Dynamic Characterization of PMUs Using Step Signals

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Abstract—**Performance evaluation of PMUs to confirm the consistency of phasor measurements is of a great importance since it promotes the interchangeability among PMUs from different manufacturers. This paper presents a method 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 PMU behavior 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. A set of programs are developed to automate step-based tests. Three commercial PMUs are selected to perform step tests using the dynamic test system developed at NIST. The test results are outlined at the end.**

Index Terms—**phasor measurement unit (PMU), synchronized phasor, power grid, dynamic behavior, step test, phasor estimation, interleaving, coordinated universal time (UTC)**

I. Introduction

SINCE phasor measurement unit (PMU) technology was developed and introduced into the power system in the early eighties, it has exhibited great superiority to traditional Supervisory Control and Data Acquisition (SCADA) system 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 August 14, 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.

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 test", is used in this paper to differentiate from the "dynamic test" using modulated 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 first. Four test types with balanced and unbalanced three-phase step signals to characterize the step response and results for three commercial PMUs obtained using the dynamic test system

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developed at NIST are discussed next. The implementation framework of the step test programs is described as well. Test results and conclusions are outlined at the end.

II. Extracting Reference Phasor

A. 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 NIST 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 NIST step testing.

To estimate the amplitude, phase angle and DC component of the reference measurement, a three-parameter Least Square Linear Fit 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 $y_1, y_2, \cdots, y_n, t_1, t_2, \cdots, t_n$ from the measurement system, for example, then these samples can be fit to the matrix model H consisting of the three column vectors as

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

The vector of fit coefficients $C^T = [C_0 \quad C_1 \quad C_2]$, where C^T is the transpose of C, are determined in the least square error sense by $\bar{y} \cong H\cdot C$ Then we obtain

$$A = \sqrt{C_0^2 + C_1^2}\ ,\ \theta = \arctan(C_1 / C_0)\ ,\ B = C_2$$

The step change in a signal may affect the accuracy of phasor calculation, particularly when the data window crosses the step point. In order to get rid of 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. Practically, there are two cases that need to be discussed: step point at output timestamp and step point between two output timestamps. Fig. 1 shows 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 calculate 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 Fig. 1, and the phase angle should be calculated at the end and beginning of the data window correspondingly.

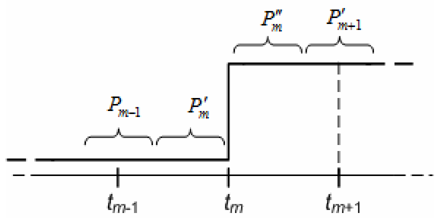

Fig. 1. Example of the step point at a time stamp

For the second case, one should select appropriate data windows to eliminate the impact of the step position, as shown in Fig. 2.

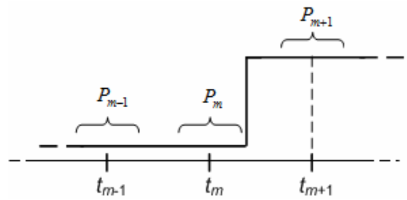

Fig. 2. Example of the step point between timestamps

B. Interleaving Phasors

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 Hz and 60 Hz nominal frequencies respectively [8]. Many commercial PMUs feature even higher rates of up to 50 frames per second and 60 frames per second for 50 Hz and 60 Hz nominal frequencies respectively. Hence, 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.

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

$$\cdots P_{m-1}^0, P_m^0, P_{m+1}^0\cdots, \cdots P_{m-1}^1, P_m^1, P_{m+1}^1\cdots, \cdots, \cdots P_{m-1}^{N-1}, P_m^{N-1}, P_{m+1}^{N-1}\cdots$$

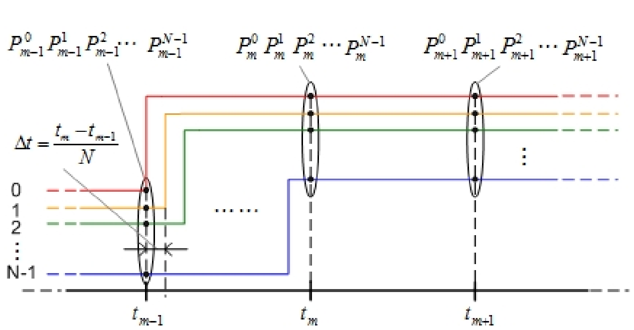

Fig. 3. N sets of output phasors obtained by repeated measurements of time-shifted step signals

If one interleaves those phasors in accordance with their timestamps relative to the step time by the way depicted in Fig. 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 Fig. 5 and Fig. 6, which display output phasors of a PMU before and after interleaving respectively, where N is 10.

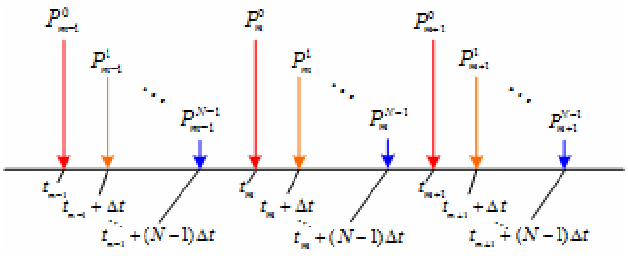

Fig. 4. Interleaving of Phasors

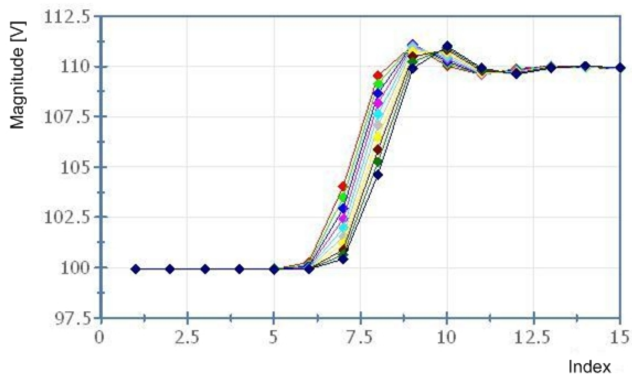

Fig. 5. Output phasors of a PMU before interleaving

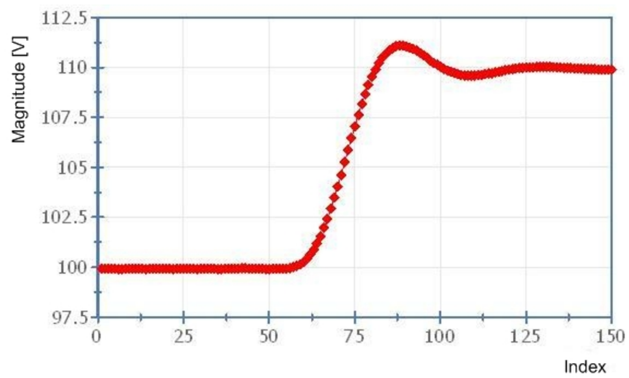

Fig. 6. Output phasors of a PMU after interleaving

III. Test Implementation

A. Step Test System

The step tests are implemented using the dynamic test system developed in the SynchroMetrology Laboratory at NIST [11]. As Fig. 7 shows, it consists of a Global Positioning System (GPS) clock used to synchronize the system to UTC (Coordinated Universal Time), a data acquisition system used to generate and sample test signals, three voltage amplifiers and three transconductance amplifiers connected to DUT (Device Under Test), three voltage attenuators and three current transducers. The system outputs six voltages with amplitudes of ±10 V peak at a strobe rate up to 1 mega-sample per second and samples those voltages with the same amplitude range at up to 500 kilo-samples per second. 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.

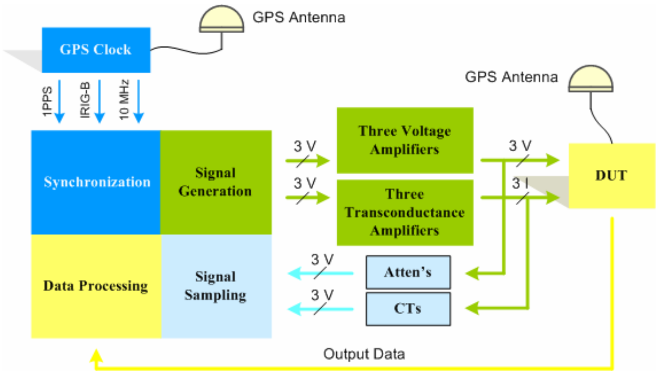

Fig. 7. Diagram of the step test system

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 to automate the test procedures. The algorithms for extracting the reference phasor are applied into these programs. Fig. 8 displays the implementation framework of the step test programs.

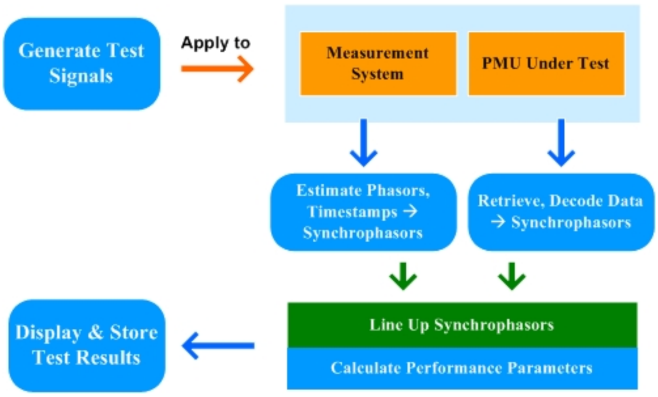

Fig. 8. Framework of step test programs

B. Test Plan

Three commercial PMUs were selected to investigate the dynamic characterization using the proposed step test system. 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.

TABLE I

FEATURE SUMMARY OF PMUS BEING TESTED

Feature	PMU A	PMU B	PMU C
Filter Type	Optional	Optional	Optional
Adaptive Tuning	N/A	Available	N/A
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 /sec)	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	Built-in	IRIG-B input

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: Amplitude test, Phase test, Recovery Amplitude 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 important performance parameters are measured to characterize the dynamic response of PMUs when exposed to step signals: response time, settling time, overshoot and undershoot, as illustrated in Fig. 9. Besides, TVE [8], errors of the amplitude, phase angle, frequency and rate of change of frequency are measured as well to evaluate the accuracy levels of PMUs. Once the amplitude error Δv (in percent of full scale) 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.

TABLE II
DESCRIPTION OF TEST TYPES AND CONDITIONS

Test Type	Reference Condition	Description
Amplitude: ±10% step of 100% rated magnitude	Balanced 3-phase voltage and current signals, amplitude 100% rated, nominal frequency	From a steady state, apply a balanced amplitude step, followed by a reversed step back to the starting state.
Phase: 10° step of inception angle	Balanced 3-phase voltage and current signals, amplitude 100% rated, nominal frequency	From a steady state, apply a balanced phase step, followed by a reversed step back to the starting state.
Recovery Amplitude: from zero amplitude of one phase to100% rated.	Unbalanced, Amplitude of non-stepped phases 100% rated, normal phase angle, nominal frequency	From a steady state, amplitude of one phase steps from zero to 100% rated, followed by the reversed step back to the starting state.
Recovery Phase: from normal phase angle of one phase to 180°	Unbalanced, Amplitude of all phases 100% rated, 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.

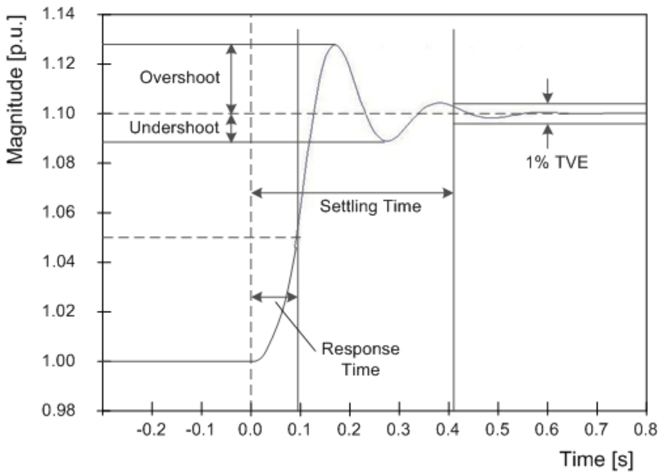

Fig. 9. Illustration of performance parameters

C. Test Results

Four types of step tests as described in Table II were performed on three commercial PMUs. To study the effect of the inception angle on test results, each test runs with the inception angle of voltages and currents from 10º to 340º in 30º 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. Fig. 10-13 display the amplitude, 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 0.4s and 0.8s, respectively. For PMU B and PMU C, two steps for each type of step tests were applied at 0.2 s and 0.4 s, respectively. Each curve consists of the result with different inception angles from 10º to 340º in 30º steps by overlaying them. Some of the performance parameters describing the dynamic step transition progresses are given in Table III-VI, where T_{resp}, O_s, U_s and T_{set} are response time, overshoot, undershoot and settling time, respectively as illustrated in Fig. 9. Their values are calculated as maximum values among different inceptions for the first step part. The uncertainty in these values for the NIST test system is about 0.5 μs for time and 0.05% for magnitude.

As it can be seen from the test results, the average response time of PMUs being tested is around 2 cycles in 60 Hz (33.3 ms). PMU A exhibits unique dynamic behavior in the transition when responding to step signals. Its overshoot is over 10% of the step, and the settling time exceeds 15 cycles in 60 Hz under recovery phase tests. That may result from the characteristics of the filter being used. Test results also indicate that inception angle has barely any effect on the dynamic performance.

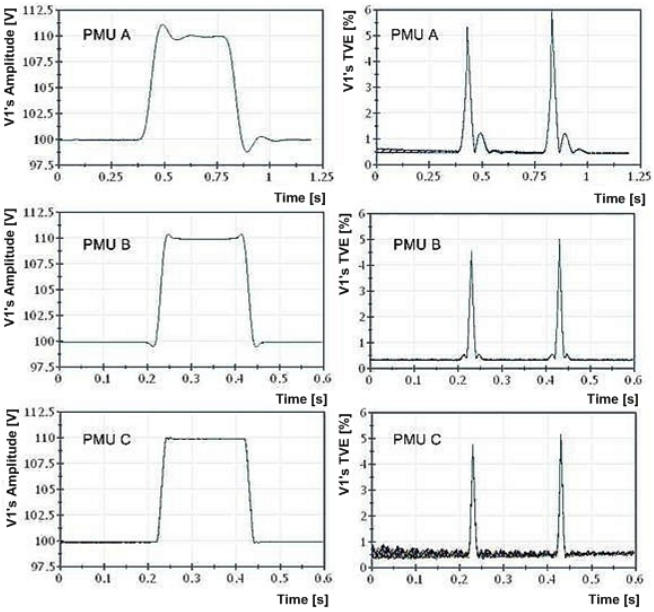

Fig. 10. Results of amplitude test

TABLE III
PERFORMANCE PARAMETERS OF AMPLITUDE TEST

DUT	T_{resp} (ms)	O_s (% of step)	U_s (% of step)	T_{set} (ms)
PMU A	34.9	12.0	-3.2	109.8
PMU B	30.0	4.7	-0.09	53.3
PMU C	30.3	2.4	-0.56	39.3

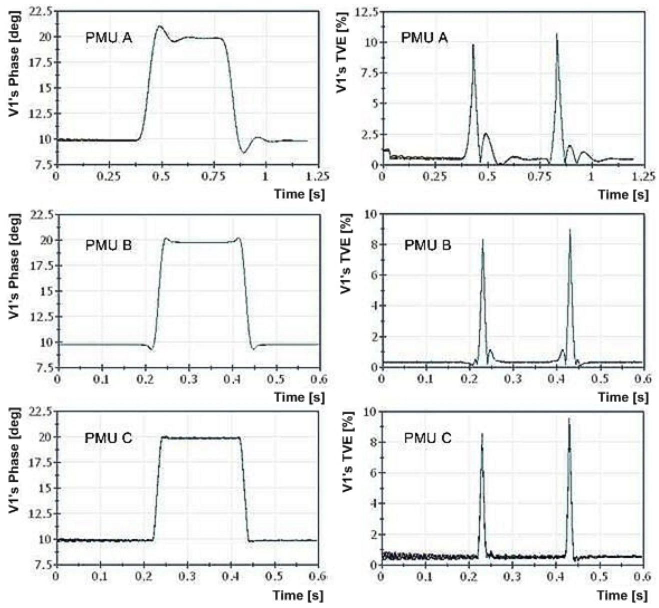

Fig. 11. Results of phase test

TABLE IV
PERFORMANCE PARAMETERS OF PHASE TEST

DUT	T_{resp} (ms)	O_s (% of step)	U_s (% of step)	T_{set} (ms)
PMU A	35.0	12.2	-3.3	126.6
PMU B	30.0	4.8	-0.2	38.9
PMU C	30.3	2.5	-0.9	38.4

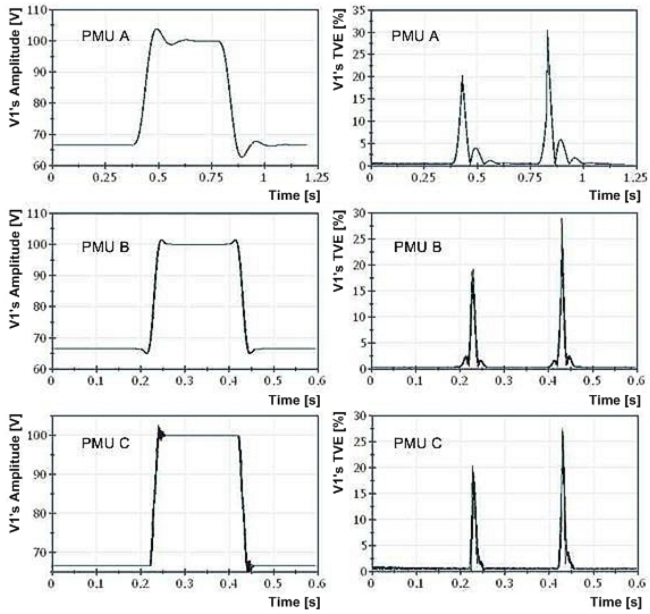

Fig. 12. Results of recovery amplitude test

TABLE V
PERFORMANCE PARAMETERS OF RECOVERY AMPLITUDE TEST

DUT	T_{resp} (ms)	O_s (% of step)	U_s (% of step)	T_{set} (ms)
PMU A	36.2	11.0	-3.2	176.5
PMU B	31.3	5.0	-0.06	56.5
PMU C	31.3	7.6	-4.1	52.1

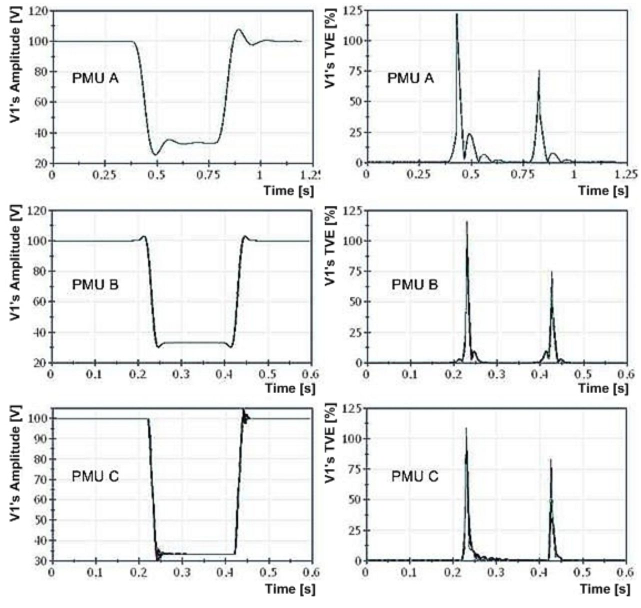

Fig. 13. Results of recovery phase test

TABLE VI
PERFORMANCE PARAMETERS OF RECOVERY PHASE TEST

DUT	T_{resp} (ms)	O_s (% of step)	U_s (% of step)	T_{set} (ms)
PMU A	36.2	-12.1	3.2	259.9
PMU B	31.3	-5.0	0.08	73.1
PMU C	31.1	-7.6	4.5	95.0

IV. 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 interchangeability 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 parameters summarized in the paper indicate good dynamic behavior consistency among most of the tested PMUs.

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VI. Biographies

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Gerard Stenbakken (M'71) received his B. of Physics from the University of Minnesota in 1964, the M.S. in Physics and the M.S. in electrical engineering from the University of Maryland in 1969 and 1986, respectively. He started working at Vitro Laboratories in 1963 and moved to the National Bureau of Standards (now the National Institute of Standards and Technology) in 1969. His areas of interest include semiconductor resistivity measurements, sampling metrology, testing strategies, electric power metrology, and magnetic field modeling.