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Published in:
Proceedings of The Seventh Conference on Innovative Smart Grid Technologies 2016

Publication date:
2016

Document Version
Peer reviewed version

Citation (APA):
Ghiga, R., Wu, Q., Martin, K. E., El-Khatib, W. Z., Cheng, L., & Nielsen, A. H. (2016). Steady-State PMU Compliance Test under C37.118.1a-2014. In Proceedings of The Seventh Conference on Innovative Smart Grid Technologies 2016 IEEE.

Steady-State PMU Compliance Test under C37.118.1a™-2014

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***Abstract*—This paper presents a flexible testing method and the steady-state compliance of PMUs under the C37.118.1a amendment. The work is focused on the changes made to the standard for the harmonic rejection and out-of-band interference tests for which the ROCOF Error limits have been suspended. The paper aims to provide an indication whether these limits should be reinstated or not. The test platform consists of a test signal generator capable of providing three phase voltages and currents, and playing back digitized files, PMUs under test, and a PMU test result analysis kit. Three PMUs from different vendors were tested simultaneously in order to provide a fair comparison of the devices. The results for the steady state tests are discussed in the paper together with the strengths and weaknesses of the PMUs and of the test setup.**

I. Introduction

PMUs are considered one of the key technologies for wide area power system protection control and monitoring systems [1]. Therefore, these units are increasingly being developed in order to improve their performance. PMU data can be used for multiple applications. Some of them include oscillation monitoring, fault detection, state estimation and model validation [2]. The reliability of these applications is based on the accuracy of the PMUs for a correct synchrophasor and frequency estimation. In this case, it is essential to understand the technical performance of these devices and to validate the measured data before using them on a larger scale.

Previous work done in the field includes different testing methods such as the one described in [3] which was developed for the compliance testing with the 2005 standard [4]. Steady-state tests according to the 2011 standard have been published before [5].

This paper extends the previous work regarding testing and validation presented in [6] by updating the test platform with the latest requirements presented in the IEEE C37.118.1a amendment. The steady-state tests vary different parameters of the input signals such as voltage and current amplitude, phase and frequency. The filtering capabilities of the units are tested by injecting harmonics and signals that are outside the bandwidth of the PMUs. The phasor estimation of the units is evaluated by the Total Vector Error (TVE). The Frequency Error (FE) shows estimated frequency accuracy of the devices under test. The harmonic and out of band interfering signals tests are modified by the amendment to the standard which suspended the ROCOF Error (RFE) limit for these two tests. The paper shows the impact of these signals on the PMUs measurements, and gives suggestions regarding the limits suspended by the IEEE C37.118.1a amendment.

The paper is organized as follows: Section II provides information regarding the hardware, methodology and the performed tests. Section III presents the results, and finally Section IV concludes the paper, summarizing the contribution of the work.

II. PMU Testing Architecture and Methodology

This section of the paper provides information of the laboratory hardware used for testing the PMUs and describes the methodology.

A. Test Bed Description

To generate the PMU input signals a standard stand alone test set for protection relays is used. It is capable of delivering 3-phase AC voltages and currents that are synchronized to the UTC with a rated time synchronization error of less than $1\mu s$.

The Total Vector Error (TVE) of the PMUs should be calculated within 1% of the nominal signal [7]. In order to achieve such precision, the test equipment should be able to produce signals with an accuracy at least ten times higher than that [8]. This translates into a precision of at least 0.1%. The test set has a rated amplitude precision of 0.02% which is within the required range. The nominal voltage level for these tests is 70 Vrms and the nominal current level is 5 Arms.

A calibration of the test set is carried out in order to verify what is the deviation in voltage amplitude from the theoretical value. For this test a signal file is created in Matlab that generates six amplitudes, including the value considered nominal (100 V peak) further on in the testing. Each of them is kept constant for 30 seconds in order to provide enough time for measurements. Due to space limitation, only the measurements for the nominal amplitude are shown in Table II.

978-1-5090-3358-4/16/$31.00

Four digital voltmeters with specifications shown in Table I are used to read the voltage output of the test set, and their average reading was used as a correction. It can be seen that two of the meters agree closely, while the other two are somewhat different. Due to this, it is hard to tell whether the readings are correct or incorrect. Therefore, uncertainty is defined as the maximum deviation of each meter from the average. The Test Set error (%TS error) is the deviation of the average measured voltage from the output set by the test file. Each TS Error is used as a correction factor for the amplitude of each phase. The standard deviation of the measurement is given by the S.D. and S.D. pu rows in the Table II.

The time synchronization check is carried out with an oscilloscope which is triggered on the 1 PPS signal obtained from a GPS clock receiver. The three phases are checked simultaneously, and a time lag of $142\mu s$ is found which translates into a phase error of 2.556 degrees. The test did not show any phase drift in time. Consequently, the angle of the reference phasor is corrected with 2.556 degrees.

The test set has the capability of playing back digitized files by converting the waveforms into analog signals and amplifying them. Its 16-bit, 10 ksamples/s digital-to-analog converter (DAC) and built-in amplifiers, enable accurate reproduction of the waveforms, including harmonics and interfering frequencies. Multiple devices can be tested simultaneously using the same input signal, providing a fair PMU performance analysis. Details about the methodology of the testing procedure are available in the next subsection.

B. Testing procedure

The test process is based on the generation of waveforms required by the C37.118.1 standard, application to the PMU and comparison of the reported PMU data with the expected result. The idea is simple and robust since a PMU estimates a synchrophasor equivalent for a given AC waveform. By taking a phasor equivalent model and producing the AC waveform that it represents with high accuracy as an electrical signal then injecting it into a PMU, the resulting synchrophasor estimate should match the original phasor model. The overall steps of the process are shown in Fig 1.

Matlab is used to create data points reproducing a specific phasor model designed to test a certain aspect of the PMU measuring capability. The phasor model is converted into the equivalent 3-phase AC signal. A discrete time representation

TABLE I: Voltmeters Used in Calibration Test

Multimeters		Rated accuracy
M1	Agilent U1242B	$\pm 1\% + 5$ (% of reading + No. of Least Significant Digit)
M2	Agilent U1242B	$\pm 1\% + 5$ (% of reading + No. of Least Significant Digit)
M3	Agilent U3606A	$\pm 0.22\% + 0.12\%$ (% of reading + % of range)
M4	Agilent U3606A	$\pm 0.22\% + 0.12\%$ (% of reading + % of range)

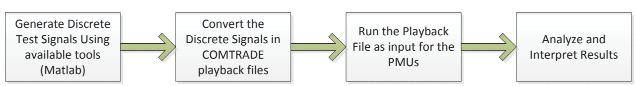

Fig. 1: Overall testing Process

TABLE II: Amplitude Calibration Results

	Phase A	Voltage Phase B	Phase C
% of nominal		100	
V (RMS)		70.7106	
M1	70.6100	70.5900	70.6100
M2	70.6100	70.5900	70.6100
M3	70.7210	70.7090	70.7250
M4	70.7160	70.7010	70.7180
Average	70.6643	70.6417	70.6658
%M1	-0.0767	-0.08139	-0.0788
%M2	-0.0767	-0.08139	-0.0788
%M3	0.0803	0.0870	0.0838
%M4	0.0732	0.0757	0.0739
%Uncertainty	0.0803	0.0870	0.0838
S.D.	0.0626	0.0664	0.0644
S.D. pu	0.00088	0.00094	0.00091
% TS Error	-0.06566	-0.0893	-0.0635

of the test signal is therefore obtained and saved as a .mat file. The .mat file does not generally transfer to a signal generator, it is converted using Matlab to the IEEE C37.111 COMTRADE format since it is widely used for time series recording and is compliant to most vendors.

Once the test data is loaded into the test set it can be played back using a time synchronized start. The output sampling is accurately synchronized, with a rated time error of less than $1\mu s$. The PMU data is recorded during the full duration of the test using a commercially available Phasor Data Concentrator (PDC).

The block diagram of the full testing procedure is shown in Fig 2.

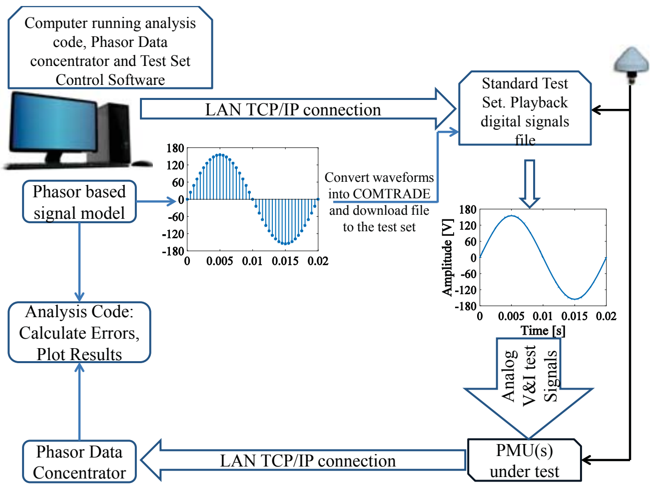

Fig. 2: Block Diagram of the Test Platform

C. Reference Phasor Definition, Measurement Evaluation and Test description

A generalized phasor function can be obtained from a sine function with amplitude and phase modifiers as:

$$X(t) = X_m[g(t)] * cos(\omega_0 t + y(t)) \quad (1)$$

Where X_m is the nominal amplitude, ω_0 is the nominal power system frequency, g(t) is an amplitude modifying function and y(t) is a phase modifying function. The corresponding phasor value is:

$$X(nT) = \{X_m/\sqrt{2}\}\{g(nT)\}\angle\{y(nT)\} \tag{2}$$

Where nT is the reporting instant. The phasor values reported by the PMU should be an estimate of this value for each given instant in time.

Frequency and ROCOF are defined as:

$$f(t) = \frac{1}{2\pi}\frac{d(\omega_0 t + y(t))}{dt} \tag{3}$$

$$ROCOF(t) = \frac{df(t)}{dt} \tag{4}$$

The analysis software uses these equations to build the reference phasor to which the TS Error for amplitude shown in Table II and the phase delay of 2.556 degrees corrections are applied.

The TVE, FE and RFE are defined by C37.118.1 standard and are well known [7]. Thus, the equations will not be presented here again. There are two new quantities defined in the Test Suite Specification document [9]. The magnitude error (ME), which gives information regarding the amplitude error of the measured phasor, and is defined as,

$$ME(\%) = \frac{\sqrt{\hat{X}_r(n)^2 + \hat{X}_i(n)^2} - \sqrt{X_r(n)^2 + X_i(n)^2}}{\sqrt{X_r(n)^2 + X_i(n)^2}} x100\% \tag{5}$$

And the Phase Error (PE) which shows the error in the angle estimation of the phasor, and is defined as,

$$PE(deg) = atan(\hat{X}_r, \hat{X}_i) - atan(X_r, X_i) \tag{6}$$

Where $\hat{X}_r$ and $\hat{X}_i$ are the measured real and imaginary parts of the phasor and X_r and X_i are the real and imaginary parts of the reference phasor.

The implemented steady state tests are shown in the following table:

TABLE III: Steady-state tests description for M-class requirements

Test Name	Varied quantity
Amplitude scan (Ascan)	Voltage 10% - 120% Current 10% - 200%
Phase Scan (Pscan)	Angle $-\pi$ to $+\pi$
Frequency Scan (Fscan)	Frequency 45 - 55 Hz
Harmonic rejection (Harm)	2^{nd} to 50^{th}
Out-of-Band (Band)	10 - 100 Hz interfering frequencies

III. Test Results

This section presents the results for steady-state compliance tests listed in Table III for the M-performance class and a PMU reporting rate of 50 samples/s. Each time a parameter is varied, the three PMUs are allowed to settle and enough time is given in order to record at least 200 data points. The transient interval is removed from the analysis and the evaluation is carried out on all data points of the settled measurements. The TVE, FE, and RFE shown in this section represent the maximum value of the analysis interval. The limits are shown on the plots with a red line at the values defined by standard [7] and amendment [10] for the specific test.

1) Amplitude Scan Test: The test varies the amplitude of the three phase voltages and currents input according to Table III. All PMUs show high TVE values when the amplitude of the input signal is 0.1 p.u. This is caused by the amplitude of the measured phasor rather than its angle as shown in Fig. 3b and Fig. 3c.

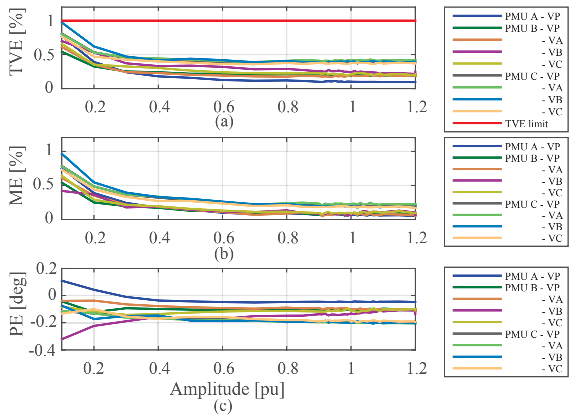

Fig. 3: Amplitude Scan Voltage: a) Total Vector Error; b) Magnitude Error (measured-reference); c) Phase Error (measured-reference)

The test reveals differences for current measurements. Fig. 4a shows that PMU A is the most accurate at rated current value. However, it exceeds the limit for current amplitudes below 0.3 p.u. Fig. 4c shows that PMU A is reporting an incorrect phase angle for low input currents. One possible explanation is the design of the current transformers in PMU A which cannot accurately measure low amplitude currents.

A curious case is PMU C. Phase B current measurement exceeds TVE and the reason is incorrect angle estimation shown in Fig. 4b. However, the other two phases are within limits. This is surprising since all three phases should have similar current transformers and the phasor estimation algorithm should be the same. In contrast, Phase A shows high magnitude error and low phase error, Fig. 4b and Fig. 4c.

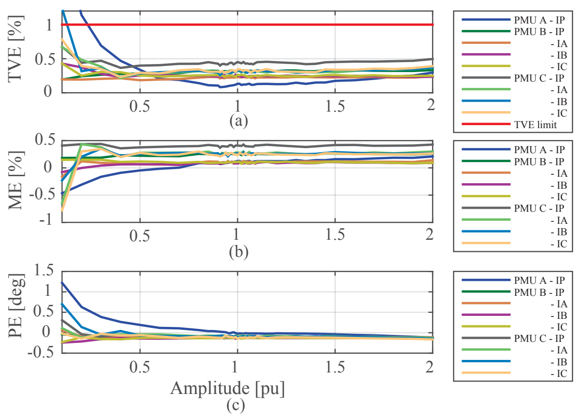

Fig. 4: Amplitude Scan Current: a) Total Vector Error; b) Magnitude Error (measured-reference); c) Phase Error (measured-reference)

2) Phase Scan Test: The test uses an input signal with an off-nominal frequency. This way the PMU is reporting a changing angle. The C37.118.1 standard recommends as frequency offset $|f_{in} - f_0| < 0.25Hz$. For this test, the chosen offset is 0.12Hz. The accuracy of the voltage and current measurements is well within the limit for all PMUs as shown in Fig. 5.

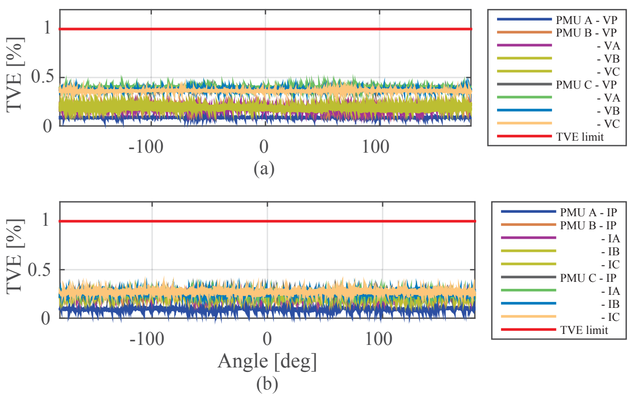

Fig. 5: Phase Scan Total Vector Error a) Voltage; b) Current

3) Frequency Scan Test: The test varies the input signal frequency from 45 Hz up to 55 Hz for both voltages and currents with a step increase of 0.1 Hz. Fig 6a shows that PMU B exceeds the TVE limit at 45 Hz. This is due to incorrect amplitude estimation seen in Fig. 6b. The vendor specifies that the limit of the off-nominal frequency that this device can handle is 45 Hz. Therefore, one possible explanation is that at exactly this frequency, the PMU does not have the bandwidth to measure correctly. PMU C exceeds the TVE limit when the signal frequency is 55 Hz. This can be explained by the higher phase error this PMU has at 55 Hz compared to the others as shown in Fig. 6c.

A frequency-phase bias can be seen for all PMUs in both voltages and current measurements in Fig. 6c and Fig. 7c. One reason could be that the test set has a frequency phase bias caused by the reconstruction filters. It can be noticed that the slopes by which the angles vary are different for each PMU. This would suggest that the estimation algorithms of the devices also have some kind of frequency phase bias since the input waveforms are the same for all three PMUs. It is difficult to point out the real reason without extended testing.

The frequency error is within limits for all devices as shown in Fig. 8a. Concerning ROCOF Error, PMU B exceeds the limit at exactly 45 Hz, similar to the TVE results probably because of the above mentioned reason.

4) Harmonic rejection Test: This test shows if the accuracy of the PMUs is decreased when measuring signals containing harmonics. Harmonics from second up to 50th are injected one by one into the input signal. The reference signal is kept at constant amplitude and frequency.

Fig. 9 shows that all PMUs estimate the voltage and current phasors with the required accuracy. In case of PMU C, the 19th

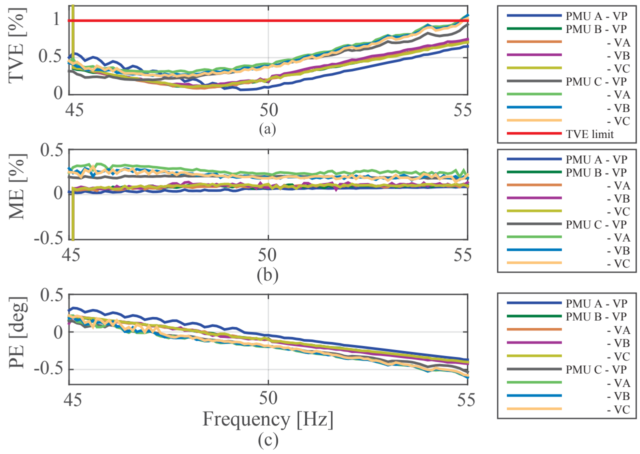

Fig. 6: Frequency Scan Voltage: a) Total Vector Error; b) Magnitude Error (measured-reference); c) Phase Error (measured-reference)

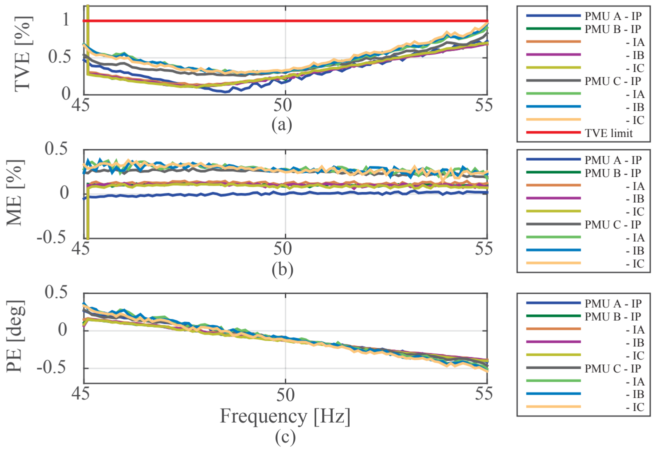

Fig. 7: Frequency Scan Current: a) Total Vector Error; b) Magnitude Error (measured-reference); c) Phase Error (measured-reference)

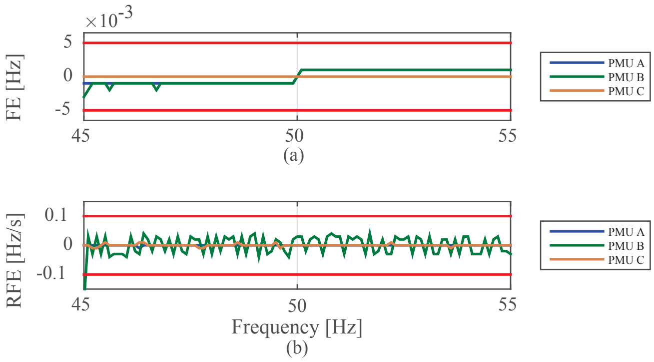

Fig. 8: Frequency Scan: a) Frequency Error; b) ROCOF Error

harmonic seems to have a large impact increasing the TVE to 0.9%. Although not shown here due to space limitations, the 19th harmonics affects both phasor amplitude and angle.

Unfortunately a reason for this is not obvious, and lack of knowledge about the PMU's algorithms makes it difficult to provide an explanation.

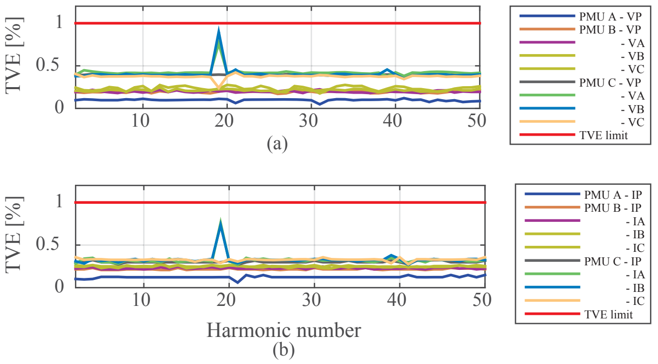

Fig. 9: Harmonic rejection Test: a) Voltage TVE; b) Current TVE

Frequency and ROCOF errors are well within the limits for all devices. The amendment C37.118.1a-2014 [10] suspends the limit for the RFE. However, based on the results shown in Fig. 10b, it seems that the PMUs are capable of delivering good ROCOF estimations when facing signals with harmonics. The authors' opinion, based on shown results, is that the RFE limit could be revised and reinstated.

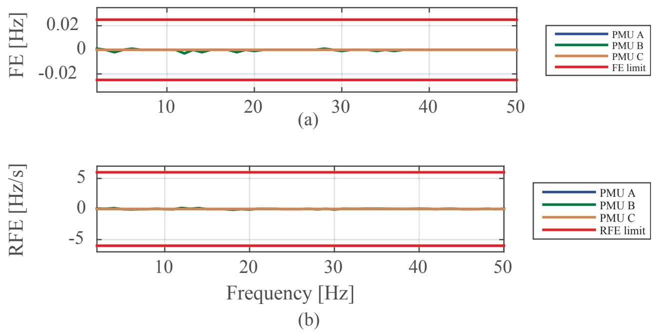

Fig. 10: Harmonic rejection Test: a) Frequency Error; b) ROCOF Error

5) Out-of-Band Test: This test is designed to inject into the PMUs a single frequency sinusoid added to the fundamental. The interfering frequency is varied over a range of 10 Hz to 100 Hz in steps of 1 Hz, and the PMUs should completely filter the interfering signals.

In order to test the filtering when the frequency is off nominal, the standard [7] requires to be varied by $\pm 5\%$ of the reporting rate which gives 47.5 Hz and 52.5 Hz for 50 samples per second. Due to space limitations, only the results for voltage TVE, FE, and RFE at 47.5 and 50 Hz will be shown in this paper. The Nyquist Cutoff is shown on the plots by the orange vertical lines. Frequencies inside the passband are excluded from the analysis.

Fig. 11 shows a clear difference between the tested devices. PMU A is particularly sensitive to the interfering signals which have a high influence on the angle measurement of the device as seen in Fig. 11c. PMUs B and C both show a good angle estimation, while the magnitude error of PMU C is higher than the others, Fig. 11b.

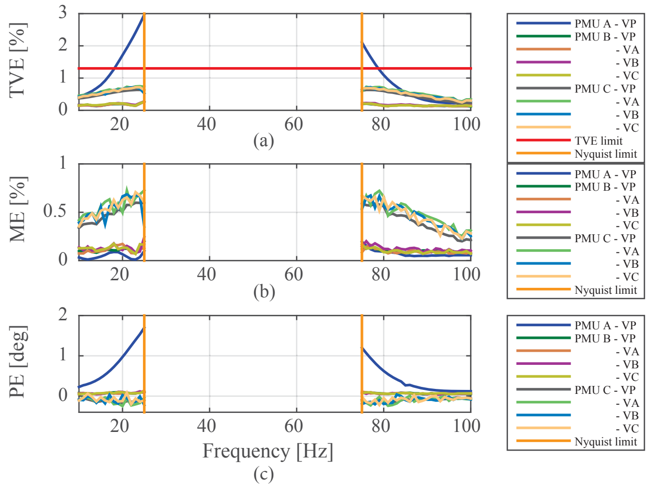

Fig. 11: Out-of-Band Test - Voltage; signal frequency 47.5 Hz: a) Total Vector Error; b) Magnitude Error (measured-reference); c) Phase Error (measured-reference)

Fig. 12 shows there is a change in the performance of the PMUs when the fundamental signal frequency is 50 Hz. The phase error of PMU A is now negative and somewhat lower. However, the TVE still exceeds the limit. Fig. 12b shows that PMU C has noticeable differences between the magnitude error of its phases. The calculated magnitude error for phase A is around 0.2% while for phase B is reaches 0.6%. It would have been expected for all phases of a PMU to show similar results, however it seems this is not always the case.

Fig. 13 shows the frequency error limit is exceeded by all PMUs. This is expected considering the mathematical relationship between frequency and phase angle, which is affected by the interfering signals. The error is further amplified when the ROCOF is calculated as the time derivative of the frequency. Therefore, it is expected to see high values for RFE as shown in Fig. 14. The amendment has suspended the RFE limit, however, it is shown in Fig. 14 in order to provide a comparison with the targeted value.

IV. Conclusion

This paper reviewed the steady-state compliance of three commercial PMUs under the C37.118.1a amendment. The evaluation method is simple and robust, and the equipment is off the shelf which makes it widely available. The analysis software is written entirely in Matlab and can be easily modified to accommodate future changes. A calibration check of the test set output is performed and correction factors are calculated for amplitude and angle which are then applied to the reference phasor in order to match the theoretical value to the ones injected into the PMUs.

The paper offers a view on the limits suspended by the amendment to the standard. The results indicate that the PMUs

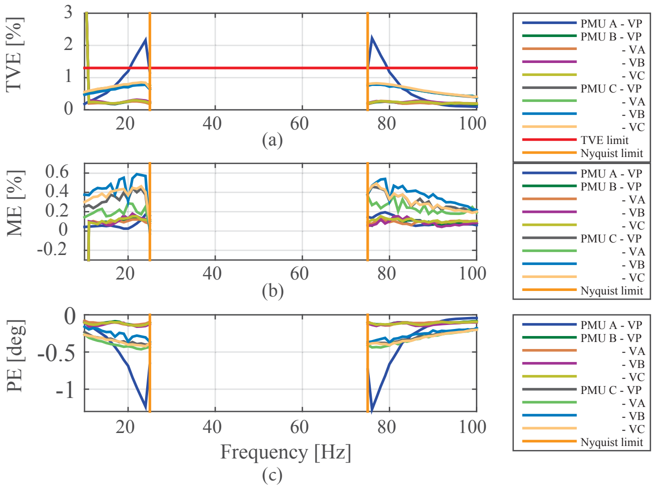

Fig. 12: Out-of-Band Test - Voltage; signal frequency 50 Hz: a) Total Vector Error; b) Magnitude Error (measured-reference); c) Phase Error (measured-reference)

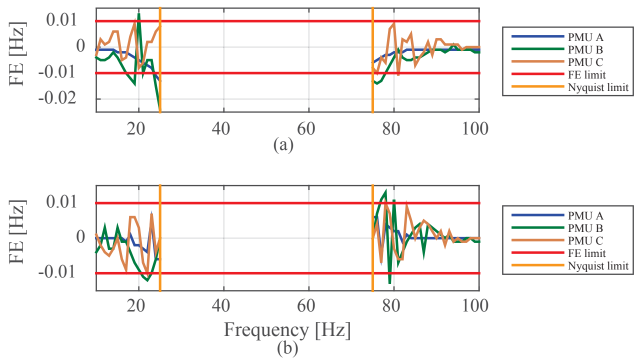

Fig. 13: Out-of-Band Test - Frequency Error: a) signal frequency 47.5 Hz; b) signal frequency 50 Hz

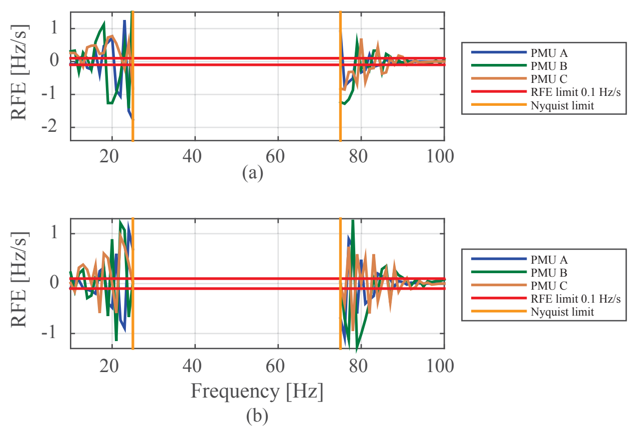

Fig. 14: Out-of-Band Test - ROCOF Error: a) signal frequency 47.5 Hz; b) signal frequency 50 Hz

are capable of estimating ROCOF within the standard limit in which case the requirements for harmonic rejection RFE could be reinstated. Still, better filtering is needed before ROCOF measurements under out-of-band interference can comply to the standard limit. For now the limit is suspended to allow qualification of such PMUs.

Concerning the hardware setup, the frequency scan test revealed a frequency phase bias. This should be investigated further to discover the real cause. A possible explanation is that the standard relay test set is causing this due to its reconstruction filters which probably do not have constant phase delay in the pass-band. If this proves to be true, either a hardware or software solution should be implemented.

Acknowledgment

The authors would like to thank the Nordic Energy Research (Norden) which supports the Smart transmission grid operation and control (StronGrid) project and made this research possible.

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