Static Calibration and Dynamic Characterization of PMUs at NIST

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Abstract—**This paper describes the development of two test systems at NIST aimed at improving the calibration and characterization of Coordinated Universal Time (UTC) synchronized electric power instrumentation. Reference to UTC is used to meet the need for precise time synchronization of instrumentation designed to monitor the state of the grid over its wide geographic area. The first test system is used to perform calibrations of Phasor Measurement Units (PMUs) for parameters that have performance requirements specified in IEEE Standard for Synchrophasors for Power Systems, IEEE Standard C37.118-2005. Tests performed on this system use static electric power signals. The second test system is being developed to perform dynamic tests of PMUs. This paper also describes the development of a PMU Testing Guideline by an industry wide task force as part of the Eastern Interconnect Phasor Project (EIPP).**

Index Terms—**Calibration, Dynamics, Global Positioning System, Phase measurement, PMU, Power system control, Power system measurements, Power system reliability, Synchronization.**

I. Introduction

POWER grid observability has been identified as an important factor in preventing future electric power blackouts [1]. Phasor measurement units, PMUs, have been identified as one of the best ways to increase the observability of the electric power grid [2]. To promote the interchangeability of PMUs and thus facilitate their rapid introduction into the electric power grid network, the Power Systems Relaying Committee of the IEEE Power Engineering Society developed a Standard for Synchrophasors [3] published in December 2005, IEEE C37.118-2005. This Standard specifies the performance requirements of PMUs with respect to the input signals amplitude, phase, frequency, and interference signals such as harmonics and interharmonics. This Standard defines the uncertainty requirements for the PMUs in terms of the Total Vector Error, TVE. This error measurement assures that compliant PMUs have minimal uncertainty in both their magnitude and time-synchronization errors. This latter error is the error in the PMU's time stamps with respect to Coordinated Universal Time (UTC).

To promote better test and measurement procedures for this type of testing, the National Institute of Standards and Technology (NIST) has established a SynchroMetrology Laboratory [4]. This laboratory is established to develop test and calibration methods where traditional waveform parameter metrology is combined with referencing these values to a synchronized timing source such as UTC. NIST has established a calibration service to calibrate PMUs for parameters referenced in IEEE C37.118. This testing is being done in support of the Consortium for Electric Reliability Technology Solutions (CERTS), which sponsors the Eastern Interconnect Phasor Project (EIPP) [5]. This project through a series of work groups is promoting wide area measurement, monitoring, and control to improve the power system reliability.

The first author is a member of the EIPP Performance Requirements Task Team and leader of the Testing Interoperability and Calibration Task Force. The objective of the task force is to reduce the risk to the utilities in adopting these new technologies. The task force is preparing the PMU System Testing and Calibration Guide (PMU Testing Guideline) to establish common methods for calibrating PMUs with the objective of making units from different manufacturers interchangeable within the electric power grid. The PMU Testing Guideline describes recommended test equipment requirements and test procedures for performing PMU C37.118 compliance testing. These tests hold the input signals to the PMU at various constant levels of magnitude, frequency, and interference signals; thus, these are called static tests. In addition to describing how to perform these static tests the PMU Testing Guideline describes how to perform dynamic tests on PMUs. Dynamic tests are intended to show the performance of PMUs under varying magnitude and frequency conditions typical of real power system conditions [6].

In addition to the C37.118 calibration system used for the PMU calibration service mentioned above, NIST is developing a dynamic PMU test system [7] to determine the dynamic performance of PMUs. The results of testing with this system will aid the development of future dynamic testing requirements for PMUs. The paper concludes with a description of future work to be done in this area by the industry, the task force, and NIST.

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II. NIST PMU Calibration System

The design of the NIST PMU calibration system is shown in Fig. 1. This system is synchronized to UTC via a Global Positioning System (GPS) clock. The calibration system provides UTC synchronized three-phase power signals to the PMU being calibrated. The PMU outputs a C37.118 standard formatted continuous data stream of 10 to more than 20 waveform measurement parameters at rates up to 60 messages per second each time stamped to UTC. The Standard requires the PMU clock be synchronized to UTC to within one microsecond. A commercial three-phase power simulator generates the voltage and current signals to the PMU. The manufacturer has modified the simulator so it can receive a sampling synchronization signal from the Synchronized Sampling and Generation unit (control unit). The control unit includes a computer with control software that automates much of the testing sequences. It also includes a six-channel sampler to measure the voltage and current waveforms supplied to the PMU under test using compensated resistive attenuators and current transformers (CTs). The time synchronization of the calibrator is maintained by triggering the waveform sampling with the one pulse-per-second (1 pps) signal from the clock. The Standard requires the PMUs to have a TVE of less than 1 percent under a number of test conditions described below. The NIST calibration system has an uncertainty of less than 0.015 percent TVE.

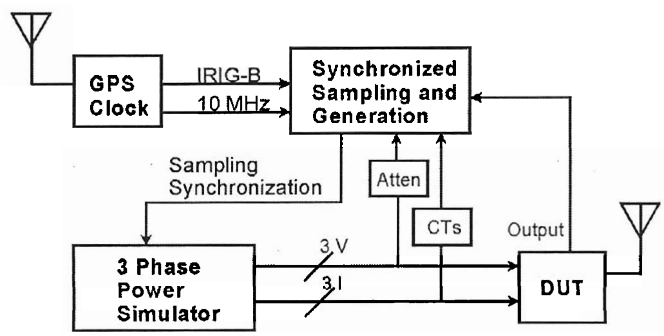

Fig. 1. NIST Phase Measurement Unit Calibration System

Fig. 1 shows both the GPS clock and device under test (DUT) connected to antennas to receive the GPS signals. Some PMUs do not have built in clocks, so usually they receive their timing information via an IRIG-B connection to an external GPS clock.

A critical parameter in the calibration of this test system is synchronizing the time of signal sampling to UTC. A common method used to perform this synchronization requires measuring the time delays of the zero crossings of the power voltage and current signals with the 1 pps signal of the GPS clock. Use of this method as the reference for signals during testing limits the test signals to frequencies that are an integer number of cycles per second. The NIST sampling system operates at a high rate (up to 500 kSps (samples per second)) and thus allows measuring the UTC relative phases of test signals that are significantly higher in frequency than power line frequencies. Once the synchronization of the sampling system to UTC has been established, the sampling system can be used to measure signals of any frequency and phase. The NIST calibration system was checked using frequencies up to several MHz. In general the use of higher signal frequencies results in a reduced timing uncertainty of the calibration system. However, the time delays of samplers can be a function of frequency. Figure 2 shows the time delay of the NIST sampling system as a function of signal frequency using two methods. The line labeled zero crossing was obtained by shifting the test signal phase to align the signal zero crossings to the GPS 1 pps signal and reading the phase angle indicated by the analysis of the calibrators samples. The lines labels FFT use a second method. The lines labeled maximum, average, and minimum are the respective time differences between the signal zero crossings and the 1 pps signal when the test signal phase is adjusted so the calibrator reads ±90°. The figure shows the slight frequency dependence of the sampler's time delay and that the projection of that time delay to power line frequencies is about 440 ns. This calibration factor has an uncertainty of 10 ns to 20 ns. This timing accuracy supports both the present and anticipated future applications of the system to calibrate UTC synchronized electric power instrumentation. The time delays of the voltage attenuator and CTs were determined to be a few ns. The GPS clock has a specified uncertainty of 45 ns.

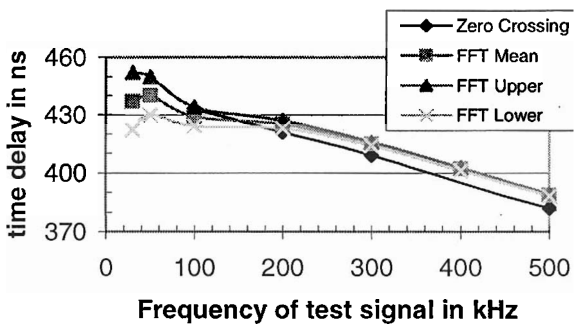

Figure 2 NIST Sampler Time Delay versus Signal Frequency

The Standard requires the PMUs to have less than 1 percent TVE for two levels of performance conditions. These conditions include various ranges of signal frequency, magnitude, and phase angle, as well as levels of harmonic distortion and out of band frequency (interharmonic) distortion. The NIST calibration covers all of these conditions with several hundred individual tests. All of these tests have been automated. The calibration also checks that the messages from the PMU are properly formatted, and that they reflect changes to the operating modes of the PMU. Messages are sent to the PMUs and proper response checked. The manufacturer specified message rates are tested and if available the change in antenna delay response is checked.

Disconnecting the GPS clock antenna checks proper PMU indication of the quality of the clock. Most of these latter tests require manual operations.

III. PMU TESTING GUIDELINE

Members of the EIPP are developing the PMU System Testing and Interoperability Guide. The goal for this PMU Testing Guideline is to support PMU interoperability by having clearly defined testing and calibration procedures. The PMU Testing Guideline will cover static tests that cover performance requirements given in IEEE Standard C37.118-2005 as well as dynamic tests beyond that Standard. The PMU Testing Guideline will cover tests on Intelligent Electronic Devices (IEDs) that integrate PMU functionality. These tests will show whether the performances of the PMU functions are affected by the other IED functions and vise versa. The PMU Testing Guideline is in draft form as of the writing of this paper and should be completed by early 2007.

IV. NIST DYNAMIC PMU TEST SYSTEM

To develop a better understanding of the dynamic performance of PMUs NIST has developed a dynamic test system. This system will apply dynamic three-phase signals to PMUs. A companion paper submitted to this conference [7] describes the test system and the algorithm model used to assure accurate parameter measurements under dynamic signal conditions. Fig. 3 shows a diagram of the dynamic test system. Its basic design is similar to the PMU calibration system. In place of the commercial power simulators, are three voltage and three transconductance amplifiers to provide the PMU test signals. The waveforms are generated in the Synchronized Sampling and Generation unit (control unit) and output as voltages with a range of up to ±10 V peak-to-peak. The six output channels have strobe rates up to 1 MSps.

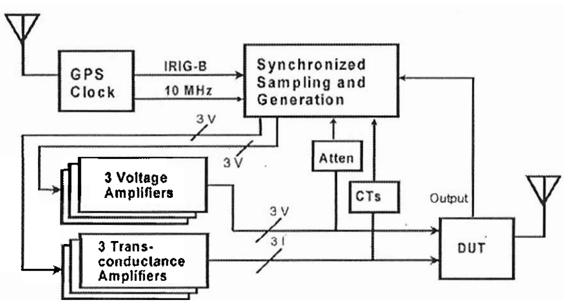

Fig. 3. Diagram of NIST dynamic test system.

The test signals generated have linearly varying magnitudes or frequency, as well as sinusoidal and damped sinusoidal magnitude (Fig. 4.) and frequency (Fig. 5.) variations. Arbitrary waveforms can be stored in the control unit memory and replayed allowing for the use of waveforms that have been sampled during electric power disturbances.

V. FUTURE WORK

Future work for this project will include characterization of commercial PMUs under dynamic signal conditions that will mimic variations in voltage, current, and phase recorded before and during instabilities on the grid. From this data and the accuracy needed to support power grid state estimator dynamic performance, new dynamic performance requirements for PMUs will be developed.

In addition to PMUs, the electric power industry makes use of numerous other instruments that require time synchronization. Such synchronization is necessary for their basic operation, such as fault location devices, or for later analysis of the sequence of events to determine the cause of a system disruption. These devices must be calibrated to assure the accuracy of the time stamps and interchangeability of units from different manufacturers. Since the NIST calibration system has the capability of sampling the signals presented to these devices, and the capability to produce dynamic signals, it can be used to calibrate the magnitude and time accuracy of many of these devices.

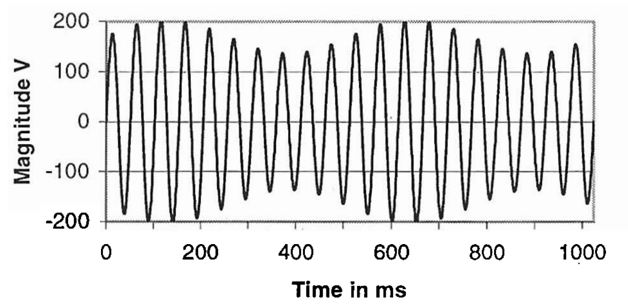

Fig. 4. Amplitude modulated dynamic test signal.

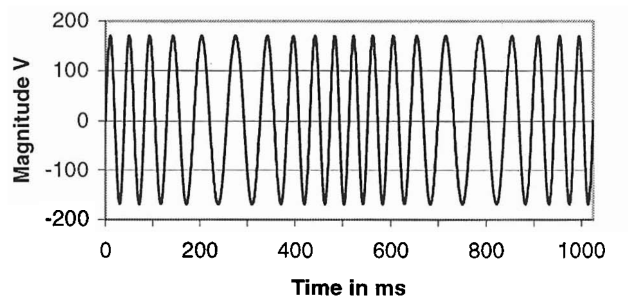

Fig. 5. Frequency modulated dynamic test signal.

VI. ACKNOWLEDGMENT

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VIII. Biographies

Gerard Stenbakken (M'86) was born in Minnesota, U.S.A. on March 17, 1941. He received a B. of Physics from U. of MN in 1964, a M.S. in Physics, and a M.S. in EE from U. of MD 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.

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