Evaluation of Steady-State and Dynamic Performance of a Synchronized Phasor Measurement Unit

Dinesh Rangana Gurusinghe, *Graduate Student Member, IEEE,* Athula D. Rajapakse, *Senior Member, IEEE,* and Krish Narendra, *Senior Member, IEEE*

***Abstract*—It is critically important to understand steady-state and dynamic performance of phasor measurement units (PMUs) to ensure reliable and secure operation of the synchrophasor based wide area monitoring, control, and protection systems. The recently published IEEE Standard C37.118.1 provides necessary guidelines to characterize both steady-state and dynamic performance of a PMU. This paper presents a performance evaluation methodology according to the IEEE Standard C37.118.1 and discusses the practical issues in the test environment. Results of the steady-state and dynamic responses tests on an actual PMU are also presented.**

The PMU performance evaluation approach of this paper is simple, repeatable, and can be performed at any facility with commonly available standard signal playback equipment. The method is based upon using test signals that are mathematically generated from a signal model and play backed into the PMU with precise global position system (GPS) synchronization.

***Index Terms*—Discrete Fourier transform, finite impulse response, global position system (GPS), phasor measurement unit (PMU), playback device, step response, total vector error (TVE).**

I. Introduction

A synchronized phasor measurement or synchrophasor is a phasor value (magnitude and phase angle) obtained from a voltage or a current waveform, precisely referenced to a common time frame. Phasor measurement unit (PMU) is a device, which can extract phasor values as well as the frequency and the rate of change of frequency (ROCOF) of the measured waveform [1]. PMU can be a stand-alone unit or a functional unit within another physical unit such as a protection relay or power system data recorder.

PMUs have many potential applications in power system monitoring, protection, operation and control including improved state estimation, frequency estimation, instability prediction, adaptive relaying, and wide area protection and control (WAPAC) [2]. Different applications of PMUs can be classified into two main categories namely online (real time) applications and offline applications. The online applications require faster data transfer rates that depend on the particular application. For example, voltage stability is a slower phenomenon and thus the monitoring voltage stability can be achieved with a slower data rate while an application such as frequency stability control, where a faster response is expected requires faster data transfer rate [3]. In contrast, the speed of data transfer over communication channels is less critical in the case of the offline applications.

Most power utilities install PMUs at the important substations, targeting various aspects of power grid including steady-state and dynamic applications [4]. They use dedicated communications to send the data to their load dispatch center (LDC) in real time. A phasor data concentrator (PDC) at the LDC collects the data from different PMUs, time align them, and send the data to local applications and archives. These systems may be further linked to other power utilities to provide a wide area view of the power system [5]. Data reporting rates for these online applications range from 10 to 60 frames per second (fps) [6].

Applications of PMU demand high accuracy and consistency in both steady-state and dynamic performance to ensure PMU accurately reflects system behavior. With growing PMU vendors, it is very important to establish the interoperability between different PMUs as different vendors typically use different algorithms [7]. Thus, PMU performance evaluation plays a vital role. The recently published IEEE Standard C37.118.1 [6] provides necessary guidelines to assure both steady-state and dynamic characterization of phasor measurements. It defines two classes of performances namely, P class and M class. P class is preferred for applications requiring fast response while M class is intended for applications demanding greater precision. Synchrophasor tests performed and discussed in this paper are to determine the PMU performance and confirm its accuracy under a variety of conditions that are specified in [6]. Signal frequency, magnitude, phase angle, harmonic distortion and out-of-band interference tests are performed to evaluate steady-state performances while measurement bandwidth, linear system frequency ramp and step response assessments are executed to assess dynamic compliances. The practical issues in test environment are also discussed with each test case, including remedial actions. Test cases were defined to satisfy requirements of both P class and M class.

This paper is organized as follows. In Section II, basic concept of phasor measurement technology is stated. The phasor measurement setup of the paper is discussed in Section III. Section IV is devoted to analysis of results. It assesses different PMU test cases with practical issues. Finally, in Section V, the main contributions of this paper are highlighted.

D. R. Gurusinghe and A. D. Rajapakse are with the Dept. of Electrical and Computer Engineering, University of Manitoba, Winnipeg, MB, R3T5V6, Canada (e-mail: umgurusi@cc.umanitoba.ca; rajapaks@cc.umanitoba.ca).

K. Narendra is with ERLPhase Power Technologies Ltd, Winnipeg, MB, R3Y1G4, Canada (e-mail: knarendra@erlphase.com).

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II. Phasor Measurement Technology

A phasor is an equivalent representation of a pure sinusoidal waveform, which is fully characterized by magnitude, phase angle, and frequency. For a given frequency, representation only requires magnitude and phase angle, that can be represented by a complex number as shown in Fig. 1.

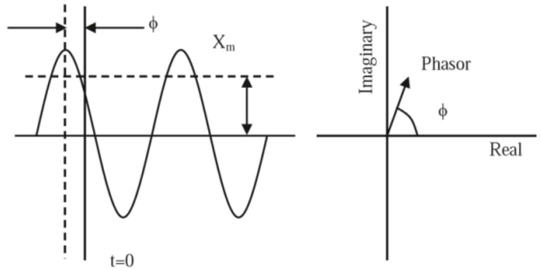

Fig. 1. Sinusoidal waveform with equivalent phasor representation on the complex plane

The sinusoidal waveform can be written as,

$$x(t) = X_m \cos(\omega t + \phi) = X_m \cos(2\pi f t + \phi) \qquad (1)$$

The corresponding phasor can be represented in (2).

$$X(t) = \frac{X_m}{\sqrt{2}} e^{j\phi} = \frac{X_m}{\sqrt{2}}(\cos\phi + j\sin\phi) = \frac{X_m}{\sqrt{2}} \angle \phi \qquad (2)$$

In the general case, where both the amplitude, $X_m(t)$ and the sinusoidal frequency, $f(t)$ are functions of time, the sinusoid can be written as,

$$x(t) = X_m(t)\cos\left(2\pi \int f(t)dt + \phi\right) \qquad (3)$$

$$f(t) = f_0 + \Delta f(t) \qquad (4)$$

where f_0 is the nominal angular system frequency (60 Hz) and $\Delta f(t)$ is an offset from the nominal frequency. The modified sinusoid can be written as,

$$x(t) = X_m(t)\cos[2\pi f_0 t + \{2\pi\Delta f(t)t + \phi\}] \qquad (5)$$

Thus, the general phasor can be simply represented as,

$$X(t) = \frac{X_m(t)}{\sqrt{2}} e^{j\{2\pi\Delta f(t)t+\phi\}} = \frac{X_m(t)}{\sqrt{2}} \angle\{2\pi\Delta f(t)t + \phi\} \qquad (6)$$

$X_m(t)$, $\Delta f(t)$ and ϕ can be replaced with suitable mathematical functions so that different steady-state and dynamic test cases can be generated.

PMUs use complex mathematical algorithms to estimate phasor and system frequency from data samples. Typically, the input signal passes through a traditional anti-aliasing low-pass filter followed by an analogue to digital (A/D) converter, where the signal is sampled at fixed frequency. The discrete Fourier transform is applied for sampled data to extract phasor estimates. The system frequency estimate methods vary from vendor to vendor, where zero-crossing and rate of change of phasor angle approaches are popular. In [6], it is proposed to apply weighted average of last four phasor angles to determine the system frequency. Use of different algorithms can result in phasor and frequency values that differ from the expected response for a particular condition. Thus, it is necessary to assess performances from different PMU vendors under the same test conditions to evaluate their steady-state and dynamic performances.

III. PMU Test Setup

The tests are performed with a real time playback device using recorded common format for transient data exchange (COMTRADE) files [8] of precisely generated test signals from mathematical equations. The test setup provides input signals at a level and format suitable for input to a PMU that accurately reproduces the COMTRADE signals in both signal amplitude and timing. The recorded signals include both voltage and current waveforms and they are fed to the PMU, which calculates magnitude, phase angle and frequency measurements. The operational flowchart of test setup is shown in Fig. 2. The test setup basically consists of:

- A COMTRADE generator that precisely produces voltage and current playback files with signals from mathematical equations.
- A real time playback device that supplies real voltage and current signals at their appropriate levels (69 V voltage and 5 A current inputs).
- A global position system (GPS) receiver that generates the time synchronization signal employed to time stamp measured values. The GPS receiver chosen for the investigations supports a pulse-per-second (PPS) signal. The signal playback unit is also synchronized to GPS and the playing back of a signal file is started exactly at a specified time. The analog test signals generated by the playback unit are thus referenced to a known time.
- Instrument transformers inside the PMU converts the generated test voltages and currents into low level signals that are within the range of its internal A/D converter.
- The digitized signals are used to extract magnitude, phase angle and frequency measurements using discrete Fourier transform (DFT).

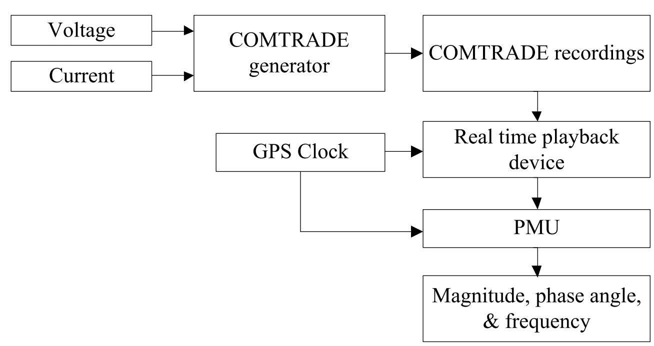

Fig. 2. Operational flowchart of test setup

The PMU calculated measurements are evaluated against the actual test signals generated from the mathematical equations, which were already used to produce COMTRADE files. Total vector error (TVE) and frequency error (FE) are determined according to (7) and (8) respectively as per [6].

$$TVE(n) = \sqrt{\frac{x_a(n) - x_m(n)}{x_a(n)}} = \frac{|x_a(n) - x_m(n)|}{|x_a(n)|} \qquad (7)$$

where $x_a(n)$ is actual synchrophasor and $x_m(n)$ is measured synchrophasor.

$$FE(n) = |f_a(n) - f_m(n)| \qquad (8)$$

where $f_a(n)$ is actual frequency and $f_m(n)$ is measured frequency. As the PMU measurements are compared with mathematical equations, errors include both measurement and operational errors of COMTRADE file, playback device amplifier, GPS receiver, and so on. COMTRADE file error occurs due to conversion of analogue into integer values and it can be minimized by selecting a scale with proper precision and suitable time step. Therefore, 16-bit A/D precision and 50 μs time step is used in the tests reported in this paper. Playback device amplifier precision is set accordingly. The accuracy of the GPS receiver used is ±1 μs (a ±26 μs timing error causes 1 % TVE in 60 Hz system). The influence of these errors can be minimized by properly calibrating the instrumentation using the known voltage and/or current waveforms. It is important to calibrate both magnitudes and time delays.

IV. Results and Discussion

Performance tests need to be performed over the entire ranges of interest and include a range of operating conditions. The M class operating range is considered in this paper as the P class range is always a subset of the M class range. Test results illustrate performances of the highest reporting rate of 60 fps. It is experienced that if a PMU satisfies performances at the highest reporting rate it also fulfills demand at lower reporting rates. However, it is necessary to evaluate PMU performances at each reporting rate according to [6].

Steady-state tests confirm measurement in constant conditions where magnitude, phase angle and frequency of test signal, and all other influence quantities are fixed for the period of measurement. They include signal frequency, magnitude, phase angle, harmonic distortion and out-of-band interference tests. Each steady-state test continues over 5 seconds of test duration. Maximum TVE and FE are compared with specified values in [6] so as to verify whether a PMU satisfies the guidelines required.

A. Steady-state Signal Frequency

As discussed in section II steady-state signal can be represented from (1). Under the signal frequency test, the frequency, f is varied from 55 Hz to 65 Hz with a step resolution of 1 Hz while all other quantities are kept constant. The maximum, minimum and mean values of percentage TVE are shown in Fig. 3.

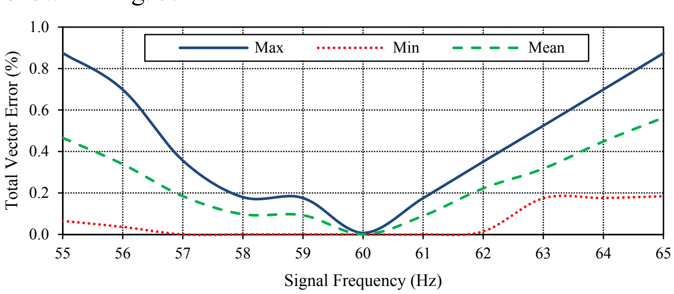

Fig. 3. Steady-state signal frequency response at 60 fps

It is important to note that the phasor rotates with time as the signal frequency deviates from the nominal frequency. This phasor rotation should be taken into account when determining TVE as per (6); otherwise calculations may show abnormal TVE values. Frequency of the signal is measured in each case and FEs are determined. The PMU satisfies signal frequency TVE compliance as the maximum TVE is less than 1% for frequencies between 55 Hz to 65 Hz.

B. Steady-state Signal Magnitude : Voltage

The per unit (pu) magnitude of voltage signal, X_m in (1) is varied from 0.1 to 1.2 with a step resolution of 0.1 pu while all other quantities are kept constant. The maximum, minimum and mean values of percentage TVE are shown in Fig. 4. The PMU satisfies voltage signal magnitude TVE compliance as the maximum TVE is less than 1% for magnitudes between 0.1 pu to 1.2 pu.

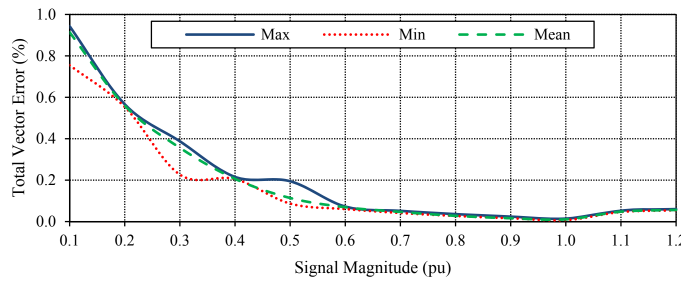

Fig. 4. Steady-state signal magnitude response for voltage at 60 fps

C. Steady-state Signal Magnitude : Current

The pu magnitude of current signal, X_m in (1) is varied from 0.1 to 2.0 with a step resolution of 0.2 pu while all other quantities are kept constant. The maximum, minimum and mean values of percentage TVE are shown in Fig. 5. The PMU satisfies current signal magnitude TVE compliance as the maximum TVE is less than 1% for magnitudes between 0.1 pu to 2.0 pu.

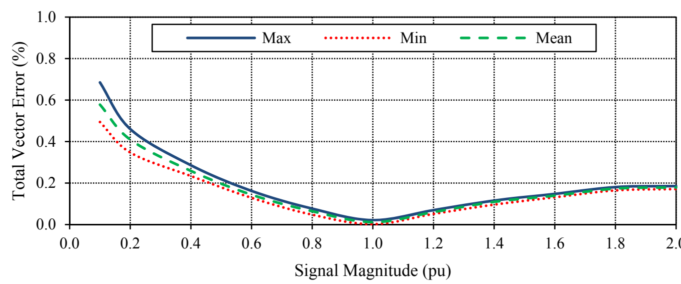

Fig. 5. Steady-state signal magnitude response for current at 60 fps

D. Steady-state Phase Angle

The phase angle, ϕ in (1) is varied from $-\pi$ to $+\pi$ radians with a step resolution of $\pi/6$ radians while all other quantities are kept constant. The maximum, minimum and mean values of percentage TVE are shown in Fig. 6. The PMU satisfies phase angle TVE compliance as the maximum TVE is less than 1% for phase angles between $-\pi$ to $+\pi$ radians.

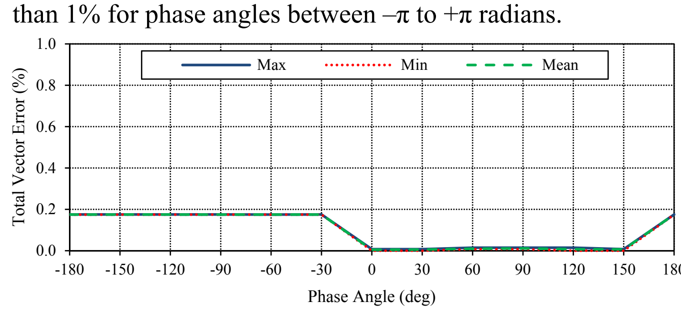

Fig. 6. Steady-state phase angle response at 60 fps

E. Steady-state Harmonic Distortion

A 10% harmonic is introduced into the test signal where (1) is modified with (9).

$$x(t) = X_m\{\cos(2\pi f_0 t + \phi) + 0.1\cos(2a\pi f_0 t + \phi_1)\} \quad (9)$$

The harmonic number, *a* is varied from 2 to 50 (integer values only) while all other quantities are kept constant. The harmonic component can either be in phase or out of phase with the fundamental component. The harmonic component is ignored when determining TVE where only the fundamental component is used for calculations. The maximum, minimum and mean values of percentage TVE are shown in Fig. 7. Frequency of the signal is measured in each case and FEs are determined. The PMU satisfy harmonic distortion TVE compliance as the maximum TVE is less than 1 % for a 10% harmonic for signals between the second and the fiftieth harmonic.

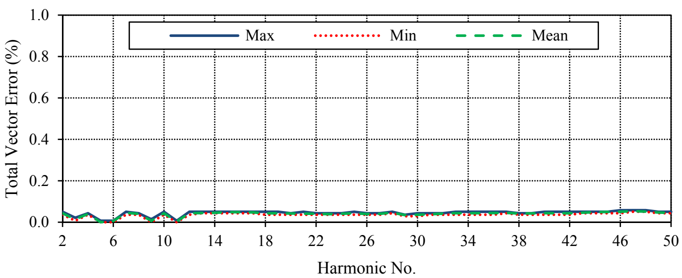

Fig. 7. Steady-state 10% harmonic distortion response at 60 fps

F. Steady-state Out-of-Band Interference

A 10% out-of-band interference is introduced into the test signal where (1) is modified with (10).

$$x(t) = X_m\{\cos(2\pi f_0 t + \phi) + 0.1\cos(2\pi f_{ob} t + \phi)\} \quad (10)$$

The frequency of an interference signal, f_{ob} is varied from 10 Hz to 120 Hz (second harmonic) while all other quantities are kept constant. The interference signal should be in phase with the fundamental component. For a 60 fps reporting rate the frequency band requirement is from 30 Hz to 90 Hz. The test frequencies are 10 Hz to 30 Hz and 90 Hz to 120 Hz. The interference component is ignored when determining TVE where only the fundamental component is used for calculations. The maximum, minimum and mean values of percentage TVE are shown in Fig. 8. Frequency of the signal is measured in each case and FEs are determined. The PMU does not satisfy out of band interference TVE compliance as the maximum TVE is greater than 1.3 % for a 10% out of band interference signal.

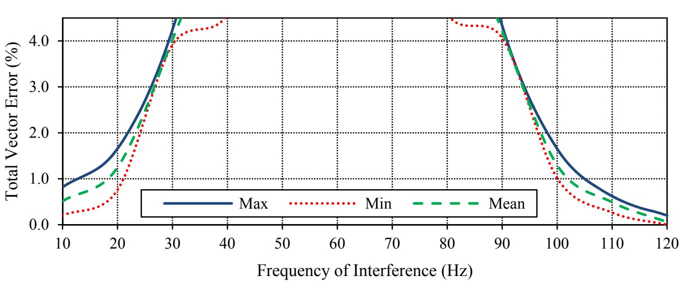

Fig. 8. Steady-state 10% out of band interference response at 60 fps

It is noted that FE compliance is not a part of magnitude and phase angle test. Further, the out-of-band interference test does require for P class. The steady-state TVE and FE results of the PMU are summarized in Table I. The PMU satisfies both P class and M class TVE compliance of steady-state except out-of-band interference.

TABLE I
SUMMARY OF STEADY-STATE TVE AND FE RESULTS

Influence quantity	Reference condition	Range	Max TVE (%)	Max FE (Hz)
Signal frequency	60 Hz	± 5.0 Hz	0.88	0.017
Signal magnitude voltage	69 V	10% to 120% rated	0.94	N/A
Signal magnitude current	5 A	10% to 200% rated	0.68	N/A
Phase angle	constant	± π radians	0.18	N/A
Harmonic distortion	<0.2 % (THD)	10% any harmhonic upto 50^{th}	0.06	0.001
Out-of-band interfering signal	<0.2 % of input signal magnitude	10% of input signal magnitude	7.34	0.547

Dynamic compliances include measurement bandwidth, linear system frequency ramp and step response assessments.

G. Measurement Bandwidth

Test signals for measurement bandwidth are primarily 60 Hz waveforms that are amplitude or/and phase angle modulated with a sine wave. They could, however, be any kind of signal modulation or other combination that could be input to a PMU to determine a specific type of response characteristic. Modulation level is kept at 10% while modulation frequency is varied over a range that will demonstrate the PMU response characteristics. The tests at each modulation frequency step continue for at least two full cycles of modulation. The input test signal is represented in (11) as,

$$x(t) = X_m\{1 + k_x\cos(2\pi f_m t)\}.\cos\{2\pi f_0 t + k_a\cos(2\pi f_m t - \pi)\} \quad (11)$$

The magnitude modulation level, k_x and phase angle modulation level, k_a are kept for 10% while the modulation frequency f_m is varied from 0.1 to 5 Hz. The maximum, minimum and mean values of percentage TVE are shown in Fig. 9. Frequency of the signal is measured in each case and FEs are determined.

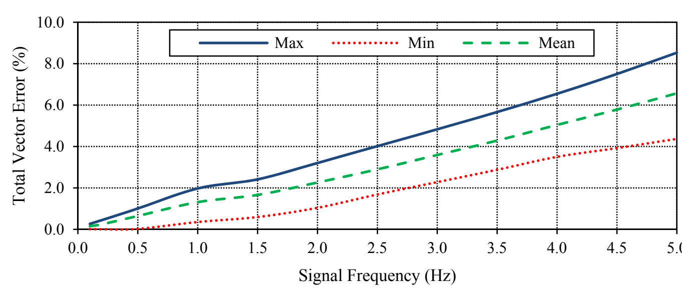

Fig. 9. Magnitude and phase angle modulation response at 60 fps

It is necessary to repeat the same test with only the phase angle modulated signal where k_x = 0 and k_a = 0.1. It is important to allow an adequate settling time to prevent parameter change transient effects from distorting the measurement. The PMU satisfies measurement bandwidth TVE compliance up to modulation frequency of 2 Hz as maximum TVE is less than 3% but it does not comply TVE requirement beyond the modulation frequency of 2 Hz. Thus, the PMU satisfies P class compliance but violates M class compliance.

H. Ramp of System Frequency

The input signal frequency is linearly ramped to test performances during power system frequency changes. The input test signal is represented in (12) as,

$$x(t) = X_m \cos\left(2\pi f_0 t + \pi R_f t^2\right) \tag{12}$$

The signal frequency ramp rate, R_f is varied from negative ramp (−1.0 Hz/s) to positive ramp (+1.0 Hz/s) while the ramp range is from 55 Hz to 65 Hz. The maximum, minimum and mean values of percentage TVE are shown in Fig. 10.

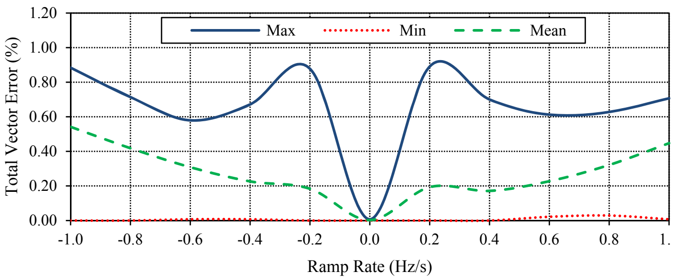

Fig. 10. Linear frequency ramp response at 60 fps

Frequency of the signal is measured in each case and FEs are determined. It is important to exclude measurements during the first two reporting intervals before and after a change in the frequency ramp. For example, period of 33 ms before and after a transition should be discarded in the reporting rate of 60 fps. The PMU satisfies frequency ramp TVE compliance of both P class and M class as the maximum TVE is less than 1 % for ramp rate between −1.0 Hz/s to +1.0 Hz/s while the ramp range is from 55 Hz to 65 Hz. The measurement bandwidth and ramp of system frequency results are summarized in Table II.

TABLE II
SUMMARY OF MEASUREMENT BANDWIDTH AND LINEAR FREQUENCY RAMP TVE AND FE RESULTS

Influence quantity	Reference condition	Range	Max TVE (%)	Max FE (Hz)
Measurement bandwidth $k_x = 0.1$, $k_a = 0.1$ radian	69 V, 60 Hz at start	Mod. Freq 0.1 to 5 Hz	8.53	0.433
Linear frequency ramp Ramp rate of ± 1.0 Hz/s	69 V, 60 Hz at start	± 5.0 Hz/s	0.89	0.058

I. Step Response

Step responses provide a simple and easily observed method of comparing the PMU response to a sudden input change. They also emulate what may be observed during load switching and faults. Step responses include magnitude and phase angle steps. Steps include positive and negative steps of 10% magnitude and 10% phase angle. The step is initiated by a signal at a precise time, which allows determining the response time, delay time and maximum overshoot/undershoot. As PMU response time and delay time are small compared to the PMU reporting interval it is difficult to characterize the response of a single step. Therefore, the equivalent sampling approach explained in [5], [6] should be used to achieve the required measurement resolution.

A unit step function $u(t)$ is applied to the input signal magnitude and phase angle and it is represented in (13) as,

$$x(t) = X_m\{1 + k_m u(t)\}.\cos\{2\pi f_0 t + k_a u(t)\} \tag{13}$$

The magnitude step size, k_m and the phase angle step size, k_a are taken as −0.1 and +0.1 for negative and positive steps respectively. Fig. 11 represents magnitude positive step waveforms of input test signal, actual and measured magnitude response, and TVE response in the same timeline. Phase angle positive step response waveforms of input test signal, actual and measured phase angle response, and TVE response are illustrated in Fig. 12.

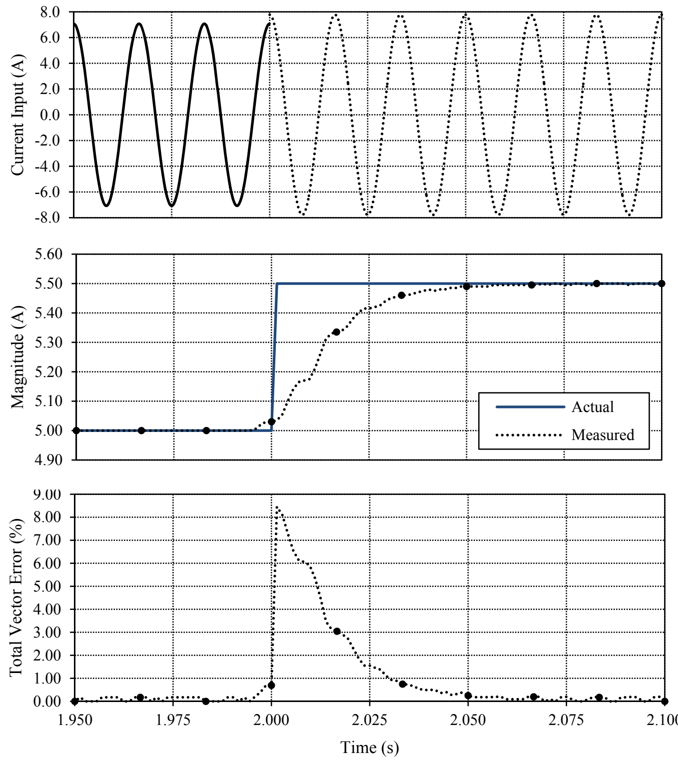

Fig. 11. Waveforms of magnitude positive step response at 60 fps

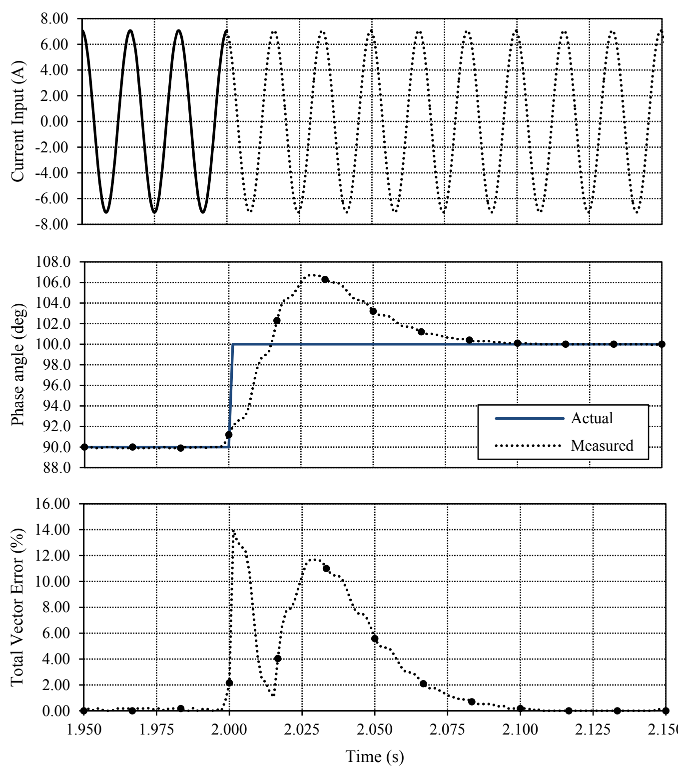

Fig. 12. Waveforms of phase angle positive step response at 60 fps

Reported values of a single step are represented by the dots on the continuous response curve, which is obtained by the equivalent time sampling approach. In magnitude step, the PMU fails to comply P class TVE demand as response time exceeds $1.7/f_0$ (0.028) seconds but it complies M class as the response time is less than 0.079 seconds. Furthermore, maximum overshoots/undershoots of the PMU is zero but the delay time is higher than 0.004 seconds at 60 fps reporting rate.

In phase angle step, the PMU fails to comply both P class and M class TVE demand as response time of TVE exceeds P class requirement of $1.7/f_0$ (0.028) seconds and M class requirement of 0.079 seconds. Furthermore, maximum overshoots/undershoots of the PMU exceeds 10 % of step magnitude and the delay time is also higher than 0.004 seconds at 60 fps reporting rate. Table III is summarized step performances of the actual PMU.

TABLE III
STEP CHANGE PERFORMANCE OF ACTUAL PMU

Step change	Reference condition	Response time (sec.)	|Delay time| (sec.)	Max overshoot / undershoot (% of step)	Frequency Response time (sec.)
$k_x = -0.1$ $k_a = 0$	$5 \angle 90^0$ A at start	0.032	0.013	0.0	0.047
$k_x = +0.1$ $k_a = 0$	$5 \angle 90^0$ A at start	0.031	0.012	0.0	0.047
$k_x = 0$, $k_a = -\pi/18$	$5 \angle 90^0$ A at start	0.085	0.007	68.0	0.047
$k_x = 0$, $k_a = +\pi/18$	$5 \angle 90^0$ A at start	0.081	0.008	67.0	0.047

V. CONCLUSION

This paper reviewed the PMU performance tests specified in the IEEE Standard C37.118.1 [6], developed a test methodology, and discussed some practical issues in the test environment. The PMU evaluation method used in this paper is simple, repeatable, and can be performed at any facility with commonly available standard signal playback equipment. The approach is based on the mathematically generated signals played back into the PMU using playback equipment with precise GPS synchronization. An actual PMU was tested using the proposed method and some sample test results were presented.

In dynamic tests, the signal is not purely sinusoidal and undergoes changes in its amplitude, phase angle, and frequency over a given interval. Even during steady-state tests, harmonics and noise superimposed on the signal are changing. Therefore, it is necessary to continue steady-state tests for over 5 seconds and the modulation tests over at least two full cycles of modulation. In the case of step response evaluation, proper resolution should be maintained to enable accurate determination of the response and delay times.

The actual PMU tested in the paper satisfied steady-state TVE compliance tests of both P and M classes except the out-of-band interference test. In dynamic tests, the PMU satisfied the measurement bandwidth test of P class, and the linear frequency ramp test and the overshoot/undershoot requirements of the magnitude step response of both performance classes. The PMU, which has been designed according to the previous synchrophasor standards, did not satisfy the other dynamic requirements. However, the performances of the actual PMU can be enhanced by implementing backend low-pass finite impulse response filters as provided in [6].

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VII. BIOGRAPHIES

Dinesh Rangana Gurusinghe (S’11) received the B.Sc. (Eng.) degree from the University of Moratuwa, Katubedda, Sri Lanka, in 2003, and the M.Eng. degree from the Asian Institute of Technology, Bangkok, Thailand, in 2010. Currently, he is pursuing the Ph.D. degree in the Department of Electrical and Computer Engineering at the University of Manitoba, Winnipeg, MB, Canada. He is a Corporate Member and Charted Engineer in the Institution of Engineers, Sri Lanka.

His main research areas are synchrophasor measurements and their applications in power system, power system protection, power system stability, power system optimization, and power system operation and control.

Athula D. Rajapakse (M’99-SM’08) received the B.Sc. (Eng.) degree from the University of Moratuwa, Katubedda, Sri Lanka, in 1990, and the M.Eng. degree from the Asian Institute of Technology, Bangkok, Thailand, in 1993, and the Ph.D. degree from the University of Tokyo, Tokyo, Japan, in 1998. Dr. Rajapakse is a Registered Professional Engineer in the province of Manitoba, Canada.

Currently, he is an Associate Professor at the University of Manitoba, Winnipeg, MB, Canada. His research interests include power system protection, transient simulation of power and power-electronic systems, and distributed and renewable energy systems.

Krish Narendra obtained his B.E. (Electrical Engineering) in 1986 from University Visweswaraiah College of Engineering (UVCE), and M.Sc. (E.E), Ph.D. (E.E) with a specialization in High Voltage Engineering from Indian Institute of Science, India in 1989 and 1993 respectively.

He is now the VP-Technology and Quality and is a member of the core corporate management team of ERLPhase Power Technologies Ltd, Canada. Dr. Narendra is actively participating in the IEEE PRSC working groups and is a member of the PRTT of NASPI. His areas of interests include Power Systems Disturbance Analysis, Protection, HVDC Controls, Neural Networks, Fuzzy logic, Phasor Technology (PMUs), and IEC 61850 application to protection and control.