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Characterizing dynamic behavior of PMUs using step signals[‡]

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SUMMARY

Evaluating performance of PMUs to verify the consistency of phasor measurements is of a great importance since it promotes the interoperability among PMUs from different manufacturers. This paper presents a set of test methodology and tools for evaluating the dynamic performance of PMUs when exposed to a step change of input signals. A phasor estimation scheme is proposed to achieve high accuracy of reference phasors. An interleaving technique applied on output phasors can equivalently increase the reporting rate and can precisely depict the transient behavior of a PMU under the step input. Four types of tests with balanced and unbalanced three-phase step signals are performed as reference signals to characterize the step responses. Three commercial PMUs are selected to perform step tests using the dynamic test system developed at NIST. A set of programs are developed based the dynamic test system to automate step test procedures. The test results are outlined at the end. Copyright © 2010 John Wiley & Sons, Ltd.

KEY WORDS: phasor measurement unit; synchronized phasor; dynamic behavior; power grid; step test; phasor estimation; interleaving; coordinated universal time

1. INTRODUCTION

Since phasor measurement unit (PMU) technology was developed and introduced into the power system in the early 1980s, it has exhibited great superiority in monitoring system dynamic behavior due to its high-speed and time synchronized measurements [1–3]. Over the years, many efforts have been focused on investigating the use of PMUs in wide area monitoring, protection, and control [4–6]. The PMU has gained wide acceptance as a tool for enhancing the situational awareness of the power grid. Particularly, its value was reinforced after the 14 August 2003 blackout [7].

Currently, a number of commercial PMUs have been deployed in the eastern and western systems in North America. There are many companies competing in this market. Thus, the performance of each individual PMU potentially becomes an essential aspect that could directly affect the performance of the entire system. IEEE C37.118-2005 standard defines synchrophasor measurements used in power system applications [8]. This standard specifies the compliance requirements for PMUs with respect to the phasor magnitude, frequency, phase angle, harmonics distortion, and out-of-band interference. It specifies the accuracy requirement of PMUs in terms of a single error parameter, defined as the Total Vector Error (TVE). This error combines the phase (timing) error with the magnitude error. One should note that the performance requirements described in IEEE C37.118-2005 are for steady-state tests, in which the test signals are held constant in magnitude, angle, and frequency during each test at values found in a possible operating state of a power system.

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The Performance and Standards Task Team (PSTT) of the North American SynchroPhasor Initiative (NASPI) prepared a PMU system testing and calibration guide [9]. This guide describes test environments and procedures for PMU in compliance with performance requirements specified in IEEE C37.118-2005. In addition to the steady-state tests, the performance requirements of PMUs under dynamic conditions are included as well.

The National Institute of Standards and Technology (NIST) has established a SynchroMetrology Laboratory [10]. Two systems for PMU testing under steady state and dynamic conditions respectively have been developed in this laboratory [11–13]. The NIST steady-state calibration service tests PMUs for compliance with the parameter requirements in IEEE C37.118-2005. In the dynamic test, modulated signals with varying magnitude and frequency are used to investigate PMU's dynamic performance. These test signals simulate the conditions of various power system dynamic oscillations.

While the test environment and methodology for PMU testing under both steady-state and dynamic conditions have already been studied [10–17], the PMU responses to a step signal, which is a typical signal in dynamic conditions, have not been discussed earlier and are presented in this paper. The term ''step tests'' is used in this paper to differentiate from other ''dynamic tests'' such as modulated signal tests.

This paper presents a set of test methodology and tools for characterizing dynamic behavior of PMUs when exposed to step signals. A least-square linear-fit based phasor estimation method for achieving high accuracy of reference phasors and a method for interleaving signal steps with timestamps to equivalently increase the reporting rate of output phasors so that they precisely depict PMU step behavior are presented. Three commercial PMUs are selected to perform step tests using the dynamic test system developed at NIST. A set of programs is developed based on the dynamic test system to automate step test procedures. Four types of tests are performed with balanced and unbalanced three-phase step signals as reference signals to characterize the step responses of PMUs. Four performance indices for step tests are defined to evaluate the dynamic performance.

The rest of the paper is organized as follows: Section 2 presents the method for estimating reference phasors. The dynamic test system and the implementation framework of the step test programs are described in Section 3. Section 4 specifies the test plan and performance indices for characterizing PMU responses. Test results and conclusions are summarized in Section 5 and Section 6, respectively. Finally, Section 7 defines the symbols and abbreviations used in the paper.

2. ESTIMATING REFERENCE PHASORS

2.1. Phasor estimation method

PMUs provide values for the electric power system voltage and current phasors at reporting times synchronized to Coordinated Universal Time (UTC). This is done by sampling the respective signals around the UTC reporting times, selecting a number of the samples (windowing), and analyzing the data with a model. When testing PMUs the test systems do something very similar. They sample the voltage and current signals applied to the PMUs with a sampler synchronized to UTC and analyze the measurements to determine the reference values to which the PMU output values are compared. This section describes the model and windowing methods used in the step tests.

To estimate the amplitude, phase angle and dc component of the reference measurement, a three-parameter linear fit model is employed. Consider a sinusoidal signal model expressed as follows:

$$y = A \cdot \cos(2\pi \cdot f_0 \cdot t + \theta) + B, \tag{1}$$

where A is the amplitude, f_0 is the fundamental frequency, θ is the phase angle, and B is the dc component.

If we rewrite (1) we have

$$y = A \cdot \cos\theta \cdot \cos(2\pi \cdot f_0 \cdot t) - A \cdot \sin\theta \cdot \sin(2\pi \cdot f_0 \cdot t) + B.$$

If we have a series of samples $y = y_1, y_2, \cdots, y_n$ at times $t = t_1, t_2, \cdots, t_n$ from the measurement system, for example, then these samples can be fit to the matrix model X consisting of the three column

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vectors as

$$X = [\cos(2\pi \cdot f_0 \cdot t) \quad \sin(2\pi \cdot f_0 \cdot t) \quad 1].$$

The vector of fit coefficients $\overline{\beta}^T = [\beta_0 \beta_1 \beta_2]$, where $\overline{\beta}^T$ is the transpose of $\overline{\beta}$, are determined in the least square error sense by $\overline{y} \cong X \cdot \overline{\beta}$ using the Normal equation. Then we can compute the amplitude, phase angle, and dc component as follows:

$$A = \sqrt{\beta_0^2 + \beta_1^2},\, \theta = \arctan(\beta_1/\beta_0),\, B = \beta_2.$$

The step change in a signal may affect the accuracy of phasor estimation, particularly when the data window crosses the step point. In order to avoid or minimize this impact, a special routine is applied to achieve accurate values, which act as reference measurements to evaluate the errors of the PMU being tested. There are two cases that need to be discussed: step point at an output timestamp and step point between two output timestamps. Figure 1 gives an example for the first case where a step occurs at the timestamp t_m. P_{m-1} and P_{m+1} are the output phasors at corresponding timestamps t_{m-1} and t_{m+1}. To estimate the phasor at t_m, one can use the data window either before or after t_m. They are P'_m and P''_m as shown in Figure 1, and the phase angle should be calculated at the end and beginning of the data window correspondingly.

For the second case, to estimate P_m and P_{m+1} appropriate data windows should be selected to eliminate the impact of the step position, as shown in Figure 2. The step position should be known precisely in advance so that the data windows for the ''special'' timestamps contain samples on only one side of the step. On the dynamic test system, which is described more fully in Section 3, the signal waveforms are typically generated with D/A converters operation at 200 ksps and the data is sampled with A/D converters operating at 50 ksps. At these sample rates the step transitions show no samples or at most one sample. At generation and sampling rates of 500 ksps, the step transitions generally show 2–3 samples.

2.2. *Increasing phasor output rate*

A PMU outputs synchrophasors at submultiples of the nominal power system frequency. The IEEE C37.118 standard requires reporting rates from 10 frames per second up to a maximum of 25 frames per second and 30 frames per second for 50 and 60 Hz nominal frequencies, respectively [8]. Although many commercial PMUs feature even higher rates of up to 50 frames per second and 60 frames per second for 50 and 60 Hz nominal frequencies, respectively, some details of the response of PMU facing a step change of signal could be lost under low output rates. The method described below, which makes use of equivalent time sampling, provides a solution for this problem. A higher resolution measurement of the PMU's step response is made from samples taken on repeated measurements of time shifted step input signals. Because the signal generation is synchronized with UTC, the absolute phase values are the same for times $t = t_1, t_2, \cdots, t_n$ relative to any UTC on second time.

Assume a set of output phasors $\cdots P_{m-1}, P_m, P_{m+1} \cdots$ at timestamps $\cdots t_{m-1}, t_m, t_{m+1} \cdots$ is measured when applying a step signal, so we have the reporting rate $R = 1/(t_m - t_{m-1})$. We repeatedly

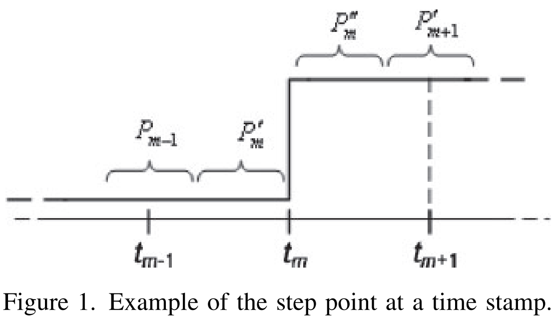

Figure 1. Example of the step point at a time stamp.

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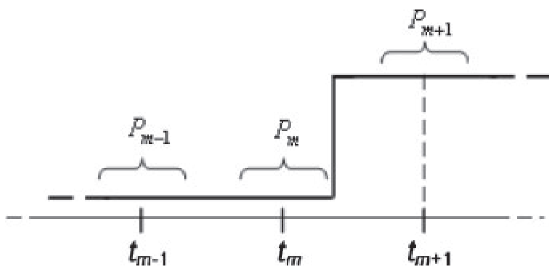

Figure 2. Example of the step point between timestamps.

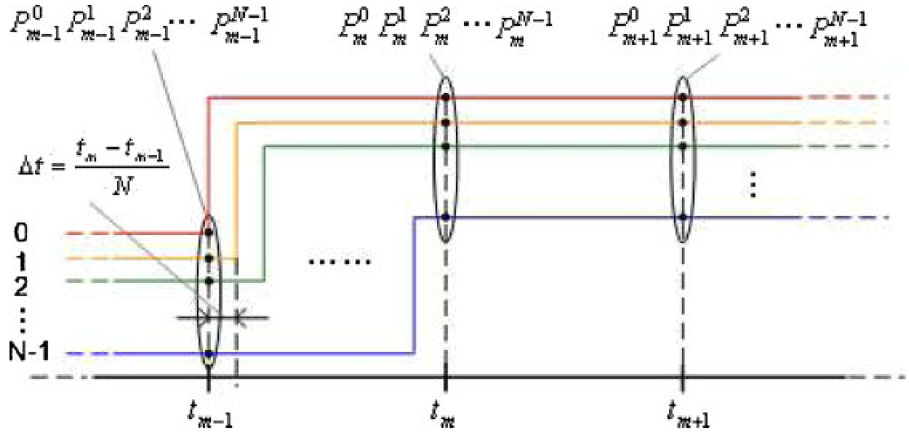

Figure 3. N sets of output phasors obtained by repeated measurements of time-shifted step signals.

apply the same step signal N times, however, with a timeshift of $\Delta t = (t_m - t_{m-1})/N$ among each other relative to the PMU reporting times. As shown in Figure 3 we obtain N sets of output phasors:

$$\cdots P^0_{m-1}, P^0_m, P^0_{m+1}\cdots, \cdots P^1_{m-1}, P^1_m, P^1_{m+1}\cdots, \cdots, \cdots P^{N-1}_{m-1}, P^{N-1}_m, P^{N-1}_{m+1}\cdots.$$

If one interleaves those phasors in accordance with their timestamps relative to the step time by the way depicted in Figure 4, then one achieves the reporting rate $R' = 1/\Delta t = N/(t_m - t_{m-1})$, which is an N multiple of the original reporting rate R. The effectiveness is presented in Figures 5 and 6, which display output phasors of a PMU before and after interleaving respectively, where N is 10.

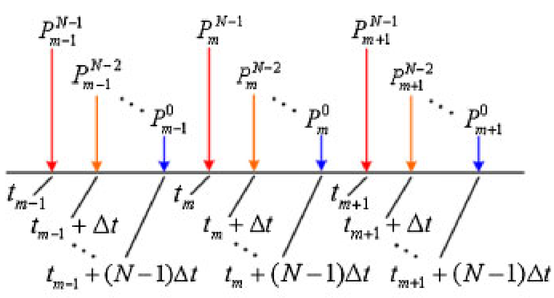

Figure 4. Interleaving of phasors.

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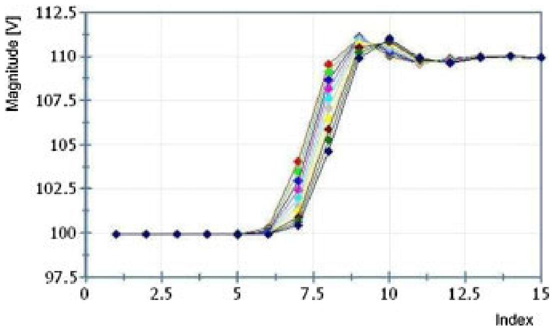

Figure 5. Output phasors of a PMU before interleaving.

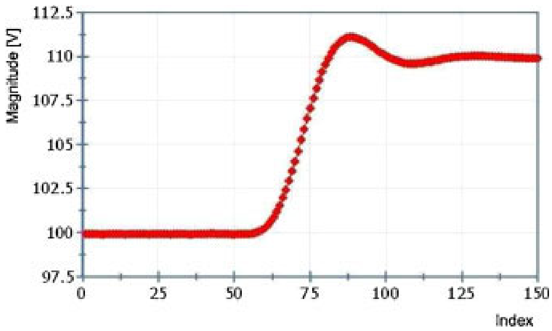

Figure 6. Output phasors of a PMU after interleaving.

3. DYNAMIC TEST SYSTEM

3.1. Description of dynamic test system

The step tests are implemented using the dynamic test system developed in the SynchroMetrology Laboratory at NIST [11]. As Figure 7 shows, it consists of a Global Positioning System (GPS) clock used to synchronize the system to UTC (Coordinated Universal Time), a signal generation system used to generate test signals, a data acquisition system used to sample test signals, three voltage amplifiers

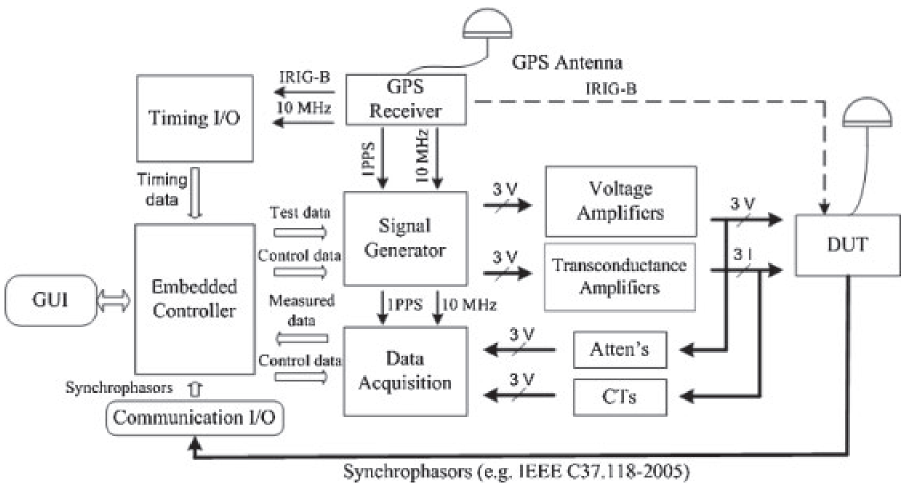

Figure 7. Diagram of the step test system.

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and three transconductance amplifiers connected to the DUT (Device Under Test), three voltage attenuators and three current transducers. The system outputs six voltages with amplitudes up to ±10 V peak at a strobe rate up to 1 Msps and samples those voltages with the same amplitude range at up to 500 ksps. The signal generation and sampling are triggered by the timing source that is synchronized to UTC. The three voltage amplifiers supply signals up to 140 V rms, and the three transconductance amplifiers deliver currents up to 10 A rms, which satisfy typical test levels for electric power instrumentation. IRIG-B signal, which gives information on the UTC time of each 1 pps, is provided by the GPS clock to those devices without built-in GPS receivers.

3.2. Test implementation procedure

One challenge for the step test is how to efficiently perform hundreds of test cases on different PMUs. A set of programs for the step tests are developed based on the dynamic test system to automate the test procedures. The algorithms for estimating the reference phasor are used in these programs. Figure 8 displays the implementation framework of the step test programs. The test procedures are outlined as follows:

(1) Initiate test environment, such as generation and sampling rates, signal types and etc., set up calibrator and PMU being tested.
(2) Generate test signals and apply to the PMU under test. It should be noted that the calibrator and PMU receive exactly the same test signals.
(3) Estimate reference phasors using the method proposed in Section 2, collect and decode phasors measured by PMU.
(4) Line up reference and measurement phasors according to the timestamps, and calculate performance indices.
(5) Display and store test results through GUI.

4. TEST PLAN

Three commercial PMUs were selected to investigate the dynamic behavior using the proposed step test method and tools. These PMUs have various features, such as filter type, output phasor type, reporting rate, communication medium, and so on, which are summarized in Table I. Three-phase voltages and currents are represented as VA, VB, VC, IA, IB, and IC, while three-sequence voltages and current are represented as V1, V2, V0, I1, I2, and I0.

In terms of a proposed update of Section 5.3 of IEEE C37.118-2005, to accommodate dynamic phasor compliance four types of step tests: magnitude test, phase test, recovery magnitude test and recovery phase test, were performed on three selected PMUs described above. Descriptions of test types and test conditions are listed in Table II.

Four performance indices are measured to characterize the dynamic response of PMUs when exposed to step signals: response time, settling time, overshoot, and undershoot, as illustrated in

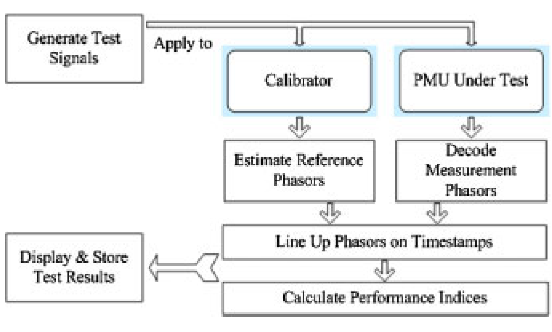

Figure 8. Framework of step test programs.

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Table I. Feature summary of PMUs being tested.

Feature	PMU A	PMU B	PMU C
Filter type	Optional	Optional	Optional
Adaptive tuning	Always on	Always on	Selectable
Output phasors	VA, VB, VC, V1, IA, IB, IC, I1	VA, VB, VC, V1,V2,V0, IA, IB, IC, I1, I2, I0	VA, VB, VC, V1,V2,V0, IA, IB, IC, I1, I2, I0
Max reporting rate (frame/second)	50 for 50 Hz 60 for 60 Hz	50 for 50 Hz 60 for 60 Hz	50 for 50 Hz 60 for 60 Hz
Communication	Serial Port	Ethernet	Ethernet
GPS receiver	IRIG-B input	IRIG-B input	Built-in

Table II. Description of test types and conditions.

Test Type	Reference condition	Description
Magnitude: ±10% step of nominal magnitude	Balanced 3-phase voltage and current signals, magnitude nominal, nominal frequency	From a steady state, apply a balanced magnitude step, followed by a reversed step back to the starting state
Phase: 10° step of inception angle	Balanced 3-phase voltage and current signals, nominal magnitude, nominal frequency	From a steady state, apply a balanced phase step, followed by a reversed step back to the starting state
Recovery magnitude: from zero magnitude of one phase to nominal	Unbalanced, magnitude of non-stepped phases nominal, normal phase angle, nominal frequency	From a steady state, magnitude of one phase steps from zero to nominal, followed by the reversed step back to the starting state
Recovery phase: from normal phase angle of one phase to 180°	Balanced, magnitude of all phases nominal, normal phase angle on non-stepped phases, nominal frequency	From a steady state, phase angle of one phase steps from normal to 180°, followed by the reversed step back to the starting state

Figure 9. Response time is defined as the time interval from when the step change response leaves the 1% TVE (total vector error [8]) until it re-enters 1% TVE of the final value. Settling time is defined as the time interval from when the transient signal first enters 1% TVE of the final value until it stays within 1% TVE of the final value. Overshoot and undershoot are defined as the differences between maximum, minimum values of transient signal after first entering 1% TVE of the final value and the

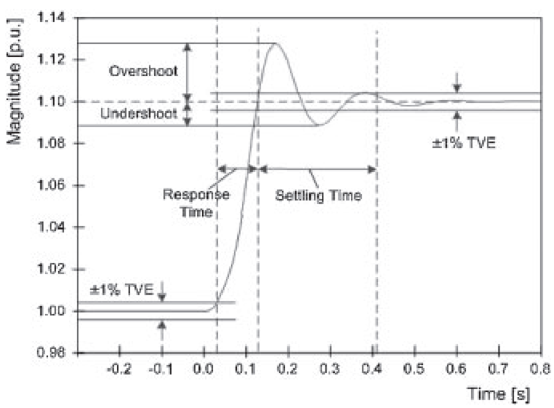

Figure 9. Illustration of performance indices.

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final value, respectively. Besides, TVE, errors of the magnitude, phase angle, frequency, and rate of change of frequency are measured as well to evaluate the accuracy levels of PMUs. Once the magnitude error Δv (in per cent of the nominal value) and the phase error $\Delta\theta$ (in degrees) are available, the expression for TVE is given by $\mathrm{TVE} = \sqrt{(\Delta v)^2 + (\Delta\theta/0.573)^2}$, where 0.573 is the arcsine of 1% in degree.

5. TEST RESULTS

Four types of step tests as described in Table II were performed on the three commercial PMUs described in Table I. The reporting (output) rate for the PMUs was set to 30 frames per second, i.e., the reporting period $F_s = 1/30$ seconds. To study the effect of the inception angle on test results, each test runs with the inception angle of voltages and currents from 10° to 340° in 30° steps. The inception angle is the positive sequence phase angle of the applied signals at the time of the step. Various digital filter types for each PMU were studied as well. In sum, over one thousand step cases were performed on each PMU.

Due to the limited space, only parts of test results are presented. Figures 10–13 display the magnitude or phase angle and TVE of the positive sequence voltage for the four types of step tests. For PMU A, two steps for each type of step tests were applied at 0.4 and 0.8 seconds, respectively. For PMU

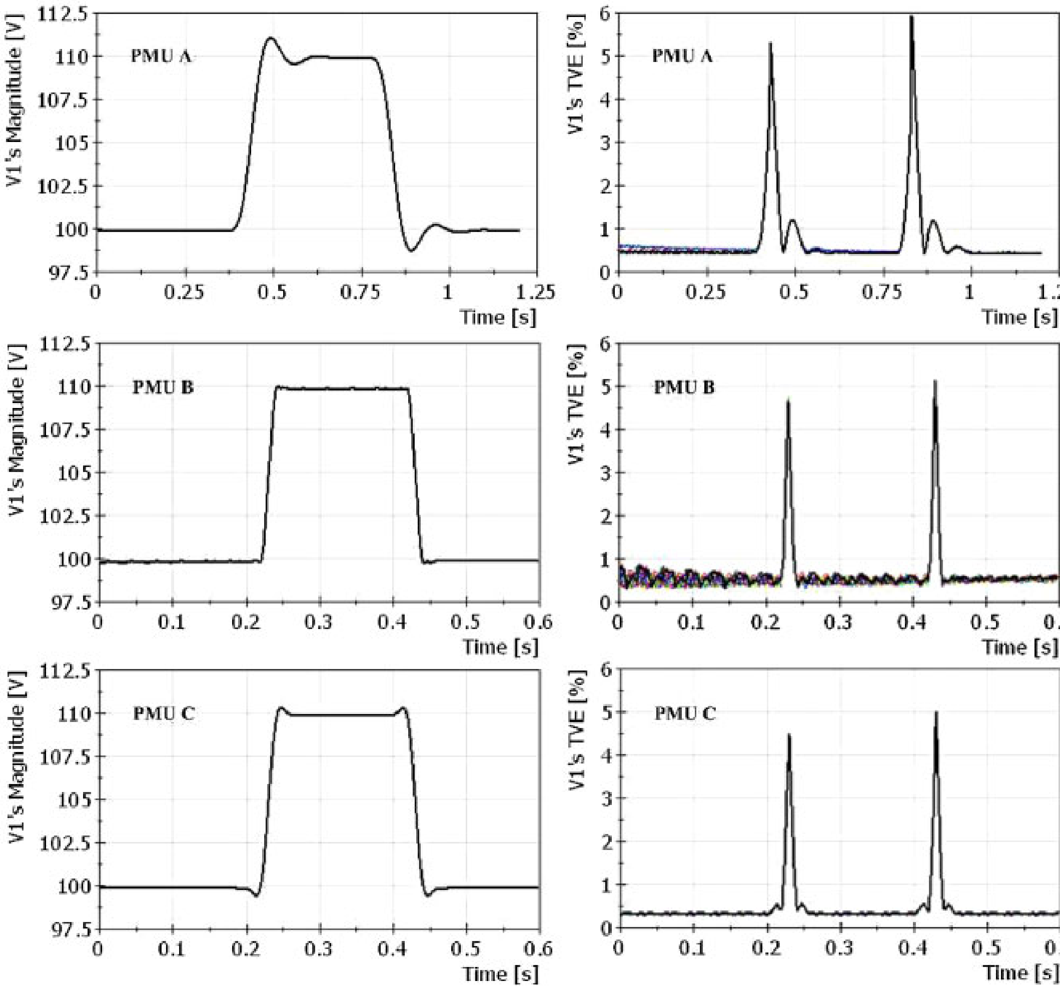

Figure 10. Results of magnitude test.

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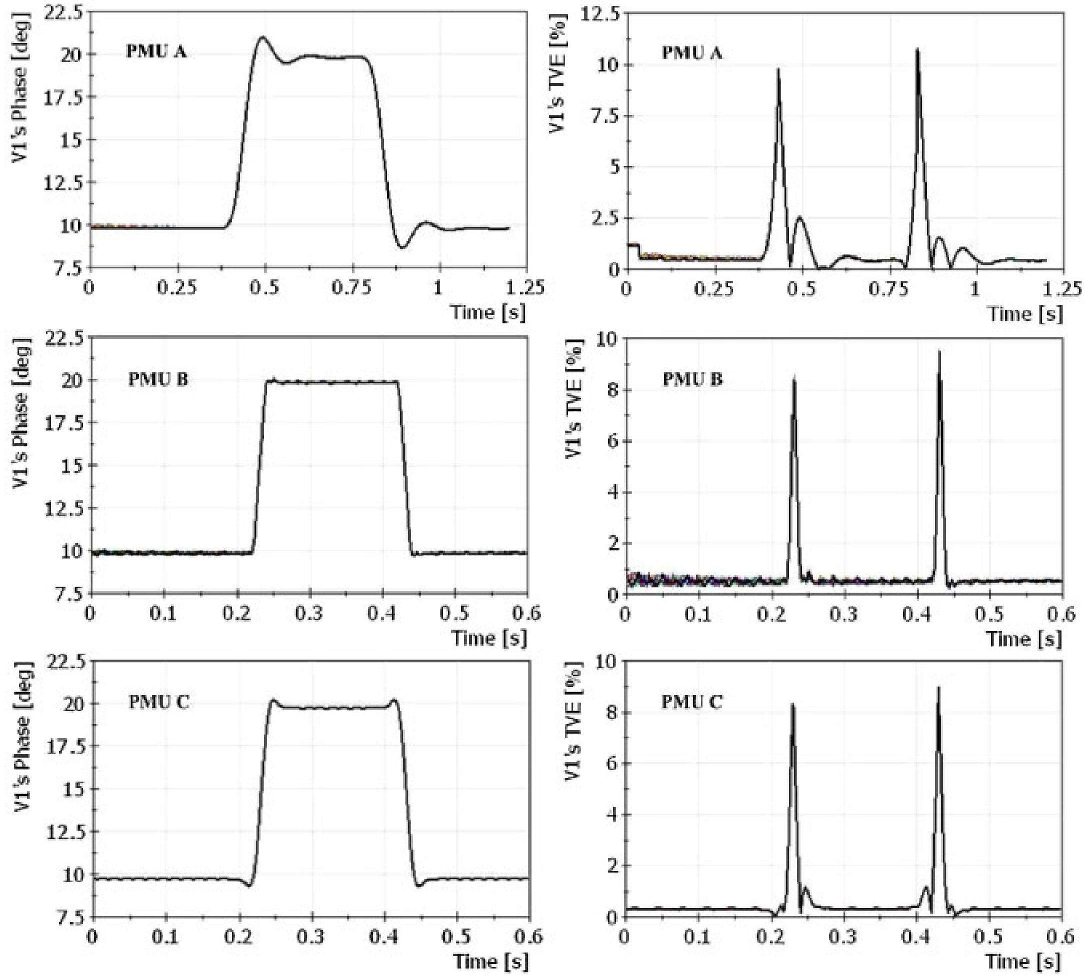

Figure 11. Results of phase test.

B and PMU C, two steps for each type of step tests were applied at 0.2 and 0.4 seconds, respectively. Each curve consists of the result with different inception angles from 10° to 340° in 30° steps by overlaying them. Some of the performance indices describing the dynamic step transition progresses are given in Tables III–VI, where T_{resp}, T_{set}, O_{s}, and U_{s} are response time, settling time, overshoot, and undershoot, respectively, as illustrated in Figure 9. Their values are calculated as maximum values among different inceptions for the first step part. The uncertainty in these values for the NIST dynamic test system is about 0.5 microseconds for time and 0.05% for magnitude. This data was taken with an interleave factor N of 10. The values of T_{resp}, and T_{set} are measured in units of reporting rate periods, rrp. For these tests the reporting rate was 30 frames per second so rrp = 33.3 milliseconds. The overshoot and undershoot, O_{s} and U_{s}, are measured in per cent of the step height.

From the test results, we can conclude:

(1) PMU A exhibits a large post step ripple on all tests. The settling time in all tests exceeds 1.0 rrp and the overshoot is over 10% of the step. That may result from the characteristics of the filter being used.
(2) PMU B shows very little ripple on all tests and PMU C shows a small symmetric pre step ripple and post step ripple. Their response time and settling time are limited within 1.0 rrp for magnitude and phase tests while 2.0 rrp for recovery magnitude and recovery phase tests.
(3) The recovery tests present similar transient responses with the normal step tests except that they are measured relative to the higher step values in performance indices.

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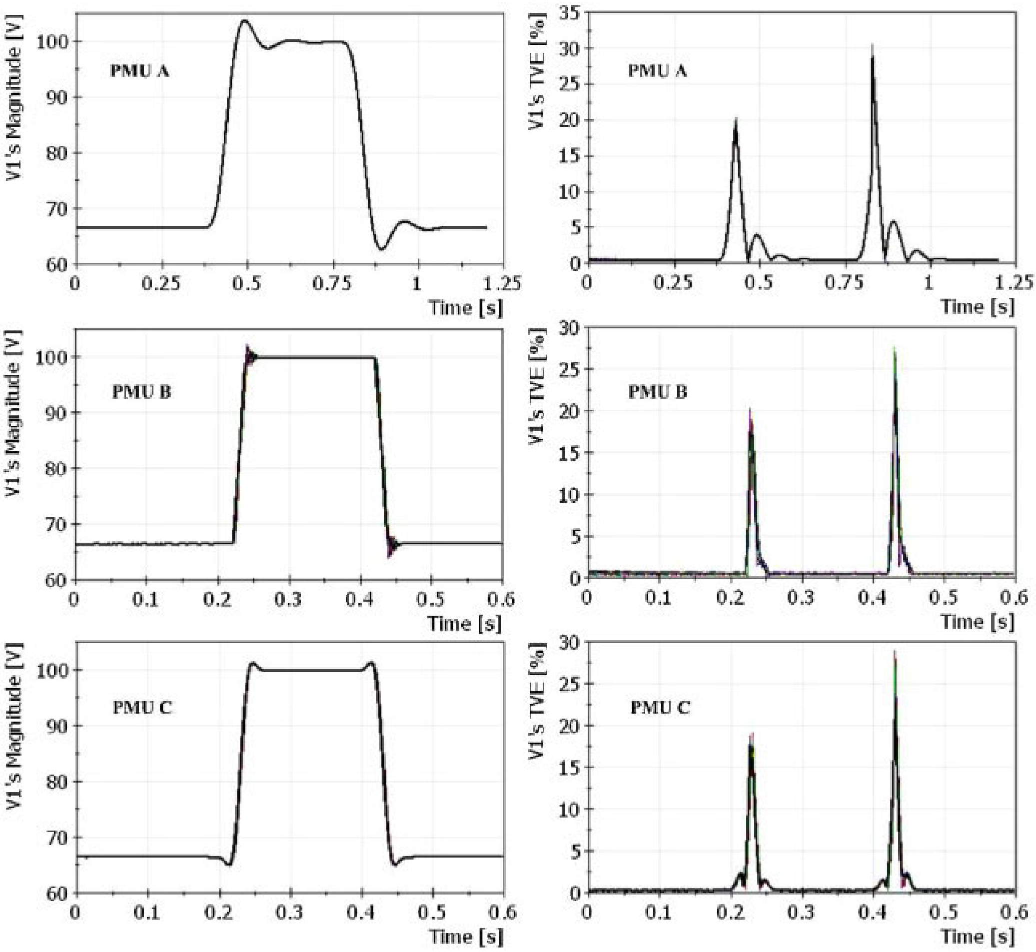

Figure 12. Results of recovery magnitude test.

(4) The inception angle for both voltage and current has barely any effect on the dynamic performance. Thus, any angle from -180° to + 180° can be picked as the reference condition for testing.

6. CONCLUSIONS

PMUs as a tool for measuring synchronized phasors has gained wide acceptance in enhancing the monitoring of power grids. However, the performance of each individual PMU manufactured by different companies may vary greatly. Standards for the performance requirements have been made to promote the interoperability of PMUs. These standardization efforts should facilitate their rapid introduction into many power system applications. To promote the common response of PMUs to rapid grid changes, this paper proposes an approach to characterize the dynamic performance of PMUs when exposed to step signals. The techniques used to achieve high accuracy and high resolution of reference phasors includes the least square linear fit, adaptive data window, and interleaving method. Four test types with balanced and unbalanced step signals are described. Step test programs are developed to automate the test procedures. Three commercial PMUs are selected to perform step tests using the dynamic test system developed at NIST. Test results including output phasors and performance indices summarized in the paper indicate unique characteristics for some PMUs and good dynamic behavior

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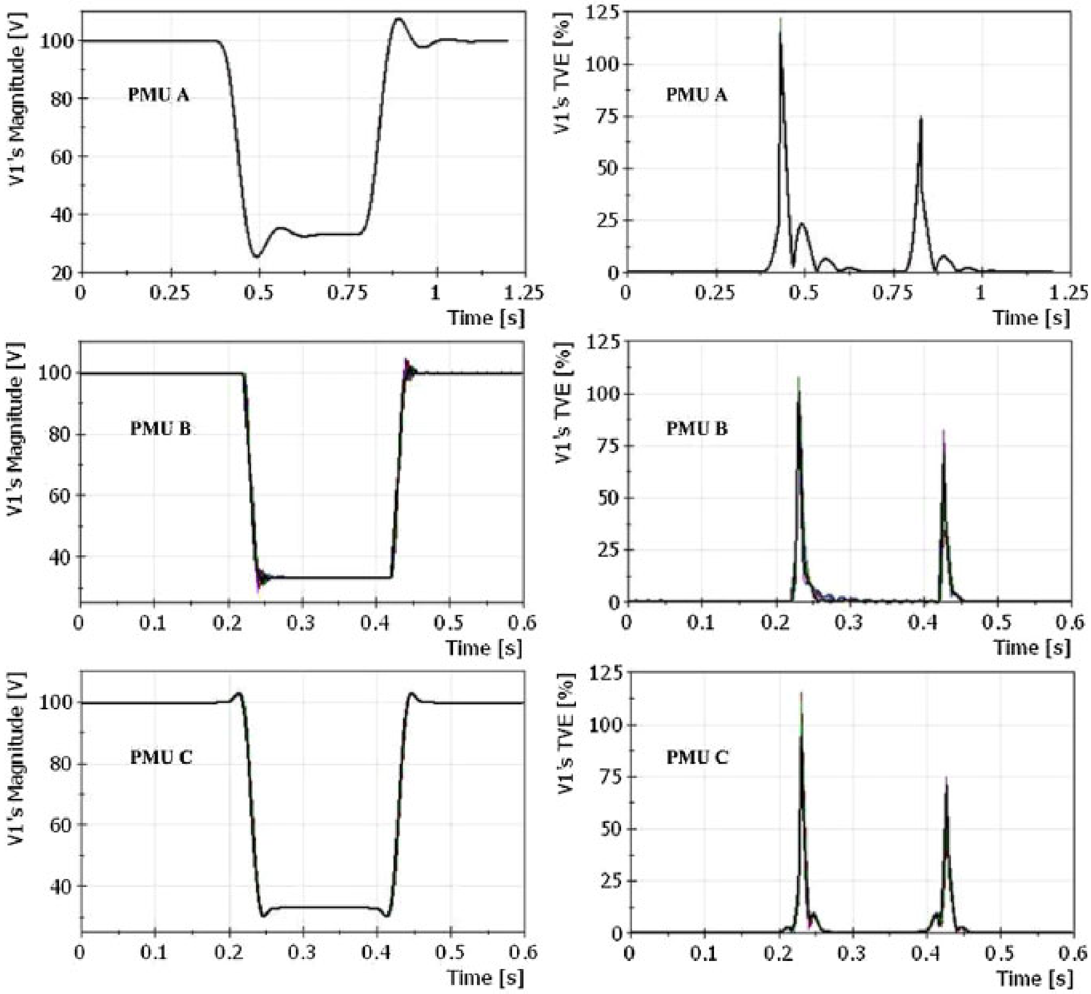

Figure 13. Results of recovery phase test.

Table III. Performance indices of magnitude tests.

DUT	T_{resp} ($/F_s$)	T_{set} ($/F_s$)	O_s (% of step)	U_s (% of step)
PMU A	1.62	1.45	11.87	−3.21
PMU B	0.43	0.00	2.43	−0.56
PMU C	0.48	0.00	4.56	−0.09

Table IV. Performance indices of magnitude tests.

DUT	T_{resp} ($/F_s$)	T_{set} ($/F_s$)	O_s (% of step)	U_s (% of step)
PMU A	1.91	1.91	12.78	−3.32
PMU B	0.51	0.00	2.54	−0.94
PMU C	0.55	0.34	4.83	−0.22

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Table V. Performance indices of recovery magnitude tests.

DUT	T_{resp} ($/F_s$)	T_{set} ($/F_s$)	O_s (% of step)	U_s (% of step)
PMU A	2.18	3.24	12.07	−3.18
PMU B	0.83	0.00	7.63	−4.07
PMU C	1.11	0.33	5.04	−0.07

Table VI. Performance indices of recovery phase tests.

DUT	T_{resp} ($/F_s$)	T_{set} ($/F_s$)	O_s (% of step)	U_s (% of step)
PMU A	4.26	3.70	−12.07	3.20
PMU B	1.29	1.72	−7.55	4.48
PMU C	0.45	1.51	−4.90	0.08

consistency among most of the tested PMUs. The IEEE Power System Relay Committee is current working on an update to the 2005 version of the synchrophasor standard, C37.118. The update will include dynamic tests, such as the step tests described in this paper as well as modulation tests. The update is expected in 2010.

7. LIST OF SYMBOLS AND ABBREVIATIONS

7.1. Symbols

1 pps	one pulse per second (on the UTC seconds)
A	amplitude of input sinusoidal signal
B	dc component of input signal
f_0	fundamental frequency of input sinusoidal signal
F_s	reporting period of PMU
IA, IB and IC	three-phase currents
I1, I2 and I0	three-sequence currents
ksps	kilo-samples per second
Msps	mega-samples per second
N	times for repeating the same step signal for interleaving
O_s and U_s	overshoot and undershoot
P_m	phasor at timestamp m
R	reporting rate of PMU
R'	equivalent reporting rate of PMU
rrp	reporting rate periods
T_{resp} and T_{set}	response time and settling time
t_m	timestamp m
VA, VB and VC	three-phase voltages
V1, V2 and V0	three-sequence voltages
$\overline{\beta}$	vector of fit coefficients
θ	phase angle of input sinusoidal signal
Δv	magnitude error
$\Delta\theta$	phase angle error

7.2. Abbreviations

A/D	analog to digital
D/A	digital to analog

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DUT	device under test
GPS	global positioning system
GUI	graphical user interface
IRIG-B	inter-range instrumentation group time code
NIST	National Institute of Standards and Technology
PMU	phasor measurement unit
TVE	total vector error
UTC	coordinated universal time

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