Dynamic Performance Evaluation and Testing of Phasor Measurement Unit (PMU) as per IEEE C37.118.1 Standard

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

***Abstract*—The recently published IEEE C37.118.1 standard describes the requirements and performance evaluation criteria for the phasor measurement units (PMUs) under steady-state and dynamic conditions. It specifies two performance class filters: P class and M class, preferred for applications demanding fast and more accurate applications respectively. The standard expands the concept of total vector error and compliance tests. In addition, it defines the frequency and the rate of change of frequency error limits for both steady-state and dynamic conditions. A guideline to implement the reference PMU and filter coefficients is also included in an annexure. This paper presents a simple but effective test methodology to verify the dynamic performance of a PMU as per IEEE C37.118.1 standard, and shares the outcome of the work.**

***Index Terms*—Frequency ramping, measurement bandwidth, phasor measurement unit (PMU), real-time playback device, step response, total vector error (TVE).**

I. Introduction

Phasor measurement unit (PMU) is a device, which can extract phasors with respect to a time synchronized reference signal. In addition, it could be able to determine analogue measurements such as frequency, rate of change of frequency (ROCOF) and power as well as digital measurements such as circuit breaker status [1], [2]. Traditionally, dedicated PMUs have provided synchrophasor measurements. These PMUs are not in widespread use because they are relatively expensive, and they are only used on critical systems [3]. With new advances in processing and equipments, PMU can be a stand-alone unit as well as a functional unit within another physical unit such as a protective relay or a power system data recorder [2], [4], [5].

PMUs were developed and deployed on an experimental basis in actual power systems in the 1990s and commercial PMUs were then installed in power systems in North America [6]. The U.S. - Canada power system task force, which examined the August 14, 2003 blackout, has reinforced the value of PMUs for enhancing situational awareness to prevent future blackouts [7].

Synchrophasor measurements, when combined with advanced communication infrastructure, enables online observation of the dynamics of a power system spread over a large geographical area. This opens an opportunity to design power system protection, automaton, and control schemes against system wide disturbances, which could lead to catastrophic failures. Today, electricity utilities worldwide install PMUs at the important substations, deploying synchrophasors to solve a variety of power system protection, automaton, and control problems [8]; but its potential is not fully utilized. Although several studies have been reported [8]-[12], further research is necessary to develop effective and practical applications that would exploit their potential to the fullest.

There are currently a number of vendors producing PMUs while hardware and algorithms from different vendors are likely implemented differently, resulting in inconsistency [13]. On the other hand, novel PMU applications especially dynamic performances demand high accuracy and consistency to ensure synchrophasor measurements accurately reflect power system behavior. The publication of IEEE C37.118-2005 standard [14] is an important step in standardizing phasor measurements but it is not enough in evaluating dynamic performances.

The recently published IEEE C37.118.1-2011 standard [2] provides necessary guidelines to assure dynamic compliances. It introduces two performance class filters: P class and M class. P class is proposed for applications requiring fast response whereas greater precision can be achieved from M class. However, the user has preference to choose a performance class that matches the requirements of each application. The concept of total vector error (TVE) and compliance tests are expanded in the new standard. In addition, it also defines the frequency and the rate of change of frequency error limits for both steady-state and dynamic conditions. The reference filter model and a guideline to implement filter coefficients are also included in an annexure and it is helpful to enhance PMU performances especially under dynamic compliance.

This paper presents a simple but effective performance evaluation approach according to [2] and shares the practical issues in the test environment. The test signals generated from mathematical models in built in power system electromagnetic transient simulation (PSCAD/EMTDC) software are played back to the PMU through the Doble F6150 real-time playback device with precise global position system (GPS) synchronization. The PMU outputs are evaluated against the actual test signals generated from mathematical models. This

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

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; athula@ee.umanitoba.ca).

paper discusses the relationship between the actual phasor, the measured phasor and the TVE as well as the magnitude - phase angle error relationship with the TVE. The dynamic compliance tests include measurement bandwidth, linear system frequency ramp and step response.

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

II. Concepts of Phasor Measurement

A general phasor, which is an equivalent representation of a pure sinusoidal waveform, can be represented [5] as,

$$X(t) = \frac{X_m(t)}{\sqrt{2}} \angle \left[2\pi \Delta f(t)t + \phi \right] \quad (1)$$

where $X_m(t)$ is the magnitude at time t, ϕ is the phase angle measured with respect to a time synchronized reference signal and $\Delta f(t)$ denotes the frequency deviation from the nominal power system frequency (50 or 60 Hz). The frequency of the reference signal is the nominal power system frequency and it is a cosine function with zero phase offset, thus it has its positive maximum at time, $t=0$ sec. (beginning of UTC second) [2]. As $X_m(t)$ and $\Delta f(t)$ are functions of time $X(t)$ represents a dynamic phasor, and by replacing them with suitable mathematical functions different dynamic test cases can be produced.

PMUs use mathematical algorithms, which may vary from vendor to vendor, to estimate phasors and other important power system measurements such as frequency, ROCOF and power from data samples. Use of different algorithms can result in phasor and other measurements 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 dynamic performances.

A. Total Vector Error (TVE) Evaluation

The standard [2] defines the TVE as a measure to assess the accuracy of measurements of a PMU and it is defined as,

$$TVE(n) = \frac{\left| x_a(n) - x_m(n) \right|}{\left| x_a(n) \right|} \quad (2)$$

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

The relationship between the actual phasor, the measured phasor and the TVE for an arbitrary limit, ε is shown in Fig. 1. The small circle with the radius of ε drawn at the end of the actual phasor is illustrated that the measured phasors fulfill the required accuracy if the end point of the measured phasor lies inside the circle. The maximum error for the magnitude measurement with no phase angle error can be easily obtained from Fig. 1, it would be $\pm\varepsilon$. The maximum phase error, θ occurs when the measured phasor is a tangent to the circular TVE region.

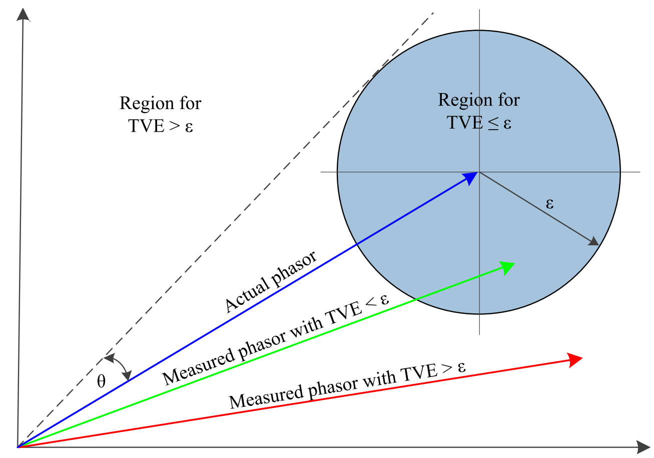

Fig. 1. Relationship between actual phasor, measured phasor and TVE

As the phase angle is measured with respect to a time synchronized reference signal timing errors creating an error in the phase angle measurement. Thus, timing errors will result different TVE depending on the system frequency.

For the 1% TVE criterion, the maximum magnitude error is ±0.01 when the error in phase angle is zero, and the maximum error in angle is $\pm 0.573^0$. The corresponding timing error at 50 Hz is ±31.8 μs and at 60 Hz is ±26.5 μs. In 3% TVE criterion, the maximum error in the magnitude is ±0.03 with no phase angle error and the maximum phase angle error is $\pm 1.719^0$. The corresponding timing error at 50 Hz is ±95.5 μs and at 60 Hz is ±79.6 μs.

B. Magnitude - Phase Angle Error relation in TVE

The TVE combines errors from the magnitude and phase angle measurements. Their relationship can be derived from (2) and it is given as,

$$TVE = \sqrt{2(1 \pm \lambda)(1 - \cos\gamma) + \lambda^2} \quad (3)$$

where λ is the magnitude error and γ is the phase angle error. The 3D plot in Fig. 2 represents the relationship between the magnitude error, the phase angle error and the TVE. Fig. 3 illustrates the TVE as a function of phase angle error for different magnitude errors, Fig. 4 shows TVE as a function of magnitude error for different phase angle errors and Fig. 5 displays the relationship between magnitude error and phase angle error for different TVEs.

III. PMU Test Setup

The tests are performed with the Doble F6150 real-time playback device using recorded common format for transient data exchange (COMTRADE) files [15] of precisely generated test signals from mathematical models built in PSCAD/EMTDC software. The Doble F6150 real-time playback device 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 TESLA 4000 PMU, which calculates magnitude, phase angle and frequency measurements. The operational flowchart of test setup is shown in Fig. 6. The test setup basically consists of:

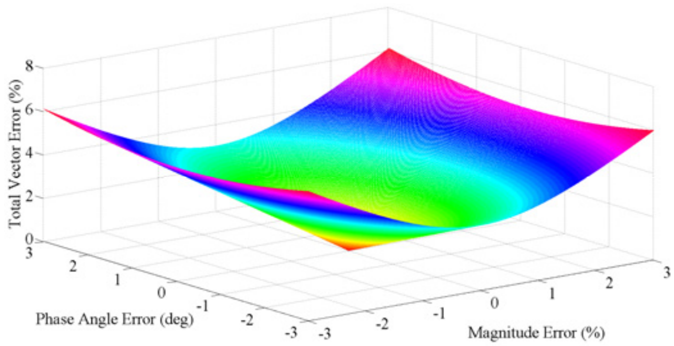

Fig. 2. TVE as a function of magnitude error and phase angle error

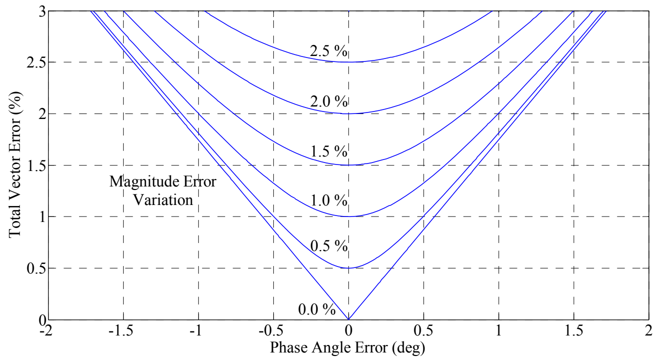

Fig. 3. TVE as a function of phase angle error for different magnitude errors

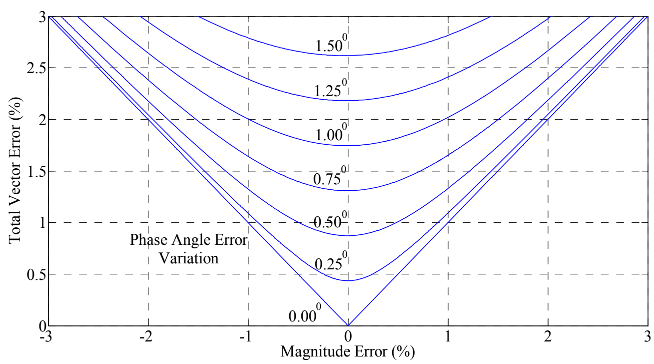

Fig. 4. TVE as a function of magnitude error for different phase angle errors

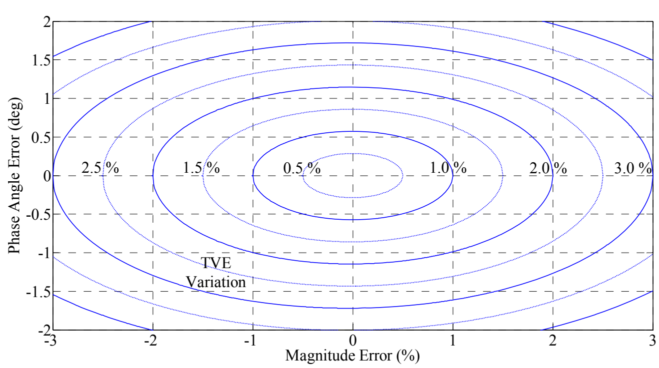

Fig. 5. Relationship between magnitude error and phase angle error for different TVEs

- PSCAD/EMTDC software precisely produces voltage and current playback files (COMTRADE files) with signals from mathematical models.
- The Doble F6150 real-time playback device that supplies real voltage and current signals at their appropriate levels (69 V voltage and 5 A current inputs).

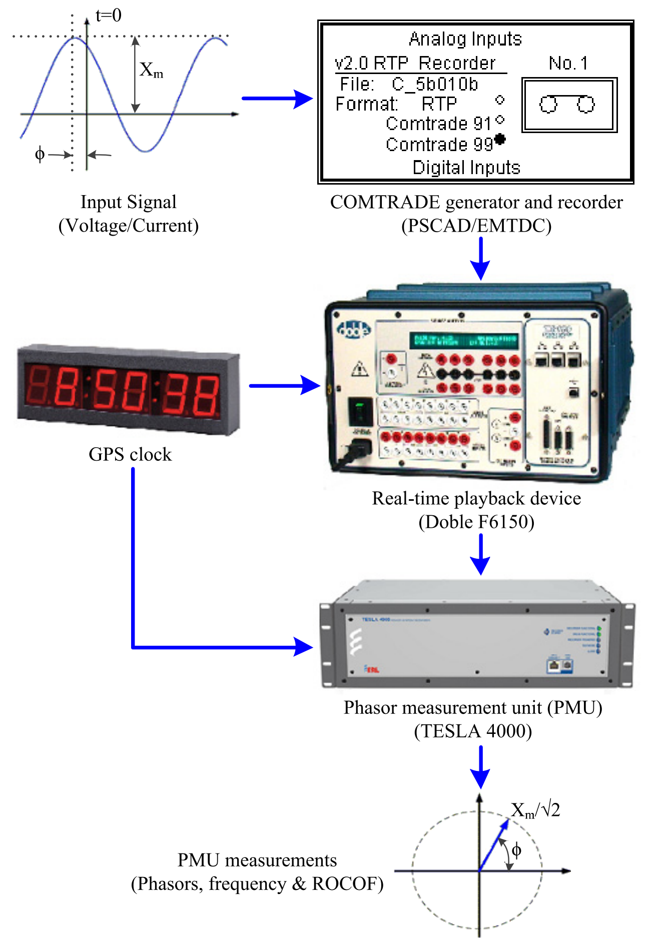

Fig. 6. Operational flowchart of test setup

- The GPS receiver that generates the time synchronization signal employed to time stamp measured values. 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 input signals to the PMU are used to extract phasors using discrete Fourier transform (DFT) and other interested analogue measurements such as frequency, ROCOF and power.

The PMU calculated measurements are evaluated against the actual test signals generated from the mathematical models, which were already used to produce COMTRADE files.

IV. Results and Discussion

Dynamic compliances need to be accomplished 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 frames per second (fps). It is experienced that if a PMU satisfies dynamic 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 [2]. Dynamic compliances include measurement bandwidth, linear system frequency ramp and step response assessments.

A. Measurement Bandwidth

Test signals for measurement bandwidth are primarily 50 or 60 Hz waveforms that are amplitude or/and phase angle modulated with a sinusoidal waveform. The input test signal is represented in (4) as,

$$x(t) = X_m[1 + k_x \cos(2\pi f_m t)].\cos[2\pi f_0 t + k_a \cos(2\pi f_m t - \pi)] \quad (4)$$

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. Time response waveforms of the input signal, magnitude, phase angle, frequency, TVE and frequency error (FE) the without performance class filters at modulation frequency of 2.5 Hz and reporting rate of 60 fps are shown in Fig. 7. The modulation is applied at time, *t=2* sec. It is observed that TVE and FE rise immediately after the modulation due transient effects. Therefore, it is important to allow an adequate settling time to prevent parameter change transient effects from distorting the measurement. Same procedure is repeated for other modulation frequencies and the maximum, mean and minimum values of percentage TVE and FE are shown in Fig. 8.

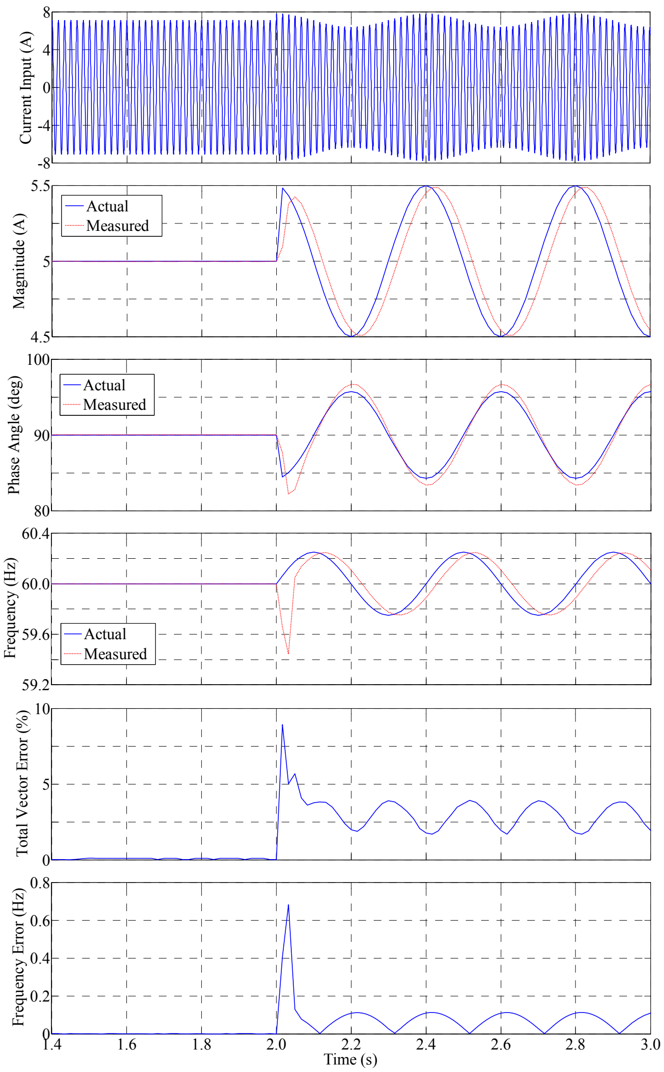

Fig. 7. Waveforms of measurement bandwidth response at 60 fps
Time response of the input signal, magnitude, phase angle, frequency, TVE and FE without the performance class filters
(k_a = 10 %, k_x = 10 %, f_0 = 60 Hz and f_m = 2.5 Hz)

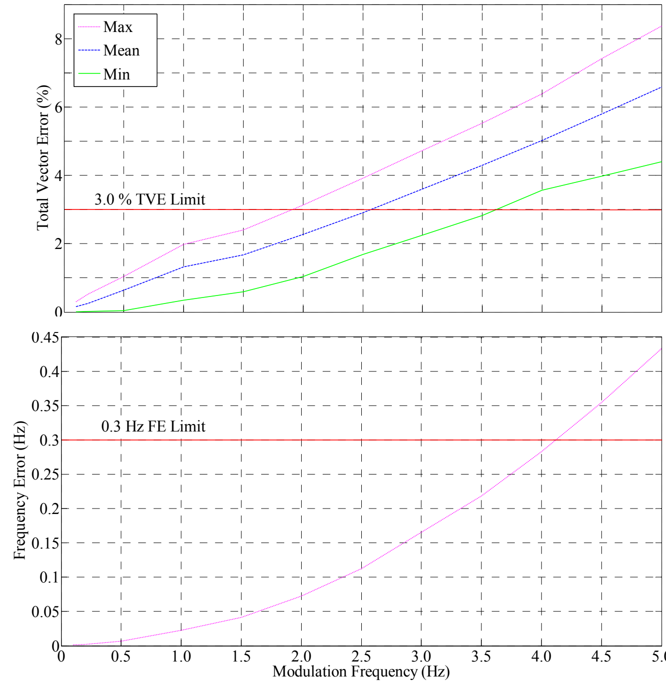

Fig. 8. TVE and FE response with modulation frequency at 60 fps without the performance class filters

The PMU satisfies measurement bandwidth TVE compliance up to modulation frequency of 2 Hz as the maximum TVE is less than 3% but it does not comply TVE requirement beyond the modulation frequency of 2 Hz. The PMU satisfies measurement bandwidth FE compliance of P class up to modulation frequency of 1.5 Hz as the maximum FE is less than 0.06 Hz whereas M class up to modulation frequency of 4 Hz where the maximum FE is 0.3 Hz. Thus, the PMU partially satisfies P class compliance but violates M class compliance.

B. 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 (5) as,

$$x(t) = X_m \cos(2\pi f_0 t + \pi R_f t^2) \quad (5)$$

The signal frequency ramp rate, R_f is varied from negative (−1.0 Hz/s) to positive (+1.0 Hz/s) while the ramp range is from 55 Hz to 65 Hz. 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.

Time response waveforms of the input signal, magnitude, phase angle, frequency, TVE and FE without the performance class filters when linear frequency ramp is 0.8 Hz/s at 60 fps reporting rate are shown in Fig. 9. The linear frequency ramp is applied at time, *t=2* sec. Same practice is repeated for other linear frequency ramp levels and the maximum, minimum and mean values of percentage TVE and FE are shown in Fig. 10. The PMU satisfies frequency ramp TVE compliance of both P class and M class as the maximum TVE is less than 1 % for ramp rates between −1.0 Hz/s to +1.0 Hz/s while the ramp range is from 55 Hz to 65 Hz. However, the PMU does not satisfy FE compliance under linear frequency ramp as both P class and M class maximum FE exceeds 0.01 Hz.

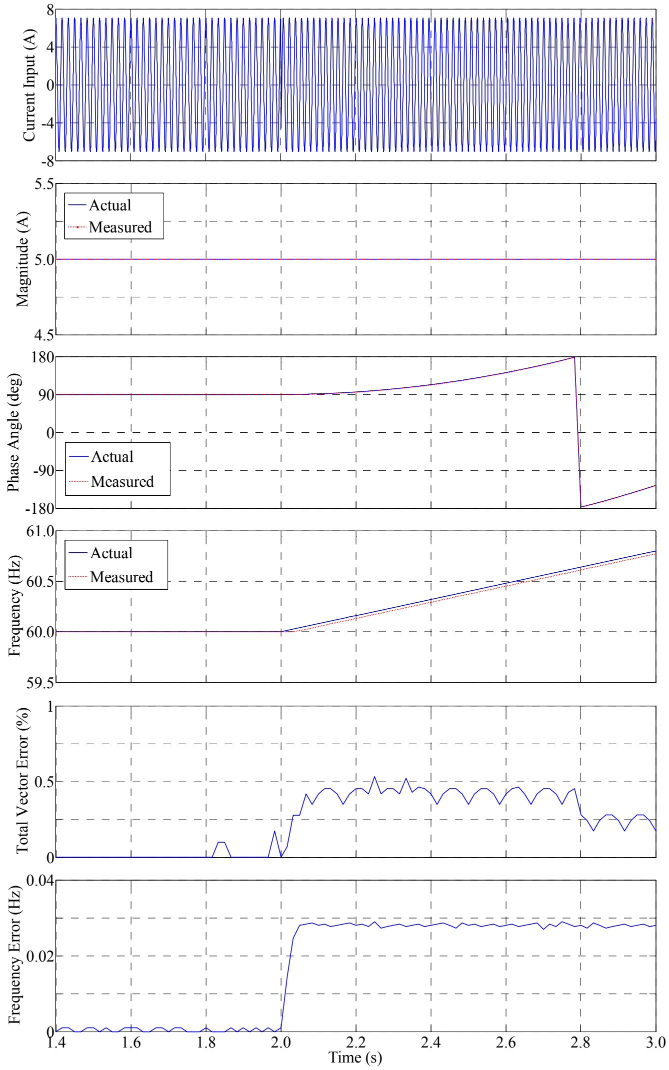

Fig. 9. Waveforms of linear frequency ramp response at 60 fps
Time response of the input signal, magnitude, phase angle, frequency, TVE and FE without the performance class filters (R_f = 0.8 Hz/s)

However, the simulation results of recorded waveforms of the PMU confirm that if the performance class filters are implemented the PMU will satisfy both P class and M class compliances. The measurement bandwidth and ramp of system frequency results of the PMU with the simulated performance class filters are compared in Table I. It confirms that the PMU with the proposed filters can realize better accuracy.

TABLE I
COMPARATIVE TVE AND FE RESULTS OF MEASUREMENT BANDWIDTH AND LINEAR FREQUENCY RAMP

Influence quantity	Range	Condition	Max TVE (%)	Max FE (Hz)
Measurement bandwidth k_x = 10%, k_a = 10%	Mod.Freq 0.1 to 5 Hz	w/o filter	8.53	0.43
		P class	0.15	0.02
		M class	0.25	0.13
Linear frequency ramp Ramp rate of ± 1.0 Hz/s	± 5.0 Hz/s	w/o filter	0.89	0.06
		P class	0.36	0.01
		M class	0.84	0.01

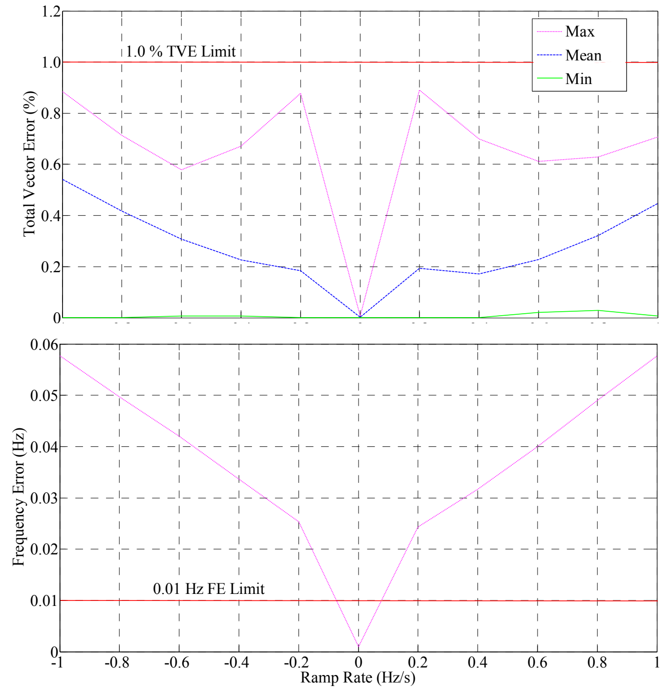

Fig. 10. TVE and FE response with linear frequency ramp at 60 fps without the performance class filters

A. Step Response

Step responses provide a simple and easily observed method of comparing the PMU response to a sudden input change. Step responses include magnitude and phase angle steps as well as positive and negative steps of 10% magnitude and 10% phase angle. A unit step function *u(t)* is applied to the input signal magnitude and phase angle and it is represented in (6) as,

$$x(t) = X_m\left[1 + k_m u(t)\right]\cos\left[2\pi f_0 t + k_a u(t)\right] \tag{6}$$

The step is initiated by a signal at a precise time, which allows determining the response time, delay time and maximum overshoot/undershoot. The magnitude step size, km 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 time response waveforms of the input signal, magnitude, phase angle, frequency, TVE and FE without the performance class filters when magnitude positive step applied at time, *t=2* sec. Corresponding waveforms for the phase angle positive step response are shown in Fig. 12.

In the 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.

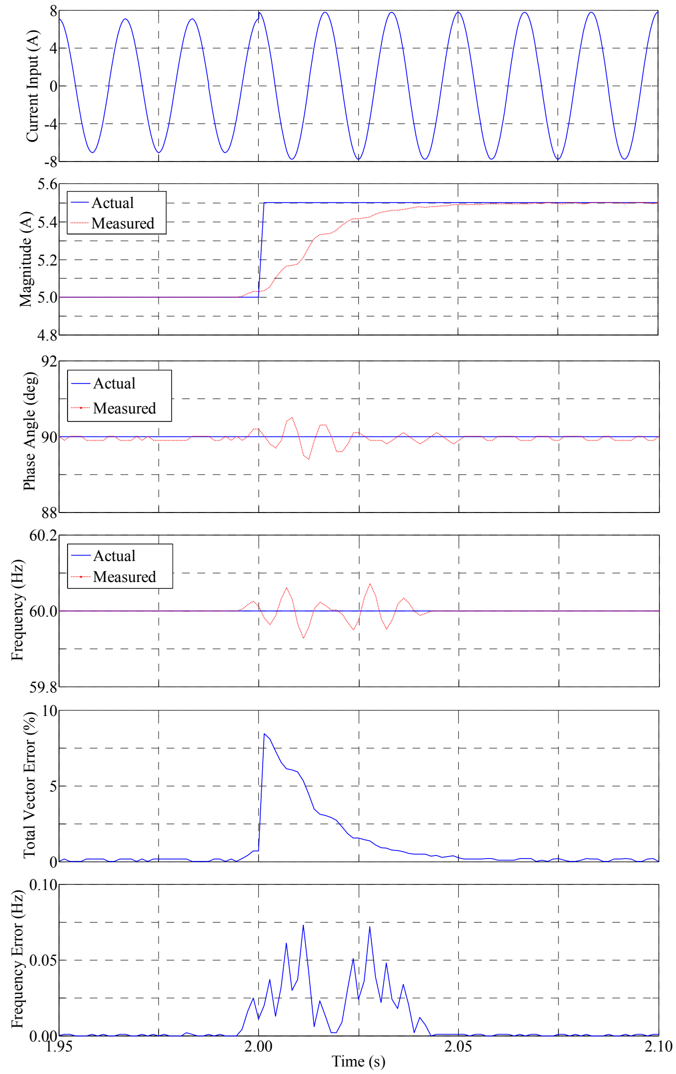

Fig. 11. Waveforms of magnitude positive step response at 60 fps
Time response of the input signal, magnitude, phase angle, frequency, TVE and FE without the performance class filters (k_m = 10 % and k_a = 0 %)

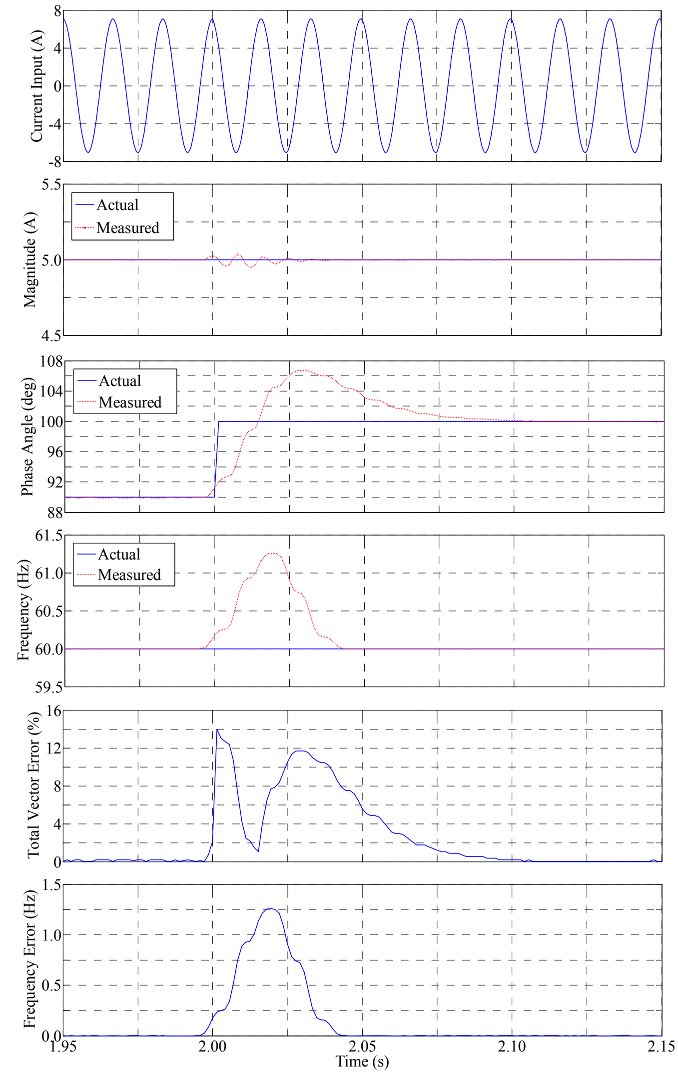

Fig. 12. Waveforms of phase angle positive step response at 60 fps
Time response of the input signal, magnitude, phase angle, frequency, TVE and FE without the performance class filters (k_m = 0 % and k_a = 10 %)

The simulation results of recorded waveforms of the PMU again confirm that if the performance class filters are implemented the PMU will satisfy both P class and M class compliances. Table II is compered step performances of the actual PMU with the simulated performance class filters.

TABLE II
STEP CHANGE PERFORMANCE OF ACTUAL PMU

Step change	Condition	Response time (sec.)	|Delay time| (sec.)	Max overshoot / undershoot (% of step)	Frequency Response time (sec.)
k_x = + 10 % k_a = 0 %	w/o filter	0.031	0.012	0.0	0.047
	P class	0.018	0.001	0.0	0.045
	M class	0.022	0.001	4.2	0.056
k_x = 0 % k_a = +10 %	w/o filter	0.081	0.008	67.0	0.047
	P class	0.023	0.001	0.0	0.049
	M class	0.027	0.002	3.4	0.098

V. CONCLUSION

This paper reviewed the PMU dynamic performance tests specified in the IEEE Standard C37.118.1 [2], 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 the Doble F6150 real-time playback equipment. The approach is based on the mathematically generated signals played back into the PMU using playback equipment with precise GPS synchronization. The 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. Therefore, it is necessary to continue the modulation tests over at least two full cycles of modulation. As the TVE combines error from the magnitude and phase angle measurements as well as the time synchronized reference signal timing error, it is important to pay attention to minimize all these error components to enhance the accuracy of PMU measurements.

The PMU tested in the paper 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 [13], did not satisfy the other dynamic requirements.

However, the simulation results of recorded waveforms of the PMU confirm that if the proposed performance class filters given in [2] are implemented the PMU can achieve both P class and M class accuracy requirement of the latest synchrophasor standard [2].

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VII. BIOGRAPHIES

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 Chief Technology Officer, Power Automation & Smart Grid at 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.

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 a 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.