

Calibration of Phasor Measurement Unit at NIST

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*Abstract*¹ — Phasor Measurement Units (PMUs) are being deployed on electric power grids to monitor their static and dynamic behavior. The information they gather is important to detect problems on these systems and to prevent blackouts. The PMUs require time synchronization of the data taken across the grids. This is done using Coordinated Universal Time (UTC) usually derived from the Global Positioning System (GPS). This paper describes the basic operating principles of PMUs and their time requirements to estimate absolute phase angles. A National Institute of Standards and Technology (NIST) PMU calibration system that tests PMU performance necessary to meet the IEEE synchrophasor standard requirements is discussed. The calibration of voltage, current and time measurements for the NIST PMU test system is described. The total vector error (TVE) of the NIST PMU test system is estimated to be 0.05 %. A comparison between the NIST PMU test system and a prototype commercial PMU calibrator was performed to assure traceability of relevant electrical measurements and time measurement.

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Index Terms — Calibration, Coordinated Universal Time (UTC), Global Positioning System (GPS), Phase Measurement Unit (PMU), total vector error (TVE), traceability, uncertainty.

I. INTRODUCTION

The electric power transmission network is being upgraded with new information technologies to more rapidly monitor the state of the grid. With the planned addition of many new energy sources, such as solar, wind, and others, the power grid observability has become important to minimizing future blackouts.

One instrument type that provides high observability of the grid state is Phasor Measurement Units (PMUs). Hundreds of PMUs have been deployed in the U.S. power grid and worldwide in the past few years. In order to observe the health of the power grid, the measurements made by the PMUs must be time synchronized. This is normally done using Coordinated Universal Time (UTC) derived from the Global Positioning System (GPS). The standard for PMUs, IEEE C37.118.1-2011 [1], was recently updated. This standard defines the uncertainty requirements for the PMUs in terms of Total Vector Error, TVE. This error measurement assures that compliant PMUs have limited uncertainty in both their magnitude and time-synchronization errors. The standard limits the TVE uncertainty for the phasors, the frequency errors, FE, for the frequency estimates, and the RFE, rate-of-change-of-frequency (ROCOF) error for various power signal conditions.

The synchrophasor representation \mathbf{X} of a signal $x(n)$ is the complex value given by Equation (1).

$$X(n) = X_r(n) + jX_i(n) = (X_m(n)/\sqrt{2})e^{j\varphi(n)} \quad (1)$$

where $X_m(n)/\sqrt{2}$ is the root mean square (rms) value of the signal $x(n)$ and $\varphi(n)$ is its instantaneous phase angle relative to a cosine function at nominal system frequency ω synchronized to UTC. $TVE(n)$ is defined as shown in Equation (2):

$$TVE(n) = \sqrt{\frac{(\hat{X}_r(n) - X_r(n))^2 - (\hat{X}_i(n) - X_i(n))^2}{(X_r(n) + X_i(n))^2}} \quad (2)$$

where $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the sequences of estimates given by the unit under test, and $X_r(n)$ and $X_i(n)$ are the sequences of theoretical values of the input signal at the instants of time (n) assigned by the unit to those values described in [2].

This paper will describe how the NIST PMU test system makes traceable magnitude and phase calibration for ac signals under static and dynamic conditions. Also, calibrated are the frequency and rate of change of frequency measurements made by the PMUs. The PMU test results are then compared to the performance requirements defined in the IEEE PMU standard. To improve traceability of PMU measurements across the many test systems a PMU round robin using a stable PMU is being planned.

II. NIST PMU TEST SYSTEM

Figure 1 shows a block diagram of the NIST PMU test system. The system is based on generating stable test signals for a PMU to measure [3]. These test signals are measured by the NIST test system as they are applied to the PMU. The traceability of the NIST PMU test system consists of showing traceability of the sampling system to national standards. Note that this includes testing of the software used to estimate the phasor values.

A. Hardware

The Synchronized Generation and Sampling System are housed in a National Instruments PXI² chassis. Two cards in the system are used to generate sampling clock signals for the generation and sampling cards of 18 MHz that is synchronized with UTC via the GPS signals. This provides a very stable clock for the system and prevents jitter in the generation and sampling caused by separate clocking. This frequency was chosen to allow the generation of both 50 Hz and 60 Hz power signals with an integer number of samples per cycle.

Six channels of 16-bit digital to analog (D/A) generate the source signals for the three voltage and three current channels. These have a maximum output of ± 10 V. These signals have a strobe rate of between 48 kHz to 500 kHz for various applications. When generating PMU test signals the generation cards usually run at 48 k samples per second (sps). A single pole filter with a 3 dB cutoff of approximately 5 kHz is used on all six channels to reduce the sampling steps.

Three voltage amplifiers with a gain of 21 are used to generate the nominal 70 V rms signals for the PMU tests. Three transconductance amplifiers with a transconductance of 1 A per 1 V are used to generate the nominal 5 A rms signals for the PMU tests.

The three resistive voltage attenuators have a nominal ratio of 21-to-1. They are NIST built and calibrated using low temperature coefficient, TC, resistors and are compensated to have flat frequency response from dc to over 5 kHz and constant time delay over that frequency range. The three current transformers (CTs) are NIST built two stage [4] designs to give stable

² Certain commercial equipment, instruments, or materials are identified in this report to facilitate understanding. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that the materials or equipment that are identified are necessarily the best available for the purpose.

transimpedance and time delays over that same frequency range. The CTs have a ratio of 10 to 1. Ten low TC 10 ohm resistors in parallel are used for the secondary burden and one 1 ohm low TC resistor is used for the tertiary burden.

The design of using the sampling of signals to the device-under-test, DUT, as the calibration reference allows this same system to be used to calibrate PMU calibrators. For such calibrations the NIST voltage and current generators are replaced with the signals from the commercial PMU calibrator. A signal from the commercial PMU calibrator to a digital input on the NIST calibrator is used to coordinate the operation of the two systems.

Synchronization of the system to UTC is maintained with a clock synchronized to UTC via reception of a GPS signal. The NIST test system is located in an underground building so the reception of the GPS signal is made more difficult. The reception is performed by use of a down up convertor. Near the GPS antenna a down convertor changes the GPS signal band from the nominal 1.575 42 GHz to an intermediate frequency (IF) of 4.092 MHz from the beating with a local oscillator (LO) of 16.368 MHz. The lower frequency signal is transmitted with much lower loss to the underground location using approximately 150 m of cable. In the testing laboratory the signal band is upconverted to the nominal 1.575 42 GHz signals. This signal is applied to the GPS clock and to the PMUs if required.

The signals from the GPS /clock used by the NIST test system are the 1 pulse per second (1 PPS) signal, an InterRange Instrumentation Group Time Code Format B [5] (IRIG-B) and a 10 MHz signal. The 1 PPS signal is used to synchronize the start of the signal generation and the signal sampling. This hardware synchronization assures that the generation and sampling rate signals are synchronized to the clock reference signal. The IRIG-B signal is used to determine the second of the year to which the test is synchronized. The 10 MHz signal is used as described

above to generate the 18 MHz clock reference signal.

B. Software

The PMU testing software is written in LabVIEW². Most critical of the software are the four analysis algorithms used to translate the sampled data into phasor estimates that are used to calibrate the DUT.

As indicated above, the same voltage and current signals applied to the DUT are sampled by the Signal Generation and Sampling System. This system also receives the timestamped phasor information from the DUT. This includes all the phasors programmed into the DUT and the frequency and rate-of-change-of-frequency (ROCOF) estimates. For testing purposes the signal samples are used to develop accurate timestamped estimates for these signals based on the calibration of the NIST test system. This calibration is described more fully in a section below. The standard specifies various test signal conditions.

The power signal conditions that are prescribed in the updated Synchrophasor Standard, C37.118.1-2011 [1], can be divided into four categories. First are the steady state conditions with various signal frequencies, phases, and magnitudes and the addition of harmonic and interharmonic signals. Second are the time changing conditions with amplitude, phase, and ROCOF steps. The ROCOF step is usually referred to as the frequency ramp test. The third and fourth categories are parts of the amplitude and phase modulation tests. Different analysis algorithms are used depending on the frequency of the modulation.

All of the analysis algorithms are variations of fitting algorithms. The differences between these algorithms are the functions used for the fitting. Since the generation and sampling are synchronized using a well-known frequency source and timing system, the

frequency and ROCOF of the steady state signals are well defined. The steady state algorithm uses a fitting function that includes one or two signal frequencies. The fitting function includes sine and cosine functions for the one or two signal frequencies along with a dc component. These allow for estimating the magnitude and phases of the one or two signals. The two signal frequencies functions are used for the harmonic and interharmonic test. The well-known frequency and ROCOF are used for determining the FE and RFE of the DUT. This algorithm always selects samples such that timestamp is at the center of the sampling window. The number of cycles of the fundamental used in each sampling window is programmable. Normally this is set at three cycles.

The fitting functions used for the time changing conditions are very similar to those for the steady state test, except that they include a rate of change parameter for defining the functions. This algorithm uses selection of the samples to avoid fitting across a parameter step [6]. The data before or after the step are used. The sampling windows for timestamps near the steps are not in the center of the sampling window. Figure 2 shows the relation between the data samples windows and the timestamps near a magnitude step, which occurs at t_{step} . Data sample windows are shown for timestamps t_x to t_{x+4} . The data sample windows for timestamps up to and including t_x are centered on the respective timestamps. The window for timestamps t_{x+1} and t_{x+2} use the same data, all using data before the magnitude step. The timestamps t_{x+1} and t_{x+2} are not centered in this window. The window for timestamp t_{x+3} uses data after the step. The timestamp t_{x+3} is not centered in that window. The windows for timestamps t_{x+4} and later all use windows centered on the respective timestamps. This algorithm allows for iterating on the signal frequency to achieve a fit with small residuals. This feature is used for the frequency ramp test to determine the frequency at each timestamp. The reference ROCOF value used is the predefined

one used to generate the signals.

As stated above the analysis algorithms used for the modulation tests depend on the frequency of the signal modulation. For modulations below about 1 Hz a Taylor expansion algorithm is used [7]. The fitting functions used in this algorithm include the sine and cosine functions for the nominal signal frequencies as the algorithms above. They also include higher order time derivatives of these functions. The sample windows are centered on the timestamps. The fit for the first time derivative functions are used to estimate the signal frequency at the timestamps and the second time derivative functions are used to estimate the signal ROCOF at the timestamps. Only third order functions are use in tests, i.e., first and second time derivatives of the sine and cosine functions.

For modulation frequencies above approximately 1 Hz the three waveform fitting algorithm is used [7]. This algorithm uses an iterative approach to fit the window of samples to three time varying sinewaves. The iterations allow for fitting the frequency and phase of the modulation from which the frequency and ROCOF are estimated.

III. CALIBRATION OF NIST PMU TEST SYSTEM

The NIST PMU test system is calibrated using calibrated test input signals. The method uses signals synchronized with UTC and with constant magnitude. The NIST test system algorithms are used to estimate the magnitude and absolute phase angle of the signals. The magnitudes and phases of the test signals are determined using laboratory test equipment with a traceable history.

The magnitude errors of the NIST PMU test system are measured using a DVM and the Swerlein algorithm [8, 9]. This requires a DVM with modeled dc sampling and a dc calibration. The meter is calibrated with a traceable source with uncertainty of 2 parts in 10^6 . Then the

uncertainty of the meter is less than 5 parts in 10^6 for readings up to 100 Hz and 100 V rms. This is used for the voltage channels and the voltage out of the CTs. This calibrates the voltage attenuators, the voltage A/Ds, and the fitting algorithms. The magnitude and phase errors of the CTs are traceable back to the NIST calculable shunt [10]. The system used to do that is described in an intercomparison published in 2005 [11]. The gain and phase errors are determined from 40 Hz up to 10 kHz. The phase errors of the voltage attenuators are done by assuring the flat gain errors of the attenuators over the 50 Hz to 3 kHz range.

PMU calibrations are somewhat unique in that in addition to determining phase errors of the channels, the time alignment of the samples to UTC must be determined. Figure 3 shows the NIST system time alignment test setup. It consists of using an oscilloscope to compare the zero crossings of the generated waveforms with a 1 PPS signal from a GPS clock. The GPS clock used in the NIST PMU calibration system has an uncertainty of less than ± 45 ns between the pulse signal and UTC. Several factors affect the accuracy of this calibration. These include how the amplitude noise on the signal affects the ability of the oscilloscope to resolve the zero crossings, the phase shift of the current transformer (CT) used to convert the current to a voltage, and the dc offset and distortion of the signals.

The calibration procedures used minimize several of the errors mentioned above. The NIST sampling system is acting as a PMU. It samples the same signals being sent to the PMU under test during PMU calibrations. Unlike commercial PMUs the NIST system can be set to use nominal signal frequencies other than 50 Hz and 60 Hz. This feature is used during the NIST system phase calibrations. For the phase calibration the nominal signal frequencies of the analysis system and the signal frequencies of the generated signals are set to frequencies from 200 Hz to 4 kHz. These higher frequency signals reduce the timing uncertainty due to the

amplitude noise on the signal and oscilloscope noise. The oscilloscope is set to amplitude over-range to display a higher voltage-to-time slope for these measurements.

IV. TRACEABILITY

The traceability of measurements requires control of many factors in the calibration process. The test equipment used must be traceable to reference standards, and the test procedures and staffs need to be qualified. This will better assure that PMUs tested by all of them will have the same behavior.

Inaccurate PMU calibration can lead to selecting PMUs that do not behave the same, which can have serious financial consequences to electric power utilities as well as reliability and safety consequences. There have been hundreds of PMUs deployed in the US power grid and several PMU calibration systems deployed in US industry, universities and research laboratories. The traceability of these PMU calibrations to a recognized standard organization (for example, to NIST or other national metrology institutes) has not been demonstrated. The NIST calibration system has an estimated one sigma uncertainty in magnitude of less than 0.01 % and a timing uncertainty of less than 0.3 μ s. This gives a three sigma total vector error, TVE, uncertainty of 0.05 %.

A prototype of commercial PMU calibration system has been developed. It includes a 3-phase electrical power standard, a GPS receiver to provide reference frequency and UTC time, a PMU calibrator device to time align the voltage and current phases of the power standard, and a MS² WindowsTM computer to receive the measurements from the PMU under test and perform analysis. The PMU calibration software is the control interface to the PMU calibrator to perform various tests defined in the C37.118.1-2011. A comparison between the NIST PMU calibration system and the prototype PMU calibration system was performed to evaluate its performance

and verify all measurements traceable to national standards with uncertainties required to perform PMU calibration.

As stated above the NIST system samples the voltage and current signals going to the PMU under test and uses that data to estimate the correct PMU response values. The prototype PMU calibration system similarly generates test signals for a PMU under test and the estimated proper PMU response values called reference PMU values. These two systems were compared using the test set-up shown in Figure 4. The two systems were time coordinated by having the prototype PMU calibration system send a trigger signal to the NIST system a few milliseconds before the beginning of a test. Then the NIST system triggers on the next PPS signal and samples the voltage and current signals as they were going to a PMU under test. These samples are used to estimate the proper PMU test results. After the test the NIST estimates are compared directly with the prototype PMU calibration reference PMU values.

Both the NIST test system and the prototype PMU calibration system are designed to work while connected to a PMU sending IEEE C37.118 messages. A PMU that is configured as two PMUs was used to provide phasor messages to both test systems as shown in Figure 4.

Independent analysis tools at the prototype PMU calibration and NIST determine TVE and other parameters. The differences between the NIST measurements and reference provided by the power source of the prototype PMU calibration system are calculated and analyzed, including the magnitudes and phases of voltages and currents for all 3 phases. Figure 5 shows the current amplitude differences of three phases between the NIST and the prototype PMU calibration system in a comparison of a steady test at 60 Hz with 70 V and 5 A. The measurements were made at 20 frames per second for 5 s. The current phase differences as well as the amplitude and phase differences in voltage measurements were also recorded. The

difference of TVE between the two measurement systems can then be calculated. Table I lists the results of the comparison for this test. The mean difference of TVE in current measurements was found to be 0.0025%, 0.0033% and 0.0031% for phase A, B and C, respectively. The mean difference of TVE in voltage measurements was found to be 0.0077%, 0.0081% and 0.013% for phase A, B and C, respectively. The differences between the two systems in voltage and current measurements are well within the requirement to make the PMU test. For this part of the comparison the difference between the NIST calibration system and the prototype PMU calibration system were the direct NIST measurements of the prototype calibration system signals, i.e., the PMU data was not used in this comparison.

A PMU calibration requires verifying a number of performance requirements for a PMU under test. In addition to verifying the errors in the PMU phasor values, frequency, and rate of change of frequency which are covered by the testing described in the tests above, other parameters must be determined. These other parameters, specified in the IEEE C37.118 Standard, include the response time of the PMU to steps in magnitude or phase, the PMU step delay time, step overshoot, and step undershoot. In another test using signals that are amplitude or phase modulated with a low frequency, 0.1 Hz up to 5 Hz, the bandwidth of the PMU must be measured. For these measurements the PMU data will be used to verify that the two calibration systems arrive at the same values for these requirements.

A PMU round robin coordinated by NIST is in preparation for other PMU calibration systems operating in industry and testing labs. This will use a stable PMU tested at NIST. This device will be shipped to several laboratories that have PMU calibration capabilities. Measurements of the traveling PMU according to well defined protocol will be carried out in

these laboratories. The results of the PMU testing by NIST and the participating laboratories will be compared.

V. IMPROVEMENT OF PMU PERFORMANCE

The benefits of PMU testing can be seen from the changes in PMU performance following the feedback to manufacturers of their PMUs' test results. Figure 6 shows the failed out-of-band interference test results for the first test on a PMU. The errors should be below 1 % TVE for all out-of-band frequencies. Following an update of the PMU's firmware by the PMU manufacturer, the out-of-band performance for a retest is as shown in Figure 7, which uses the same vertical scale for comparison. All the test results are below the 1 % TVE limit. The PMU passed this test and all other IEEE C37.118 requirements. This improved performance has happened for several PMUs tested at NIST following feedback of the results to the manufacturers.

VI. CONCLUSION

NIST has developed a PMU calibration system. The measurements in voltage, current and phase made by the NIST PMU calibration system have been calibrated against the reference traceable to the national standards. The NIST PMU calibration system has an estimated TVE uncertainty of 0.05%. This uncertainty is 5 times smaller than the requirements of C37.118.1 for TVE of the PMU test system. The system is being used for testing of PMUs. The NIST PMU calibration system has been compared with a prototype PMU calibration system. The difference between the two systems for PMU test for measurements in voltage, current and their phases are well within the requirements for PMU calibration purpose. The NIST system will also be used in a planned round robin to improve traceability of PMUs.

Acknowledgement

The authors would like to thank B. C. Waltrip for his assistance for calibrating CTs.

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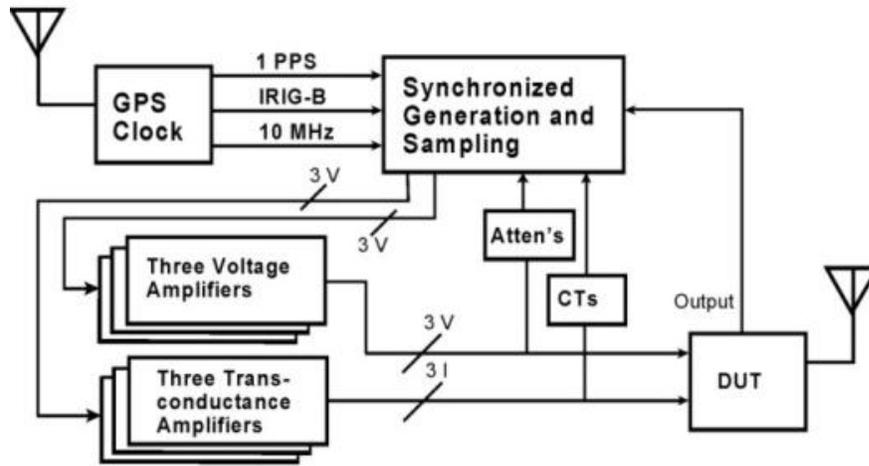


Figure 1. Block diagram of NIST PMU test system. IRIG-B stands for the Inter-Range Instrumentation Group time code B. CT refers to Current Transformer.

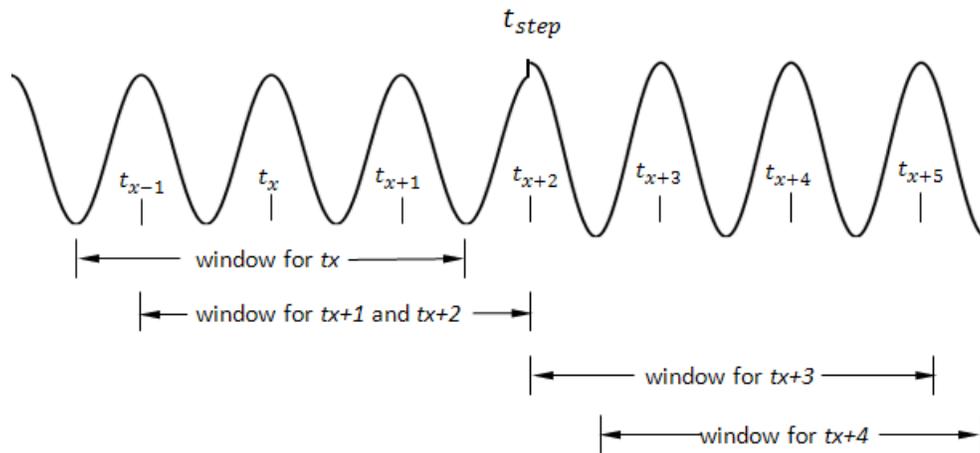


Figure 2. Relation between data sample windows for timestamps near a magnitude step. Windows shown are for data samples over three cycles of the fundamental signal. Timestamps reflect a reporting rate the same as the fundamental frequency. The magnitude step occurs at time t_{step} .

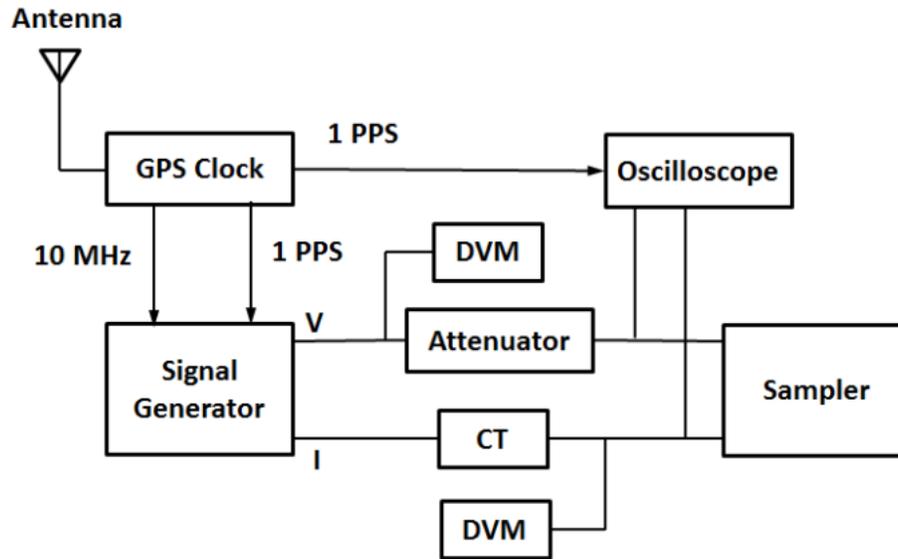


Figure 3. Block diagram of NIST magnitude and phase calibration test setup where DVM stands for digital voltmeter and CT for current transformer.

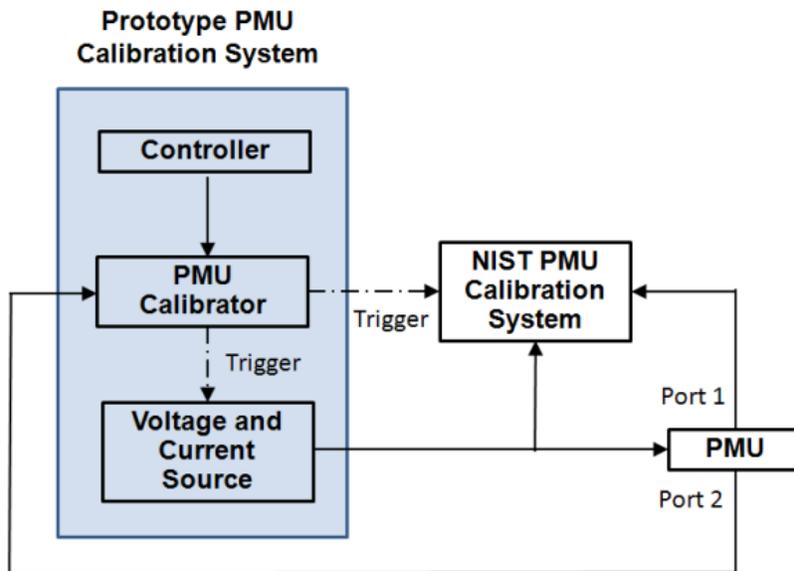


Figure 4. Setup for comparison between the NIST and the prototype PMU calibration systems.

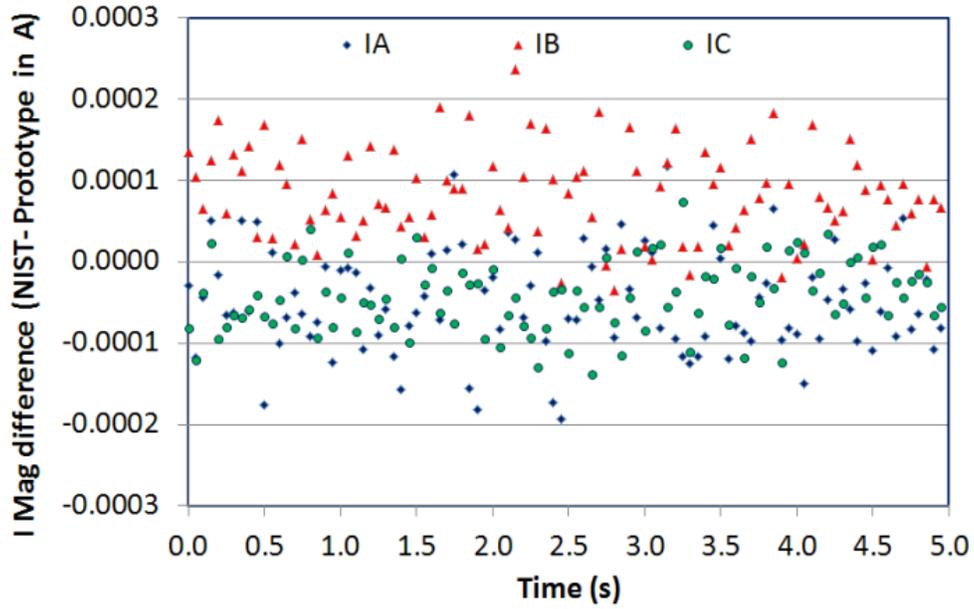


Figure 5. Current amplitude differences of three phases between the NIST sampling and the power reference from the prototype PMU calibration system are shown for a steady state test at 60 Hz for 70V and 5 A.

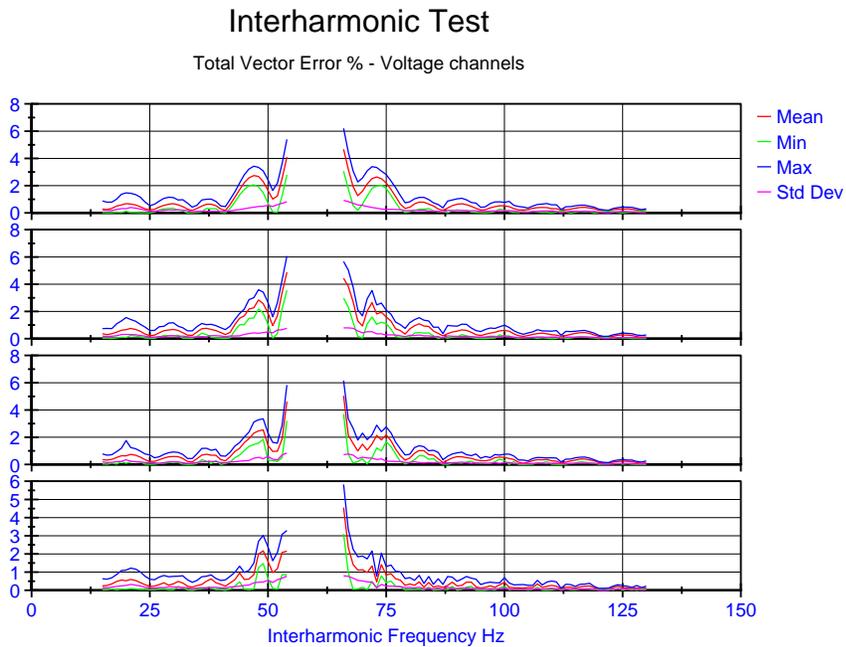


Figure 6. Out-of-band interference test results on first test.

Interharmonic Test

Total Vector Error % - Voltage channels

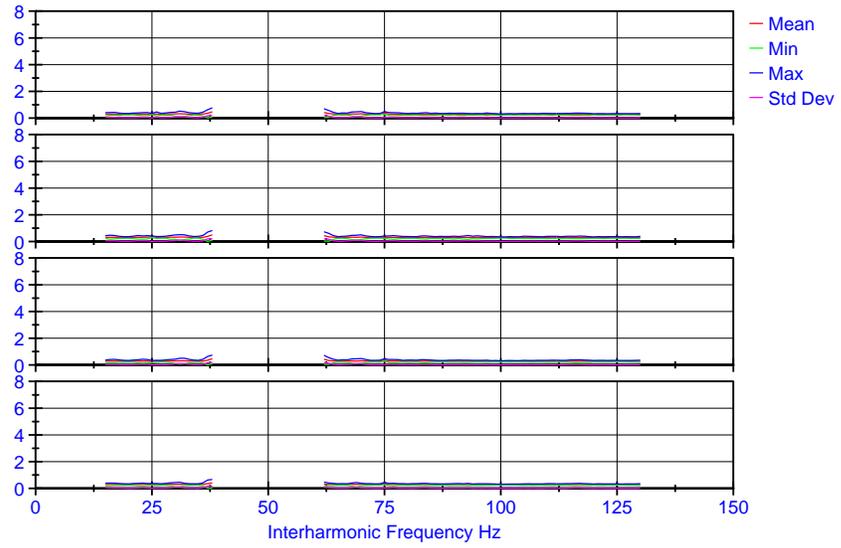


Figure 7. Out-of-band interference test results on second test.

TABLE I

CURRENT COMPARISON RESULTS BETWEEN NIST AND THE PROTOTYPE PMU CALIBRATION

SYSTEMS (ALL TVE IN %)

	IA TVE	IB TVE	IC TVE
Max.	0.0048	0.0058	0.0052
Min.	0.0002	0.0014	0.0009
Mean	0.0025	0.0033	0.0031
STDEV	0.0010	0.0009	0.0010



Yi-hua Tang received his Ph.D. in low-temperature physics from the University of Florida in 1987. He worked in the private sector from 1991 to 1996 in the field of Josephson arrays and voltage standards. He joined the National Institute of Standards and Technology, Gaithersburg, Maryland in January 1997 and is now working on the Josephson voltage standard and its applications in metrology. He is responsible for maintaining the U.S. legal volt and providing for the dissemination of an internationally consistent and traceable voltage standard tied to the SI units. His research interest is to develop applications of Josephson technology for dc and ac voltage metrology. In recent years he is also engaged in the Phasor Measurement Unit (PMU) research to develop traceable measurement technology for the Smart Grid. He is the recipient of a U.S. Department of Commerce Gold Medal. Dr. Tang is a member of the American Physical Society.



Gerard Stenbakken (M'71) received his B.S in 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 electric power metrology, semiconductor measurements, sampling metrology, testing strategies, and magnetic field modeling. He left NIST and formed GNS Consulting in 2009 to do research in power metrology.



Allen Goldstein received his B.S. in Electrical Engineering from the University of Southern California in 1982. From 1982 to 1987 he served as a U.S. Naval Submarine Officer. He worked in the private sector focusing on designing professional and consumer audio and video products based on emerging international standards. In 2008 he switched his focus to the design of electric power transmission and distribution products, also based on emerging standards. For the past two years Allen has been the Technical Project Manager for PMU Calibration at Fluke Calibration in Everett, Washington.