A PRECISION PRIMARY SIGNAL FACILITY TO TEST PHASOR MEASUREMENT UNITS

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SUMMARY

Synchronous measurements of ac power-system voltage, current, and frequency are commonly known as synchrophasors. This technology has been of greater interest at transmission-voltage levels, but recent advances in measurement and communication technologies now allow synchrophasor measurements at many points along power-distribution feeders. Consequently, electric utilities can now derive key insights into the workings of their distribution feeders and network.

Phasor measurement unit (PMU) capabilities have recently been added to an advanced distribution-protection device (ADPD) that is designed to meet the synchrophasor standard requirement using the primary voltage and current signals instead of the more common secondary-level signals used in traditional PMUs. However, with integrated voltage and current sensing within each pole-unit, a high-voltage test facility had to be developed to test the primary-level PMU capabilities of the ADPD. This test facility produces precisely controlled three-phase distribution feeder primary-level voltages and currents using a monitoring and control platform and precision power supplies.

These power supplies operate in tandem with step-up voltage and current transformers to achieve voltage levels up to 18 kV at 2000 amps. The purpose of this test facility is to compare a primary-level PMU device to a PMU device certified at the secondary level and connected to laboratory-grade current transformers (CTs) and class 0.15 metering grade voltage transformers (VT).

This paper discusses the design, construction, and testing of the facility, including the reasoning behind design decisions and equipment-selection options. The paper also describes how the control and monitoring system is used to manage the signals sent to the power supplies and how the primary level signal values are monitored.

INTRODUCTION

PMUs capture power system voltage and current signals based on their signal sampling rate and convert these signals into magnitude and angle values known as phasors. Because these phasor values are typically precision time-stamped using a common and accurate time source, phasor values from various points along a distribution feeder or network can be locally or remotely realigned to detect or identify power system anomalies. These time-stamped phasor values are referred to as synchrophasors. The latest requirements for PMU accuracy are defined in the IEEE/IEC 60255-118-111 standard, while the communication protocol is defined in IEEE C37.118.222.

Synchrophasor measurements provide more detailed and timely visibility into the power system compared to existing SCADA systems. This increased awareness allows system operators to make quicker and better decisions and allows wide-area protection schemes to operate faster and more reliably. The precise time-aligned nature of the data also simplifies analysis of historical data.

[1]IEEE/IEC 60255-118-1-2018, "Measuring relays and protection equipment - Part 118-1: Synchrophasor for power systems - Measurements," IEEE, 2018.

[2]C37.118.2-2011, "IEEE Standard for Synchrophasor Data Transfer for Power Systems," 2011.

In a recent report by Quanta Technology and Oak Ridge National Laboratory[3], five priority applications of synchrophasors on the distribution network include:

- Advanced microgrid applications and operation
- High-accuracy fault detection and location
- Advanced monitoring of distribution grid
- Improved load-shedding schemes
- Wide-area visualization

A phasor data collector (PDC) is a device that gathers the synchrophasor data from one or more PMUs and makes the data available for subsequent download and analysis. Capturing power system voltage and current signals is accomplished by converting primary-voltage level signals (kilovolts to tens of kilovolts and hundreds to thousands of amperes) to secondary-level signals (volts and amperes) expected by today's PMUs. However, primary-to-secondary signal conversion using conventional current and voltage transformation devices can introduce PMU measurement errors not captured by the certification procedures available today.

Compensating for these signal-conversion errors can be arduous because transformation devices are typically in situ, and their performance specifications are frequently unknown or the devices themselves are inherently inaccurate. Wiring between the secondary terminals of the transformation device and the PMU is usually lengthy, which also contributes to secondary signal errors. And unlike transmission-voltage level PMU installations, where phasor data from adjacent measurement nodes is used to null errors introduced by secondary signal irregularities, distribution circuit inconsistencies between PMU nodes typically prevent using this method to compensate for secondary signal inaccuracies.

The format of the PMU command, configuration, and data frames are dictated by the IEEE C37.118.2 Standard.

PMU CERTIFICATION

The IEEE/IEC 60255-118-1 standard divides the PMU-capable devices into two main classes, P-Class for protection applications and M-Class for metering applications. The P-Class PMUs are required to respond faster to transient events and stream this data to the PDC with low latency. The M-Class PMUs respond slower during transient events and have long data latency. However, they are more accurate and resistant to noise and interference in the signal. For both the P and M classes, the standard defines four main categories of requirements for testing PMU performance:

3 Quanta Technology, Oak Ridge National Laboratory, "Distribution Synchronized Measurements Roadmap," 2021.

- Steady State Tests are designed to evaluate the accuracy of the PMU during Steady state conditions. This includes the magnitude range test as well as the frequency range tests.
- Interference Tests evaluate the ability of the PMU to reject interference signals. Tests in this category include the harmonics distortion test and the out-of-band interference test.
- Dynamic Tests evaluate the ability of the PMU to accurately track a signal that is changing in magnitude, phase, or frequency. These tests also check the accuracy of the synchrophasor timestamping. Tests in this category include the magnitude modulation test, the phase modulation test, frequency ramp tests, and step response tests.
- Latency Tests check how fast a PMU can reliably convert voltage/current waveform samples into C37.118 data stream and send the digitized packets upstream.

The present standard and associated test suite are designed to validate the algorithm of PMU-capable devices without considering the type of sensors that will be connected. However, for PMUs installed on the distribution system, the voltage and current sensors are major sources of overall total vector error (TVE). To evaluate the accuracy of the PMU, it is very important to include the sensor errors.

According to the IEEE C57.13 Standard Requirements for Instrument Transformers, a typical accuracy class 0.3 voltage or current transformer can have a worst-case magnitude error of 0.3% at 100% rated voltage and 0.6% at 10% rated voltage. The worst-case phase error is ~30 minutes (0.5 degrees) at rated voltage[4]. This means a class 0.3 metering grade voltage transformer can potentially introduce a 0.924% TVE at 100% rated voltage. This error contribution is even larger for voltage below 90% of rated voltage. When similar calculations are done for accuracy class 0.3 current transformers, the resulting worst-case TVE is ~0.4% at 100% rated current at 1.0612% at 10% rated current.

The overall TVE contribution caused by sensors is even worse for distribution reclosers. Typically, the reclosers installed on distribution lines are optimized for protection and limited by overall size and weight. The sensors used normally have much worse accuracy than class 0.3 instrument transformers. An example from a third-party product specification document states voltage magnitude accuracy of 2% and phase accuracy of 1.5 degrees, which would mean a worst-case TVE of 3.3%. Typical CTs used for reclosers are between class 0.6 and 1.2, with a worst-case magnitude error of 0.6% to 1.2% and a phase error of between 60 and 120 minutes, resulting in a worst-case TVE of 3.7%.

[4]IEEE Standard C57.13-2008, “IEEE Standard Requirements for Instrument Transformers,” 2008.

ADVANCED DISTRIBUTION PROTECTION DEVICE

PMU capabilities have recently been added to an advanced distribution protection device (ADPD). This device has integrated three-phase voltage sensing on both sides of the interrupters and performs fault interruption, fault isolation, and circuit restoration in a single package. It also includes three fault-current sensing Rogowski coils to provide linear output over the full range from load to fault current. The synchrophasor data message format of the ADPD is shown in **Table 1**.

TABLE 1. ADPD Synchrophasor Data Message Format

Field	Size (bytes)	Comments	Approx. Resolution
Sync	2		
FrameSize	2		
ID code	2	ID of unit (1 to 65534)	
SoC	4	Seconds since 01-Jan-1970	
FracSec	4	Time quality & Fraction of second	60 ns
Stat	2	PMU Status	
Phasors	8	VX_1	10 mV
Phasors	8	VX_2	10 mV
Phasors	8	VX_3	10 mV
Phasors	8	VY_1	10 mV
Phasors	8	VY_2	10 mV
Phasors	8	VY_3	10 mV
Phasors	8	I_1	0.1 mA
Phasors	8	I_2	0.1 mA
Phasors	8	I_3	0.1 mA
Freq	4	FREQ_X	12 µHz
DFreq	4	ROCOF_X	0.1 µHz/s
Analog	4	FREQ_Y	12 µHz
Analog	4	ROCOF_X	0.1 µHz/s
Digital	2	Pole_Position_1 Pole_Position_2 Pole_Position_3	
Chk	2	CRC	
TOTAL	**112**		

The Rogowski current sensors are more accurate than typical distribution recloser CTs and have a much wider frequency response. This makes the ADPD more accurate than a typical PMU designed to use CTs, especially at off-nominal frequencies.

Unlike current transformers, Rogowski current sensors measure the rate of change of current instead of the current itself. The step-response requirements of the present standard are not suitable for Rogowski current sensors because a step-in magnitude or angle in current translate into an impulse response on the Rogowski current sensor output. To pass the same step-response tests, a PMU that uses Rogowski current sensors requires much more filtering compared to typical PMUs designed for current transformers. In real power systems, the impedance of the power system restricts the rate of change of current, so the step tests described in the present standard test procedure are not realistic on the power grid.

The ADPD firmware uses the existing ADPD hardware for M-class and P-class PMU calculations. When installed on a 50-Hz power network, the system can provide data at 10, 25, 50, and 100 frames per second. When installed on a 60-Hz system, the ADPD supports 10, 12, 15, 20, 30, 60, and 120 frames per second. The typical latency for P-class measurements is less than 30 ms.

DESIGN OF PRIMARY-LEVEL TEST FACILITY

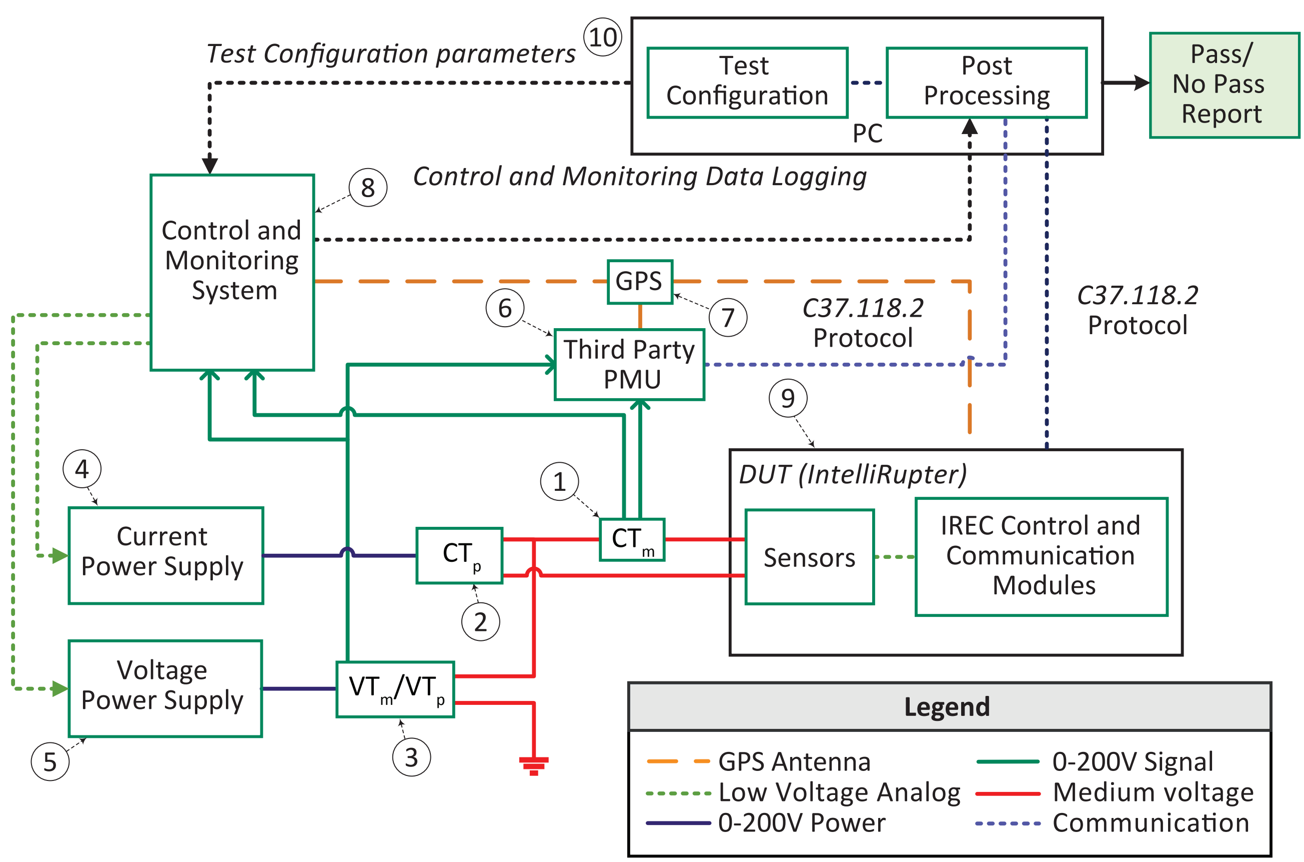
Traditional PMUs are designed to measure the secondary output of a primary transducer; however, the primary transducer is not a part of the PMU product. To design and test primary measurement capability for a PMU system that is part of an ADPD, a primary test facility was needed to validate the ADPD's components and verify its PMU functionality.

The authors are only aware of one active standard, IEEE 60255-118-1:2018, that provides guidance on the requirements for such a PMU test facility. The standard is geared toward the testing and qualification of traditional PMUs and does not account for the challenges associated with primary measurements and control. A major challenge faced with the ADPD to be tested is that its voltage and current sensors are integrated within the pole-unit during manufacturing. This simplifies calibration and installation.

To test the PMU performance, however, the current sensors have to measure primary level currents while at primary level potential. A traditional power source could not be used, both because the cost of power would be prohibitive and it could not be controlled precisely to meet the PMU standard testing procedures.

To test the ADPD at rated voltages and currents, a primary injection facility was constructed with the components shown in **Figure 1**.

FIGURE 1. Overview diagram of the primary injection system.



The components in this figure are the.

1. Precision current transducer used for measuring the primary level amperage
2. Step-up current transformer used to amplify the current signal from the secondary level of the power supplies to the desired primary-level amperage
3. Precision step-up transformer used to both amplify the signal from the power supplies and also to provide the secondary-level voltage signal to the control and monitoring system
4. Power supply used to generate the secondary voltage for the current channels
5. Power supply used to generate the secondary voltage for the voltage channels
6. Third-party PMU used to compare against the values reported by the device under test (i.e., the ADPD)
7. GPS signal repeater used to provide precise time signals to the control and monitoring system, the third-party PMU, and the ADPD
8. Control and monitoring system that receives signals in accordance with the IEEE Conformity Assessment Program (ICAP) test profiles and converts those to the appropriate corresponding inputs to the power supplies

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9. Device Under Test (DUT), the ADPD under test that is fed the primary level signals
10. The test configuration computer that (a) provides the ICAP test profiles to the control and monitoring system, (b) receives PMU data from both the third-party PMU and the ADPD, and (c) provides comparisons between two inputs

Note that items 1 through 5 show only a single phase for clarity. In practice, the test facility has three phases of primary-level signals driven by multiple power supplies.

FIGURE 2. Instrument voltage transformer.

CT/VT selection and installation

To increase the voltage output of the programmable power supplies to medium-voltage levels, 0.15-accuracy-class voltage transformers (see **Figure 2**) were used. According to IEEE Std C57.13.6 Standard for High-Accuracy Instrument Transformers, the 0.15-accuracy-class voltage transformers have a worst-case accuracy error of 0.15% and phase error of about 8 minutes (0.13 degrees) for voltages close to the rated voltage. This translates to a worst-case TVE of 0.27%.

Because this is the highest accuracy class of instrument transformers normally deployed in substations, using this class of VTs in our primary injection test facility provides a good reference point for realistic PMU accuracy in the field. Furthermore, individual calibration and minimizing each unit's burden can further improve each VT's accuracy. By minimizing the burden on the VT, the accuracy is maintained even when the same VT is used as a step-up and measurement transformer in our setup. Therefore, we can measure the signal from source or the low-voltage side of the VT, and a separate measurement VT is not needed.

For the current measurements, the back feed and measurement CTs were separated because the CTs needed for back-feed and for measurement have very different requirements. The back-feed CTs must handle a very high burden without going into saturation and a multiple of these CTs must be used to achieve the current level required for some of the certification tests.

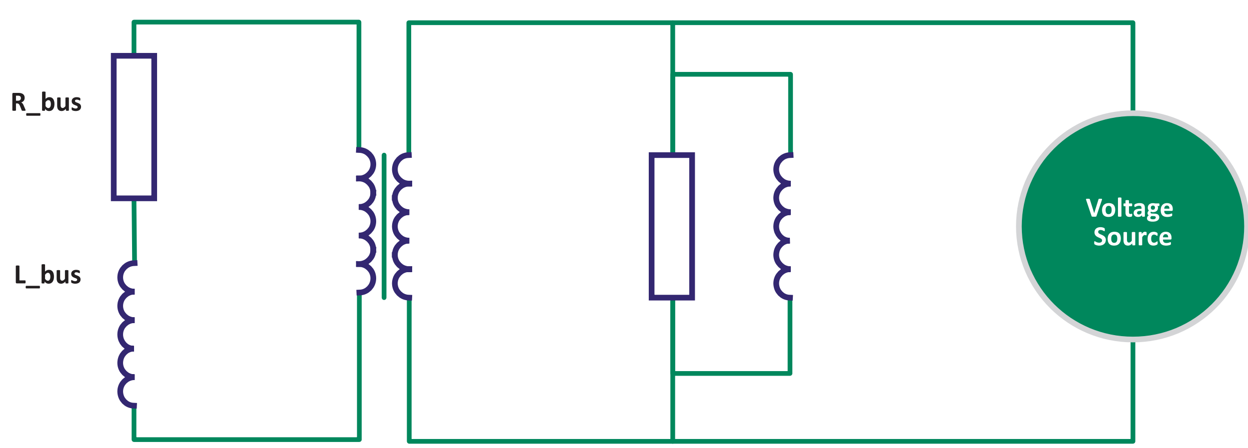
The large burden operates the back-feed CTs in their nonlinear range, which means the primary to secondary ratio is no longer accurate. For current measurement, laboratory-grade active current transducers were used (see **Figure 3**). These current sensors have a magnitude error of less than 0.01% and a phase error of less than 0.04 degrees for frequencies less than 2 kHz.

FIGURE 3. Current-monitoring sensor.

To translate the low-level signals generated by the control and monitoring system into voltage and current levels that can be used to supply the primary injection, high-bandwidth and programmable precision ac supplies were used. These power supplies amplify the low-level signal generated by the control and monitoring system (0-10 V) to the 0-200 V RMS range, which can then be used to drive medium-voltage step-up instrument transformers. The power supplies can generate up to 400 VRMS, supply up to 6 kW of power, and support frequencies up to 5 kHz. This high-frequency capability is required because the harmonics interference tests require the injection of voltage/current harmonics up to 3 kHz.

To accurately generate primary level current, high-burden rating current transformers were connected in reverse. A voltage applied across the secondary winding generates a large primary current flow proportional to the applied voltage. From a CT-equivalent circuit model shown in **Figure 4**, we know the primary resistance as seen by the secondary winding scales by the square of the turn ratio between the primary and secondary. This means a very small primary impedance of less than 1 mΩ can translate into more than a 100 Ω impedance when seen from the CT secondary winding.

FIGURE 4. A simplified CT back-feed circuit.



To make the problem worse, the impedance also increases linearly with frequency, which means generating 60 amps 50th harmonics takes much more voltage/power compared to generating 600 amps current at 60 Hz. For the 60-A 50th harmonics test, the output power for the current channels greatly exceeded 3 kVA. Generating 600 amps current at nominal frequency takes less than 100 VA. A spectral analysis of the CT and bus bar was performed to identify the impedance seen by the power supply at different frequencies. The result of this analysis, together with the turns ratio, is used to determine voltage needed to obtain the desired primary current.

CONTROL SYSTEM SELECTION, PROGRAMMING, AND VALIDATION

The control and monitoring system accurately and reliably generates the required test signals specified in the IEEE/IEC 60255-118-1 standard for both the M class and P class and for both the 60-Hz and 50-Hz nominal frequencies. In addition, the system must be able to precisely record both the low-level signals commanded by the control and monitoring system as well as the high voltage/current waveforms seen by the PMU under test. The recorded signals must also be GPS-timestamped to the level of accuracy required by the standard. This is important for validation and troubleshooting of the overall test system.

To avoid latency and jitter associated with computer processors, a field-programmable gate array (FPGA)-based control system was used to guarantee exact timing of the generated test signals. The FPGA-based system communicates with a workstation computer to receive commands and streams monitoring data back to the computer for storage and analysis. A client application was developed on the workstation computer to configure, control, and monitor the overall test system.

To evaluate the phase performance of a PMU, the timing accuracy of the control system that generates the test signal is critical. The GPS clock is the frequency reference for the control and monitoring system that directly affects the output waveforms. This requires the control and monitoring system to be synchronized to a GPS time source with better than 1 µs accuracy. It also requires the test system be in an area with good GPS reception or have access to GPS antennas mounted outside the building.

For the primary injection facility, the test control and monitoring system has a built-in IEEE-1588 clock module and an ability to synchronize the FPGA board analog outputs to this precision time clock. Any delays introduced by the power supplies themselves are typically quite small and in any case are constant and can therefore be accounted for. A GPS repeater system was installed to receive a GPS signal from the roof of the building and re-broadcast the GPS signal inside the building.

Implementation of the ICAP test suites was based on sets of equations from the IEEE/IEC 60255-118-1 standard. The basic set of equations describes a balanced three-phase system in a **Steady** state. See **Equation 1**.

Equation 1

$$X_a = X_m \cos(2\pi f_{in} t + \theta)$$

$$X_b = X_m \cos(2\pi f_{in} t - \frac{2\pi}{3} + \theta)$$

$$X_c = X_m \cos(2\pi f_{in} t + \frac{2\pi}{3} + \theta)$$

The X_m is the amplitude of the test signal, f_{in} is the frequency, and θ is the phase of the injection signal in radians. The term t represents time, which is the reference for all other signals in the test system. These equations form the basis of the steady state test signals with X_m, and f_{in} varying for each individual test. It is important to note again that timing is critical for accuracy of the test signal because even an error of a few microseconds in timing can affect the accuracy of the TVE calculation. For the harmonic distortion and out-of-band interference tests, sinusoidal interference terms are added to the steady-state equations to describe the interference signals. See **Equation 2**.

Equation 2

$$X_a = X_m \cos(2\pi f_{in} t + \theta) + X_m k_x \cos(2\pi f_i t)$$

$$X_b = X_m \cos(2\pi f_{in} t - \frac{2\pi}{3} + \theta) + X_m k_x \cos(2\pi f_i t - \frac{2\pi}{3})$$

$$X_c = X_m \cos(2\pi f_{in} t + \frac{2\pi}{3} + \theta) + X_m k_x \cos(2\pi f_i t + \frac{2\pi}{3})$$

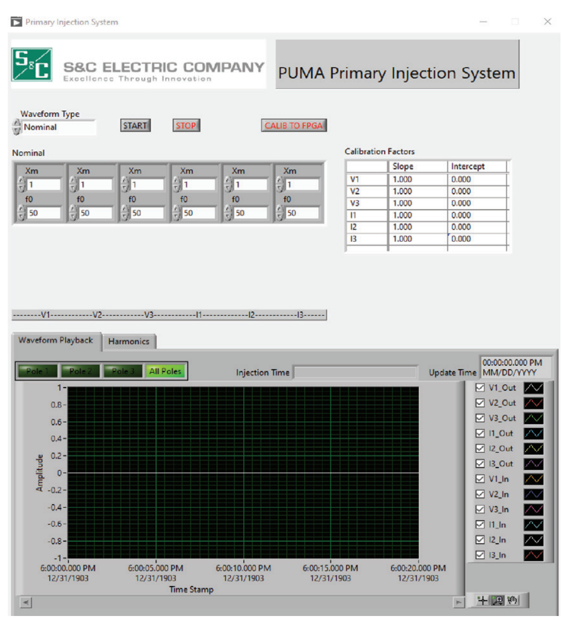
The k_x term is the magnitude of the interference, while the f_i is the frequency of the interference. Because of bandwidth limitations of the step-up instrument transformers, the magnitude of the interference also depends on the frequency of the interference. To accurately represent the ICAP test suite at the primary level, the k_x term must be adjusted based on actual measurement of the interference voltage/current at the primary level.

For the dynamic test cases, the same equations as steady state still apply, except the amplitude, frequency, and phase of the injection signals are dynamically changing during the tests.

After these equations are programmed into the FPGA, a client application was developed to calibrate the individual sensors, configure test parameters, and control the test execution. The calibration process involves the addition of a slope and offset correction for each phase voltage or current stored inside the FPGA. These corrections compensate for impedance or ratio differences between the three phases.

A screenshot of the client program is shown in **Figure 5**. During each test execution, the FPGA

FIGURE 5. A PC client application.



triggers the signal injection precisely at the start of the second based on timing from the built-in IEEE-1588 precision time clock, then starts streaming the time-stamped test signals and the high-voltage/primary current feedback measurement signals back to the client application for real-time display and storage.

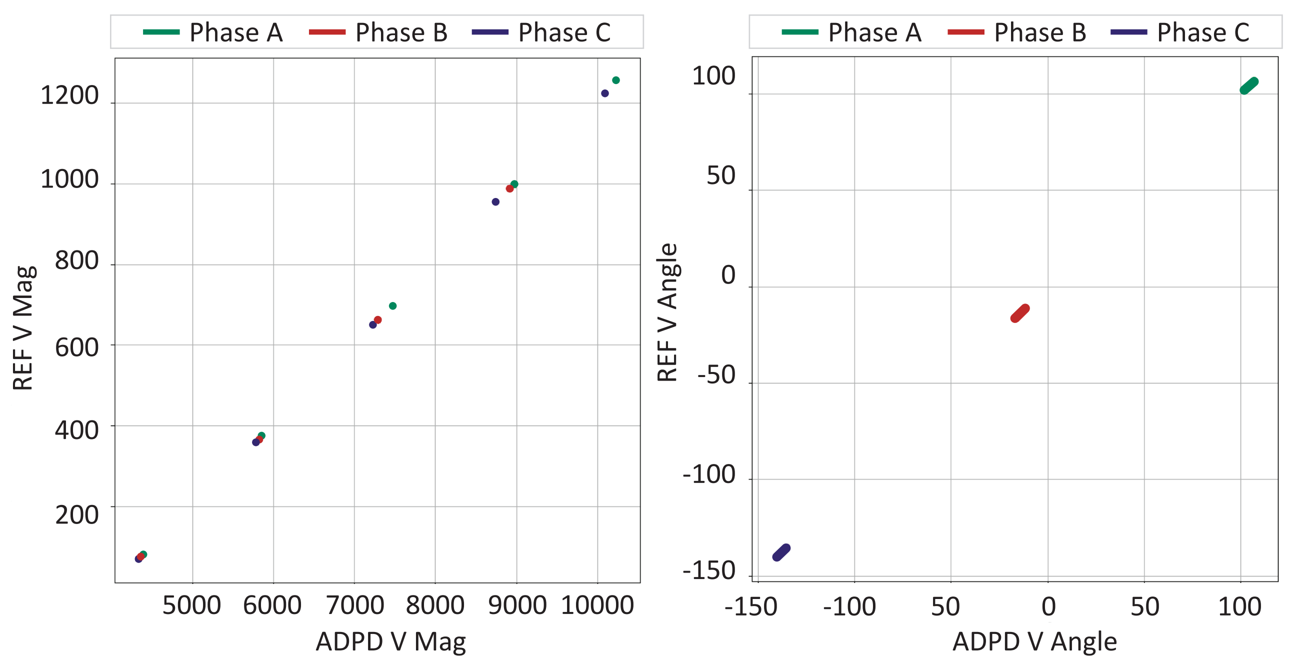
All the test cases from the ICAP test suites have been implemented into the primary injection test facility, with future plans to add direct Comtrade playback ability to evaluate real system events captured in the field.

TEST RESULTS

This section describes some of the results obtained during testing of the primary injection facility. The results from the ADPD are compared to those of the conventional PMU operating in parallel with the ADPD. This is done for a fairer evaluation of the ADPD capabilities, given there are no standards in place for PMU certification at primary levels.

Results from the voltage-range tests are shown in **Figure 6**. For each test, the magnitude of the voltages injected into the system is varied with the frequency, voltage angle fixed. The plots show good agreement between the ADPD PMU voltage measurements versus the third-party reference PMU for both voltage magnitude and angle.

FIGURE 6. Voltage comparison between reference PMU and ADPD.



For the current-range tests, the magnitude of the currents injected into the system is varied with the voltage magnitude, voltage angle, and frequency fixed. Results from the current-range tests are shown in **Figure 7** that again show good agreements between the ADPD PMU output versus the third-party reference PMU. The actual TVEs from the same test are shown in **Table 2 on page 14**.

FIGURE 7. Voltage comparison between reference PMU and ADPD.

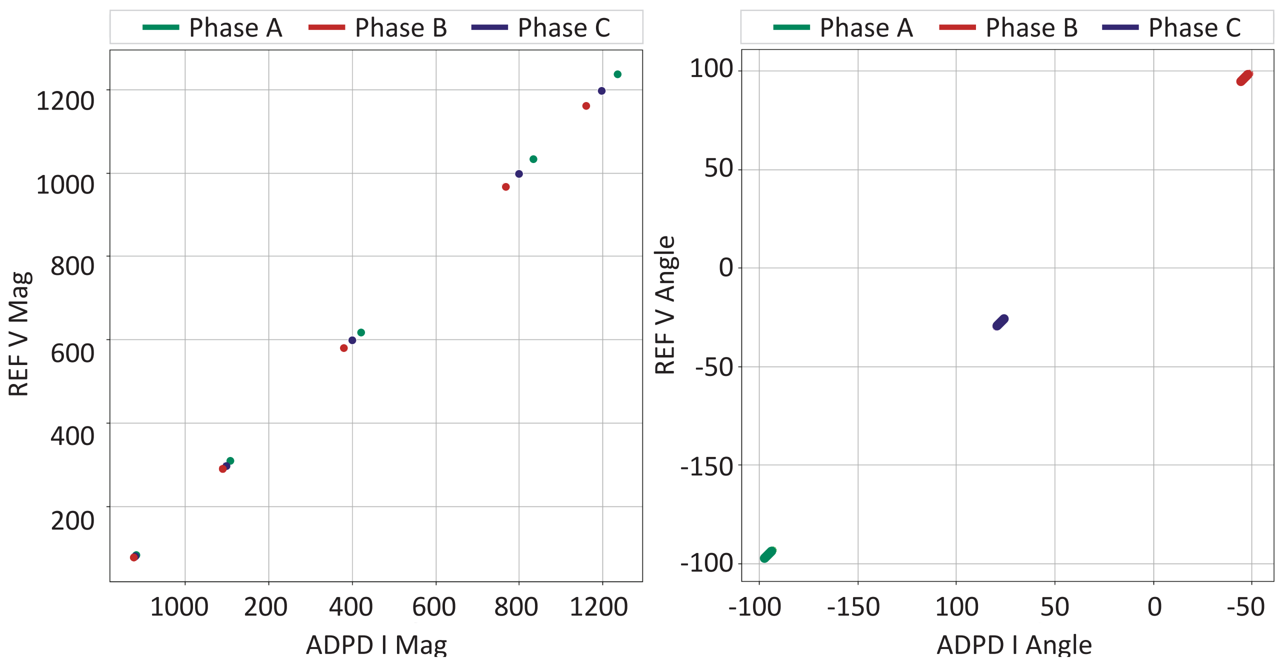


TABLE 2. Current Range Test Results for the ADPD

Current Level	# Of Data Points	Voltage TVE Median	Voltage TVE Max	Current TVE Median	Current TVE Max
Standard Requirement			1%		1%
80 A	**1139**	0.28%	0.30%	0.17%	0.47%
300 A	**1252**	0.28%	0.30%	0.13%	0.27%
600 A	**966**	0.28%	0.30%	0.11%	0.23%
1000 A	**1253**	0.27%	0.30%	0.16%	0.35%
1200 A	**1772**	0.27%	0.30%	0.15%	0.35%

Current Level	# Of Data Points	Frequency Error (Hz) Median	Frequency Error (Hz) Max	ROCOF Error (Hz/s) Median	ROCOF Error (Hz/s) max
Standard Requirement			0.005		0.4
80 A	**1139**	0.00016	0.00061	0.00342	0.01790
300 A	**1252**	0.00016	0.00068	0.00342	0.01628
600 A	**966**	0.00017	0.00066	0.00326	0.01790
1000 A	**1253**	0.00016	0.00061	0.00342	0.01563
1200 A	**1772**	0.00016	0.00061	0.00342	0.01742

CONCLUSION

The challenges of performing synchrophasor measurements at primary voltages and currents are complicated by the lack of facilities to test and verify the reported values. While there are labs capable of generating these values for testing purposes, they typically are not configured to perform regulated control to the level of precision necessary for synchrophasor certification.

The work described in this paper demonstrates it is possible to design and assemble a precision primary-level testing facility. It has been successfully used to compare the data of an ADPD operating at distribution-scale voltages and currents with those from a conventional substation PMU. The advantages of such a facility include both testing of certification test profiles as well as evaluating the behavior during realistic contingency scenarios.

100-T141
March 27, 2023