c) Phasor magnitude errors are seen to have increased 3.67 times and the swing range is over 1kV.
d) Phasor angle errors experience only a slight increase of 0.03 degrees.
e) Peak errors in the impedance measurements show a marginal increase but the values are seen to be more erratic in nature.

In contrast, the expert analysis system estimates show almost no variations due to the intelligent filtering and window selection abilities. This clearly emphasizes the susceptibility of the IEEE/IEC P class reference model to inter-harmonics and the associated negative effects.

## 5 Conclusion

The observations in this paper highlight the challenges associated with the usage of synchrophasor measurements collected during power system anomalies. Based on the obtained results, the following considerations can be made when using this data for fault analysis applications –

1. Phasors obtained from the IEEE/IEC P class reference model are susceptible to errors due to off-nominal fundamental frequency, presence of inter-harmonics and lower order harmonics, loss of phases, etc. anomalies in the power grid.
2. The cause of the errors can be attributed to the fixed frequency filter design and fixed window length of the reference model.
3. Frequency tracking phasor estimators such as the Ametek expert analysis system presented in this paper show higher levels of accuracy and lower susceptibility to interference signals. While this version of the frequency tracking ability is specific to offline analysis applications, there are real-time implementations which offer a subset of this functionality in limited capacity and are shown to be compliant with the requirements of the IEEE/IEC 60255-118-1 standard [6].
4. Intelligent window length selection and adjustment, an offline analysis ability, is seen to provide excellent immunity to interference signals. The adaptive nature of this feature allows the phasor estimator to dynamically adjust the window length to provide fast response times during transients as well as high attenuation in their absence. When accurate analysis is preferred over latency and real-time response, this ability would prove to be very useful.
5. Traditionally, protection relays operate in synchronization with the line frequency to minimize phasor estimation errors [7] unlike the IEEE/IEC PMU model which opts for a fixed frequency design. While validating the operation and performance of relays, this factor might introduce a disagreement between the measurements made by the PMU and the relay. The latter might in fact be more accurate during the conditions described in this paper.
6. Fault recorders with intelligent analysis capabilities and high sampling rates can provide very accurate measurements and serve as a benchmark for evaluating the performance and operation of different equipment, especially under challenging fault conditions where there’s a higher level of uncertainty about the measurements obtained from other families of phasor measurement devices.

In future revisions of the IEEE/IEC 60255-118-1 standard, contemplation about the use of frequency tracking in the reference models could be made.

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