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Performance of Phasor Measurement Units under Harmonic Influences

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Abstract

The performance of Phasor Measurement Units (PMUs) is essential and must ensure accuracy before installation in the substation. In the field, various interference conditions would occur in the power systems and were tested as per IEC/IEEE 60255.118.1:2018. Three number of PMUs from different manufacturers was configured for the M-class and P-class requirements. They were tested for two interference condition scenarios. The first case injected single harmonics with the input to test the impacts on accuracy. The second scenario was considered for inter-harmonics and checked the accuracy of PMUs. This will be useful in selecting high-quality PMUs, to obtain the most precise and dependable measurements under real-time power system operating conditions, the testing procedures, findings, and analysis are presented in this paper.

Keywords: Accuracy, Harmonics, IEC/IEEE Std, Interharmonics, M-Class, P-Class, PMUs

1. Introduction

Numerous recent studies have emphasized the performance of Phasor Measurement Units (PMUs). Real-time power system functioning is simulated under steady-state and dynamic situations, as described in IEC/IEEE 60255.118.1:2018[1]. Guidelines for testing and calibrating PMUs have been released in the form of the IEEE Test Suite Specification[2]. Commercial PMUs are assessed for both M class and P class using a precision PMU calibration method[3,4]. The PMU measurements occur in the presence of interference, such as numerous harmonics, noise, and CT saturation[5]. The Discrete Fourier Transform (DFT) is the foundation of the PMU measuring techniques[6,7]. Current works provide techniques to enhance the accuracy in various dynamic or interference settings[8,9] and a non-DFT model[10–13] enhanced one in a dynamic state. Parameter estimation is complicated by noise, harmonics, and state changes brought on by load variations, control, and protective measures. Non-linear loads introduce extreme harmonics. Measuring the generation and load characteristics at or close to the system's fundamental frequency becomes more difficult as a result. The calculation of phasors, frequency, and ROCOF will be impacted by connected factors such as harmonics and inter-harmonics, which PMU designers and end users must take into account.

The performance of three commercial PMUs is presented in this study under two typical operating situations of actual power systems. In the first test, readings from PMUs were predicted to be rather excellent, adding single harmonics at a time and second harmonics to 50^{th} harmonics. The testing using one harmonic at a time is described in this standard with the nominal system frequency. The second test, which only applies to M-class commercial PMUs, was conducted on all three of them and measures out-of-band interference or inter-harmonics. Three PMUs-two with the same hardware and software and one with different hardware and software are available. The structure of the paper is as follows. The creation of these test signals is covered in Section 2. Section 3 describes the PMU test system. The analysis and findings are shown in Section 4. Section 5 contains the conclusions.

2. PMU Test Set-up and Procedure

Six separate components work together as a system to form the Phasor Measurement Unit Calibration System. This includes the Fluke 6135A, a high-precision three-phase voltage and current signal source, which is made up of the

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Fluke 6105A and two 6106A units combined. To test and calibrate PMUs, these signals must be synchronized with Coordinated Universal Time (UTC). To guarantee precise timing and synchronization with the output frequency and phase angles of the 6135A, the PMU System Timing Unit within the system establishes a connection with a GPS receiver. A server PC controls the equipment during calibration processes; the PMUCal software, which is installed on the client computer, provides instructions. By simulating both steady-state and dynamic situations that PMUs experience in the electric power grid system, the system is intended to evaluate performance in accordance with applicable standards.

Figure 1. Test setup.

The PMU testing system, which is run by the PMUCal Software, is shown in Figure 1. The PMUCal Software uses non-editable files based on global standards for automated compliance testing to certify a PMU. Sequenced tests are included in these files; a certification test usually consists of more than a thousand separate sequenced tests that are based on standards. Certain parameters, including nominal frequency, reporting rate, M class, and P class, are set up for the automated test. PMUCal Software interacts with the Server PC to set up and carry out the test procedures during automated testing. The complete calibration system is actively managed by the Server PC, which also gathers data and sends it to the Client PC as shown in Figure 2. The PMUCal Software records the maximum test values and updates the actual results once the tests are finished. The results can be viewed on the results page or exported to a Microsoft Excel file in Comma Separated Value format.

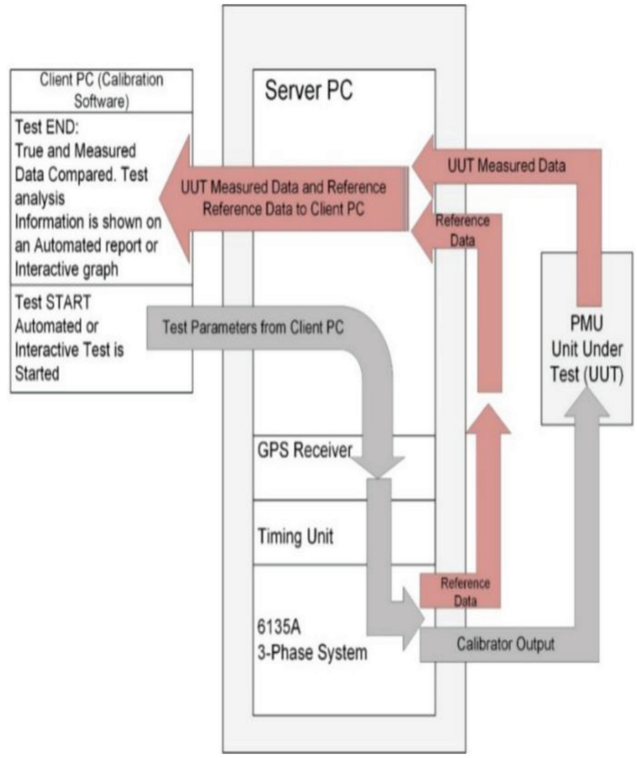

Figure 2. PMU calibration data flow system.

3. Steady State Measurements

To verify compliance, five seconds are allotted for comparing the steady state voltage phasor, current phasor, frequency, and RoCoF estimations with their theoretical values. This includes checking for single harmonics (harmonic distortion) and inter-harmonics (out-of-band interference). Both P class (except out-of-interference) 25FPS and 50FPS and M class in the reporting rate of 25FPS and 50FPS are covered by these PMU measurements under steady state compliance. ±2.0 Hz for Fo≤10, ±Fo/5 for 10≤Fo<25, and ±5.0 Hz for Fo ≥25 are the reference frequency conditions for M class. The ranges for nominal frequency, current, and voltage are 10 to 200% and 120%, respectively. The same ranges apply to the P class: ±2.0Hz, 10 – 200%, and 80 – 120%, in that order.

Equations (1) through (3) shall be used to represent the input signals for the harmonic distortion test.

$$X_a = X_m \cos(2\pi f_0 t) + X_m k_x cos(2\pi n f_0 t) \quad (1)$$

$$X_b = X_m cos(2\pi f_0 t - \frac{2\pi}{3}) + X_m k_x cos(2\pi n f_0 t - \frac{2\pi n}{3}) \quad (2)$$

$$X_c = X_m \cos(2\pi f_0 t + \frac{2\pi}{3}) + X_m k_x \cos(2\pi n f_0 t + \frac{2\pi n}{3}) \quad (3)$$

where n is the harmonic order; f_0 is the nominal power system frequency (Hz); and where X_m is the harmonic amplitude factor.

The input signals for the out-of-band interference test are represented by Equations (4)-(6):

$$X_a = X_m \cos(2\pi f_{in}\, t) + X_m k_i \cos(2\pi f_i t) \quad (4)$$

$$X_b = X_m \cos(2\pi f_{in}\, t - \frac{2\pi}{3}) + X_m k_i \cos(2\pi f_i t - \frac{2\pi}{3}) \quad (5)$$

$$X_c = X_m \cos(2\pi f_{in}\, t + \frac{2\pi}{3}) + X_m k_i \cos(2\pi f_i t + \frac{2\pi}{3}) \quad (6)$$

Where k_i is the amplitude factor of the interference frequency; fi is the interference frequency (Hz);

As stated in Equation (7), PMU generates a phasor for each steady-state test.

$$X(nT) = \frac{Xm}{\sqrt{2}} \angle \left\{ 2\pi \Delta f n T + p\frac{2\pi}{3} \right\} \quad (7)$$

where T is the phasor reporting interval, t is the reporting time tag at nT, n is an integer, and p = 0 for A phase, -1 for B phase and 1 for C phases.

Frequency offset, $\Delta f = f_{in} - f_0$

Additionally, it will generate the appropriate frequency and ROCOF measurements: $f(nT) = f_0 + \Delta f$ (8)

$$\Delta f(nT) = \Delta f \quad (9)$$

$$ROCOF\ (nT) = 0 \quad (10)$$

4. Results and Discussion

4.1 Harmonics

The Input signals for steady-state tests are specified mathematically. The three phases of input signals are shown in a positive sequence. For the out-of-band interfering signals test, the interfering signal is also specified to be a positive sequence. However, for the harmonic distortion test, the harmonic signals are not always positive sequences.

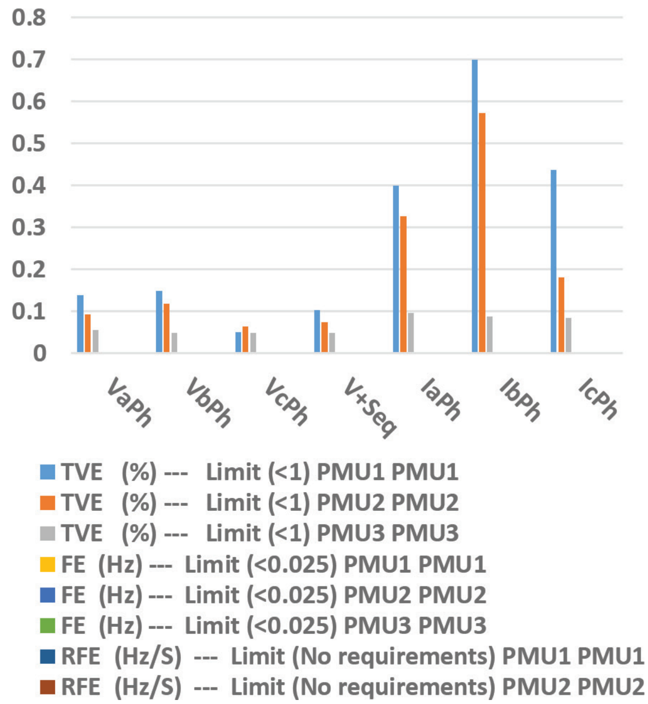

Figure 4. Single harmonic distortion steady state: 25FPS/M class.

For harmonic distortion tests, a balanced three-phase system is used and the harmonic sequence will cycle from positive to negative to zero depending on the harmonic number being injected. In other words, when the fundamental power signal of each phase crosses zero in the positive going direction, the injected harmonic signal should also be crossing zero in the positive direction. In this case, the second harmonic will be negative sequence, the third harmonic will be zero sequence, and the fourth harmonic will be positive sequence. The cycle repeats with the 50^{th} harmonic being negative sequence and so on.

The significance of this test is to ascertain whether harmonics have an impact on PMU accuracy. One by one, harmonics ranging from the second to the 50^{th} are added to the steady-state input signal. Figure 4 plots the computed and measured values.

The findings of all three PMUs are summarised in Figure 4, and the TVE, FE, and RFE values are within bounds and comply with the 25FPS for M class requirements. Max(TVE) in phase B current for PMU1, PMU2 in phase A and + current sequence, and PMU3 in phase B current is 0.7002, 0.572, and 0.09535%. FE is fully inside RoCoF's bounds.

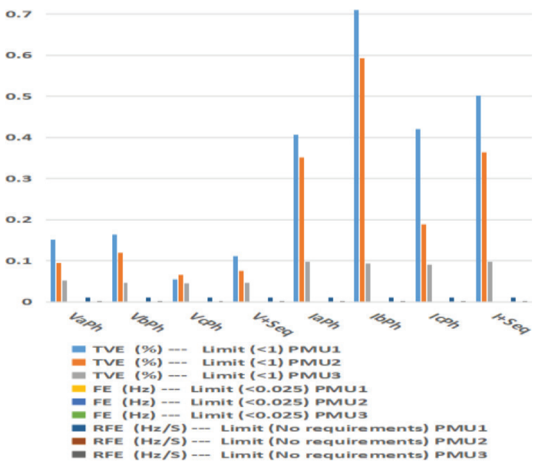

Figure 5. Single Harmonic distortion steady state: 50FPS/M class.

Figure 5 shows the results of all three PMUs and shows that the TVE, FE, and RFE values are within the acceptable ranges and comply with the 50FPS for M class standards. Max(TVE) for PMU1, PMU2, and PMU3 in phase B current is 0.7102, 0.5922, and 0.097%, respectively, in the A phase and + current sequence. FE is fully inside RoCoF's bounds.

The findings of all three PMUs are plotted in Figure 6, and the TVE, FE, and RFE values are within bounds and comply with the 25FPS for P class requirements. Max(TVE) in phase B current for PMU1, PMU2 in phase B current, and PMU3 in phase A current sequence are 0.5352, 0.5988, and 0.09585%, respectively. FE is fully inside RoCoF's bounds.

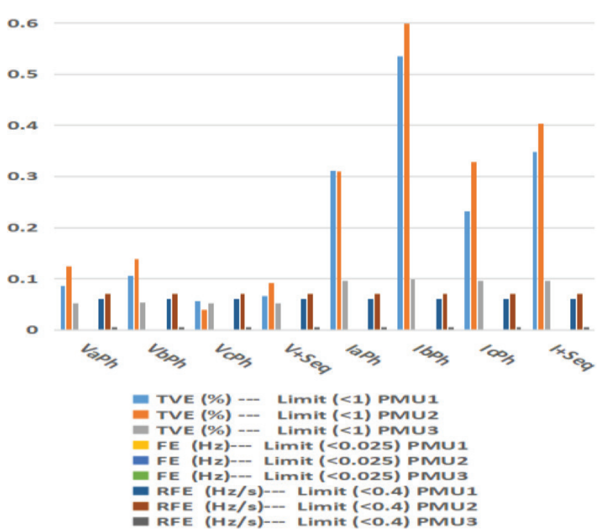

Figure 6. Single Harmonic distortion steady state: 25FPS/P class.

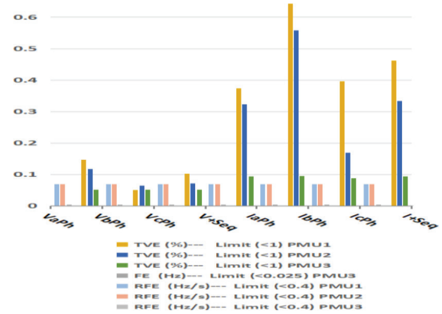

Figure 7. Single Harmonic distortion steady state: 50FPS/P class.

The findings of all three PMUs are in Figure 7, and the TVE, FE, and RFE values are within the acceptable ranges and comply with the 50FPS for P class standards. Max(TVE) in phase B current for PMU1, PMU2 in phase A and + current sequence, and PMU3 in phase B current is 0.6433%, 0.5586%, and 0.09385%. FE is fully inside RoCoF's bounds.

4.2 Out-of-band Interference test (Inter-harmonics)

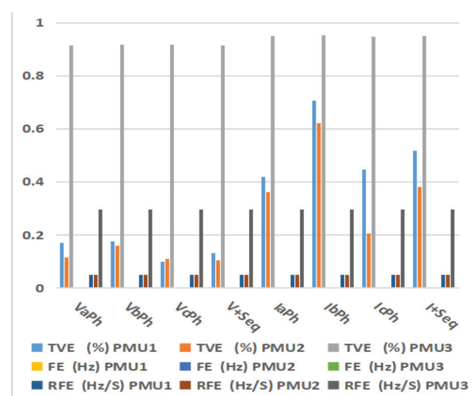

Figure 8. Out-of-band interference test steady state: 25FPS/M class.

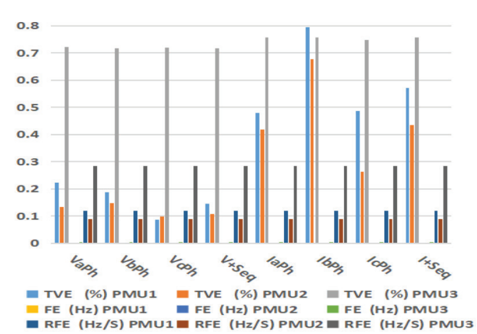

Figure 9. Out-of-band interference test steady state: 50FPS/M class.

During steady-state testing, out-of-band interfering signals that could lead to measurement mistakes are examined. The filtering capacity is evaluated in order to eliminate all interfering frequencies.

The findings of all three PMUs are plotted in Figure 8, and the TVE, FE, and RFE values are within bounds and comply with the 25FPS for M class requirements. Max(TVE) in phase B current is 0.09585% for PMU3, 0.627% for PMU2, and 0.7051% for PMU1. FE is fully inside RoCoF's bounds.

The findings of all three PMUs are tabulated in Figure 9, and the TVE, FE, and RFE values are within bounds and comply with the 50FPS for M class requirements. Max(TVE) in phase B current for PMU1, PMU2 (0.6784%), and PMU3 (0.7577%) in A phase current and + current sequence. FE is fully inside RoCoF's bounds.

5. Conclusion

Large-scale deployments of phasor measurement units are made under the smart grid umbrella for control, protection, and monitoring. It is critical to understand the PMU's features to deliver high-quality data. Applications for PMUs include visibility, situational awareness, smart power system control, protection, and monitoring. How PMUs measure phasors when harmonic impacts appear in contemporary power systems, particularly when large-scale renewable energy integration is linked to the grid. PMU must hold accreditation and adhere to the most recent global standards. This study offers an innovative and distinctive approach to PMU testing that satisfies compliance requirements. Using a high-precision PMU calibrator, PMUs were evaluated under steady-state settings for scenarios involving harmonics and interharmonics. In every instance, every PMU passed. In summary, these PMUs have enough filtering to reduce harmonic interference for both inter harmonics and single harmonic contents.

6. Acknowledgement

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7. References

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