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CIGRE US National Committee
2014 Grid of the Future Symposium

Virtual-Instrumentation-Based PMU Calibrator for IEEE C37.118.1-2011 Compliance Testing

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SUMMARY

It is recognized that synchrophasor technology is undergoing rapid changes and that both the PMU manufacturers and the PMU calibrators will change in the near future due to the release of the new standard IEEE C37.118.1-2011 and its corresponding latest amendment IEEE C37.118.1a-2014. This paper will share the experience in developing a customizable, automated, multi-functional, and accurate PMU calibrator using modular instrumentation and an FPGA-based platform. Thanks to this novel approach, the entire compliance testing with the IEEE C37.118.1 standard becomes fully automated and the testing period is shortened to a few hours. Various synchronized signals can be generated to cover all the steady-state, dynamic-state, and reporting latency tests for both M class and P class at all reporting rates. The virtual-instrumentation-based PMU calibrator achieves the same testing results as traditional instruments, with a fraction of cost and much higher performance.

KEYWORDS

Phasor Measurement Unit, PMU calibrator, Synchrophasor, FPGA, Virtual Instrumentation, IEEE C37.118.1-2011, IEEE C37.242-2013, Compliance test

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1. INTRODUCTION

Phasor measurement unit (PMU) is a device that measures and transfers synchronized phasor values on the electrical power grid, using a common time source for synchronization. Since its invention in the 80s, PMU gained wide acceptance around the world and became one of the most important devices for the applications in power system analysis, control and protection [1][2]. The performance standard, IEEE C37.118-2005 (IEEE Standard for Sychrophasors for Power Systems) [3], specifies the methods for evaluating PMU’s measurements. Because IEEE C37.118-2005 defines requirements for compliance only under steady-state power system conditions, its revision IEEE C37.118.1-2011 [4] and its corresponding latest amendment IEEE C37.118.1a-2014 [5] extend the definition and specify the requirements under practical dynamic conditions. Future revisions and amendments may be necessary due to further research and developments of smart grids and power systems. As a result, it becomes a great challenge for equipment manufacturers to quickly respond to fast-changing requirements of PMUs.

Performing comprehensive PMU calibration is the only way to guarantee the accuracy and the seamless interchangeability among PMUs from different vendors [2]. PMU calibration requires not only approved performance standards, but also adequate specialized calibration equipment and clear calibration procedures. IEEE C37.242-2013 (IEEE Guide for Synchronization, Calibration, Testing, and Installation of Phasor Measurement Units (PMUs) for Power System Protection and Control) [6] provides the calibration procedures for laboratory or field applications and the performance requirements of PMU calibration equipment, which is also called PMU calibrator. Using the PMU calibrator compliant with the standard, the designers of PMU can simplify testing procedure and accelerate development process, the manufacturers of PMU can perform the performance verification of each new PMU, and the users of PMU can validate a PMU before deployment and perform periodic validation as required.

Currently, many off-the-shelf PMU calibrators only support manual compliance calibration test with the older standard IEEE C37.118-2005 [7][8][9][10] and only few automated calibrators [11][12] are currently available. The conventional manual method has the following limitations and shortcomings.

1) A complex system with various devices from different manufacturers results in difficult setup, operation, and maintenance [11].
2) Manual operation requires trained, proficient operators and cannot guarantee calibration reliability and repeatability.
3) A calibration procedure that is highly time-consuming.
4) High costs of off-the-shelf calibrators limit availability to broad users.
5) Conventional hard-coded system platform cannot be modified to track the requirements of changing standards and users.

All these limitations of conventional PMU calibrators create unnecessary hurdles for PMU manufacturers to efficiently develop PMU devices with guaranteed performance at lower costs. This paper proposes a new method based on virtual instrumentation and shares the experience in developing a customizable, automated, multi-functional, and accurate PMU calibrator using an FPGA-based platform. The section 2 in this paper lists the requirements of a full-featured PMU calibrator. Section 3 introduces a newly-designed PMU calibrator based on virtual instrumentation, and shares experiences in implementing this system based on FPGA. Section 4 introduces considerations and test procedures to ensure that the PMU calibrator is calibrated to the reference standard. And at the end of this paper, the advantages of this design, compared with the conventional solution, are summarized.

2. Requirements for PMU Calibrator

2.1 Required Test Items as Defined in IEEE C37.118.1-2011

IEEE C37.118.1-2011 specifies the methods for evaluating PMU's measurements and the detailed requirements for compliance under both steady-state and dynamic power system conditions. Table 1 describes the test parameter needs and conditions for test [4].

Table 1: Required Test Items in IEEE C37.118.1-2011

Test Category	**Test Parameter**	**Section in C37.118.1-2011**
Performance class	P class / M class	5.5.2
Reporting rate	10/25/50 Fs @50 Hz system 10/12/15/20/30/60 Fs @60 Hz system	5.4.1
Steady-state compliance	Signal frequency	5.5.5
	Signal magnitude: voltage	
	Signal magnitude: current	
	Phase angle	
	Harmonic distortion	
	Out-of-band interference	
Dynamic compliance	Amplitude modulation	5.5.6
	Phase modulation	
	Ramp of system frequency	5.5.7
	Step changes in amplitude	5.5.8
	Step changes in phase	
Reporting latency	PMU reporting latency (RLP)	5.5.9

2.2 Requirements as Defined in IEEE C37.242-2013

To perform compliance testing, the PMU calibrator shall be traceable to national standards and it is generally recommended that uncertainty of calibrator should be less than 10% of the allowed error. Table 2 shows the main relevant accuracy requirements for output channels of the PMU calibrator under steady-state and dynamic conditions in IEEE C37.242-2013 [6]. Challenging as it is for the PMU calibrator to meet these high-accuracy requirements, what makes the process harder is that the PMU compliance test procedure itself is a very time-consuming task. According to the required procedures of the IEEE standard, the last two columns list the ideal time necessary for P and M class verification without consideration of hardware warm-up/switch time, GPS locking time, optional test items, etc. As a result, a high performance calibrator is extremely important for reducing the total time necessary to verify of all of the 18 configurations.

Table 2: Requirements for PMU Calibrator in IEEE C37.242-2013

Requirements in C37.242-2013		**Requirements of Uncertainty**	**Ideal Time Per Configuration**	
			P Class	**M Class**
Time reference		Support synchronization to UTC	N/A	N/A
Steady-state	Magnitude	0.10%	250 s	300 s
	Balance	0.30%		
	Phase	1 mrad (0.057 degrees)	60 s	60 s
	Freq	0.1 mHz	360 s	900 s
	ROCOF	1 mHz/s		
	Harmonic	N/A	450 s	450 s
	Out-of-band	N/A	N/A	450 s
Dynamic	Modulation	Fundamental: 0.2% of Un,0.3 mrad,0.5 mHz,10 mHz/s Magnitude modulation: 0.2% of Un Phase modulation: the equivalent of 1 ms	1200s	2500 s
	Frequency ramp	Fundamental: 0.2% of Un,0.3 mrad,0.5 mHz,10 mHz/s	30 s	30 s
	Magnitude step	Magnitude:0.2% ; Phase: 2 mrad (0.12 degrees); Step change: 0.1% of Un	60 s	90 s
	Phase step	Magnitude:0.2% ; Phase: 2 mrad (0.12 degrees); Step change: 2 mrad (0.12 degrees)	60 s	90 s
Reporting latency		Maximum uncertainty = 100 µs	20-100 s	20-100 s
Total minimum time per configuration			**~ 45 mins**	**~ 80 mins**

The standard also requires that a full-featured PMU calibrator should support various communication methods such as EIA-232, EIA-485, and Ethernet 10/100BaseT.

3. VIRTUAL-INSTRUMENTATION-BASED PMU CALIBRATOR

3.1 Virtual Instrumentation

A virtual instrument [13] consists of an industry-standard computer or workstation equipped with powerful application software, cost-effective hardware such as plug-in boards, and driver software, which together perform the functions of traditional instruments. Virtual instruments tend to emphasize modular hardware approaches that facilitate expandability and reduce cost significantly. PXI (PCI eXtensions for Instrumentation) [14], launched in 1998, becomes the most important one of several modular electronic instrumentation platforms in current use with the largest selection of chassis, high performance controllers, and more than 1,500 modules from various manufacturers. Utilizing the flexible architecture of virtual instruments, virtually any engineering challenge can be addressed, including the PMU calibrator. Since its adoption, the FPGA technology [15] continues to empower the PXI platform to be more reconfigurable and high-performance. With the reconfigurable FPGA technology, high-speed signal processing, I/O synchronization, and advanced algorithms can be implemented directly on the hardware to minimize latency. FPGA-based implementation avoids the system crashing possibilities and lower uncertainty caused by common operating system or application software since algorithms running on the FPGA are converted to bitfiles that run directly on HW, without the need of an operating system to execute them. In order to achieve high performance to meet the requirements of timing and signal generation for PMU calibrator, this paper describes a design based on FPGA and PXI technologies.

3.2 Virtual-Instrumentation-Based Design for PMU Calibrator

Figure 1 shows the functional architecture of a virtual-instrumentation-based PMU calibrator using PXI modular platform.

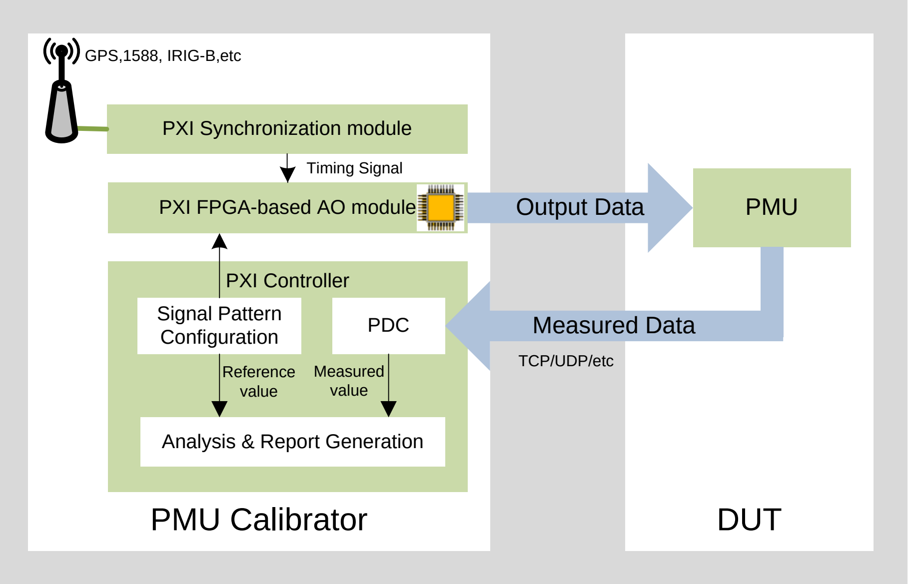


Figure 1: Architecture of Virtual-instrumentation-based PMU Calibrator

3.2.1 Synchronization Module

Each signal output sample must be synchronized with accurate timestamp from various sources. The PXI timing and synchronization module [16] can synchronize PXI systems using GPS, IEEE 1588, IRIG-B, or PPS. The PXI module can provide accurate time reference to other PXI analog output modules for synchronizing real-time timestamps with all samples in the FPGA. Its PPS accuracy can be typically within 15 ns to GPS/UTC [16].

3.2.2 FPGA-Based Signal Generator

High-accurate, synchronized signal generation is the most important feature of a PMU calibrator. We choose the PXI I/O module [17] as the signal generator, which can provide 8 analog outputs with independent update rates up to 1 MHz and with 16-bits of resolution. Its amplitude error is less than 0.04% according to its specifications and less than the specified accuracy requirements in Table 2. The PXI signal generator is equipped with an FPGA chip which is open to allow custom implementation of various signal processing algorithms. Figure 2 shows the function block of the PXI signal generator including the FPGA-based functions implemented. The FPGA Timekeeper technology [18], which is a set of code running in the FPGA, can provide accurate, synchronized timestamps at the rate of 40 MHz and achieve an accuracy of 100 ns for PPS signals. The PXI synchronization module is used to provide a high-accuracy time reference via the PXI backplane bus, which is used by the FPGA TimeKeeper technology to calculate synchronized timestamps. Next, real-time phase samples are generated at 40 MHz rates according to mathematical equations and output at a high rate of 1 MHz.

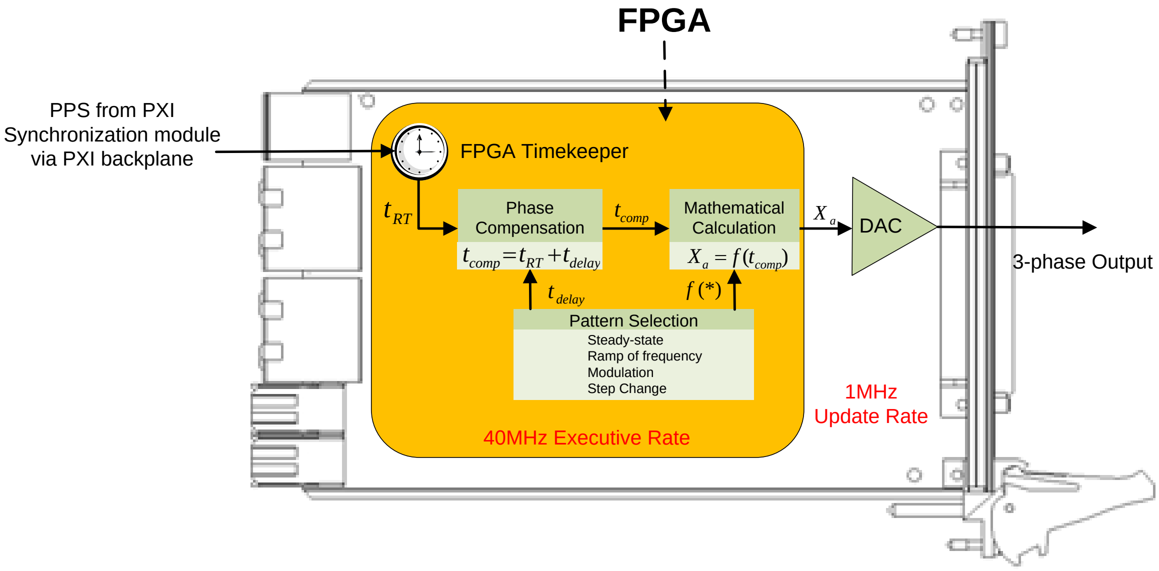


Figure 2: Function Block of FPGA-Based Signal Generation

Phase Compensation

PMU testing requires the signal phase angles to be determined with respect to a UTC time reference. However, phase delay caused by various factors always exists during signal generation for both steady-state and dynamic conditions:

$$\begin{aligned}\textit{Phase delay: } t_{delay} &= \textit{Synchronization error} + \textit{FPGA processing time delay} + \\ &\textit{DAC output filter delay} + \textit{loading effects}\end{aligned} \tag{1}$$

It is difficult to get accurate delay values based on mathematical analysis. So the delay is measured and timestamp values compensated to ensure the precision of the output phase. Different signal pattern generations will cause different delay values, and compensation is achieved by adding the real-time timestamps with the measured delay values according to the selected signal pattern:

$$t_{comp} = t_{RT} + t_{delay} \tag{2}$$

3.2.3 High-Performance PXI Controller

The PXI embedded controller provides the higher performance than a standard PC and can afford long-time running tasks under high load.

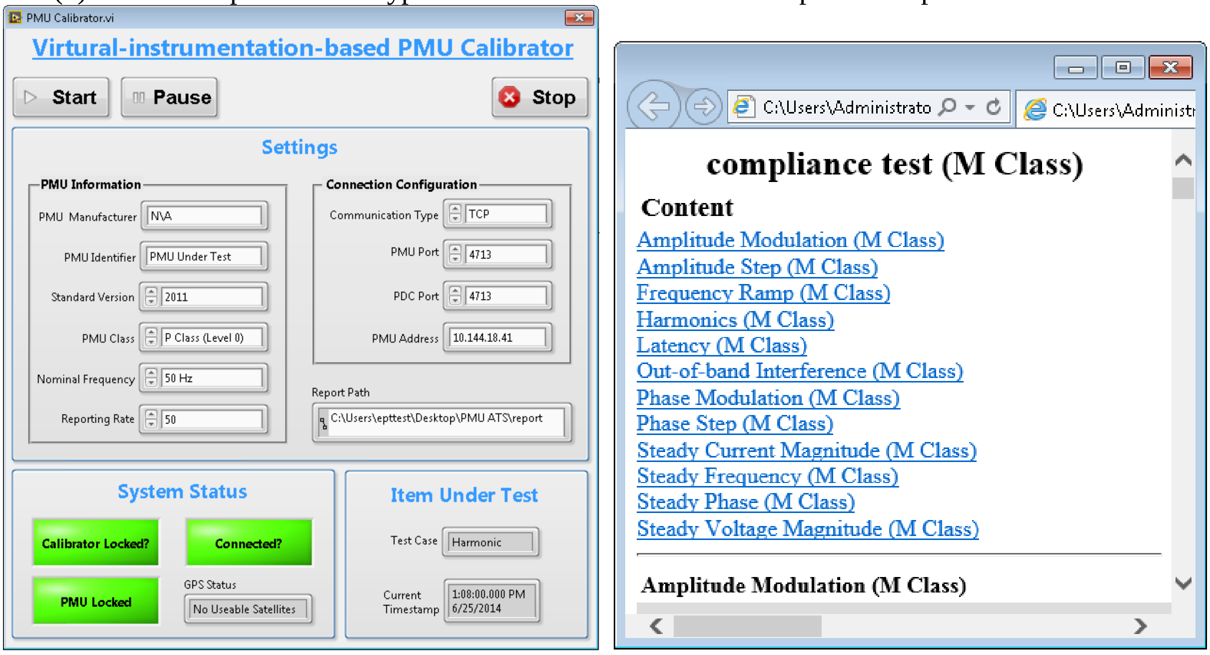
Internal PDC: To fully automate the PMU Calibrator, an internal PDC running in the PXI controller was developed for parsing the PMU message frames and get the measured phasor values of the PMU under test. It supports the protocol requirements of the latest communication standard IEEE C37.118.2-2011 [19].

Mathematical-Model-Based Error Analysis: In order to check the measurement error of the PMU under test, the calibrator must compare the measured value with the signal reference value. A signal reference value, also called ’true’ phasor value, can be achieved through two methods: (1) Use a calibrated reference PMU (external or internal) that has an accuracy level at least one level higher than that of the PMU under test and utilize its measurement output as the reference values [20]. This method is utilized by many PMU calibrators [2][7][21]. (2) Calculate the ‘true’ synchrophasor values according to the reported timestamp of PMU message frames based on the mathematical model of the generated signals [11]. The second method offer proves to be more attractive as it removes the potential negative effects of uncertainty and unrepeatability when using additional external devices. After receiving the reported phasor measurements and its corresponding timestamp, the algorithm uses this timestamp to calculate the ’true’ phasor value with the known mathematical model, and then compare the error between measured phasor value and ’true’ phasor value to achieve its compliance results.

Functional Expansibility: Standards are constantly evolving, and keeping up with future requirements can be a complex, and expensive task. For example, PMUs in the future may support higher reporting rates up to 200/240 frames per second and various communication methods such as EIA-232, EIA-485, Ethernet 10/100BaseT, and IEC 61850-90-5 [21]. Additionally, some PMUs may accept low-level power signals, while others require high-level inputs. Lastly, future revisions of IEEE standards may require more compliance test items. All these new specifications require that both the hardware and software of the PMU calibrator are flexible and customizable enough to respond to fast changing requirements. A Virtual instrumentation platform provides hardware modularity and open-source software toolkits for implementing new measurement algorithms, compliance tests as well as integration with the latest communication protocols such as IEC 61850.

3.2.4 User Interface

Virtual instrumentation software makes it easy to implement customized control interfaces with user-defined features, such as various operation modes, custom report formats, and flexible indicators in the monitor screen. Figure 3 (a) shows the default start-up screen of the top-level user interface for operators. Operators can navigate to configure the PMU information, report path and other connection details. During testing, it can indicate the status of the calibration system and GPS signals. Once a specific configuration is selected, the application starts the automated test procedure. Using the relevant toolkit [22], the system automatically generates reports summarizing manufacturing test results in user-defined formats, such as Word, Excel, or HTML as shown in Figure 3 (b). Figure 3 (c) and (d) show the reports of two typical test cases--harmonic and amplitude step case.



Virtual-instrumentation-based PMU Calibrator

PMU Manufacturer: N\A
PMU Identifier: PMU Under Test
Standard Version: 2011
PMU Class: P Class (Level 0)
Nominal Frequency: 50 Hz
Reporting Rate: 50
Communication Type: TCP
PMU Port: 4713
PDC Port: 4713
PMU Address: 10.144.18.41
Report Path: C:\Users\epttest\Desktop\PMU ATS\report
GPS Status: No Useable Satellites
Test Case: Harmonic
Current Timestamp: 1:08:00.000 PM 6/25/2014

compliance test (M Class)

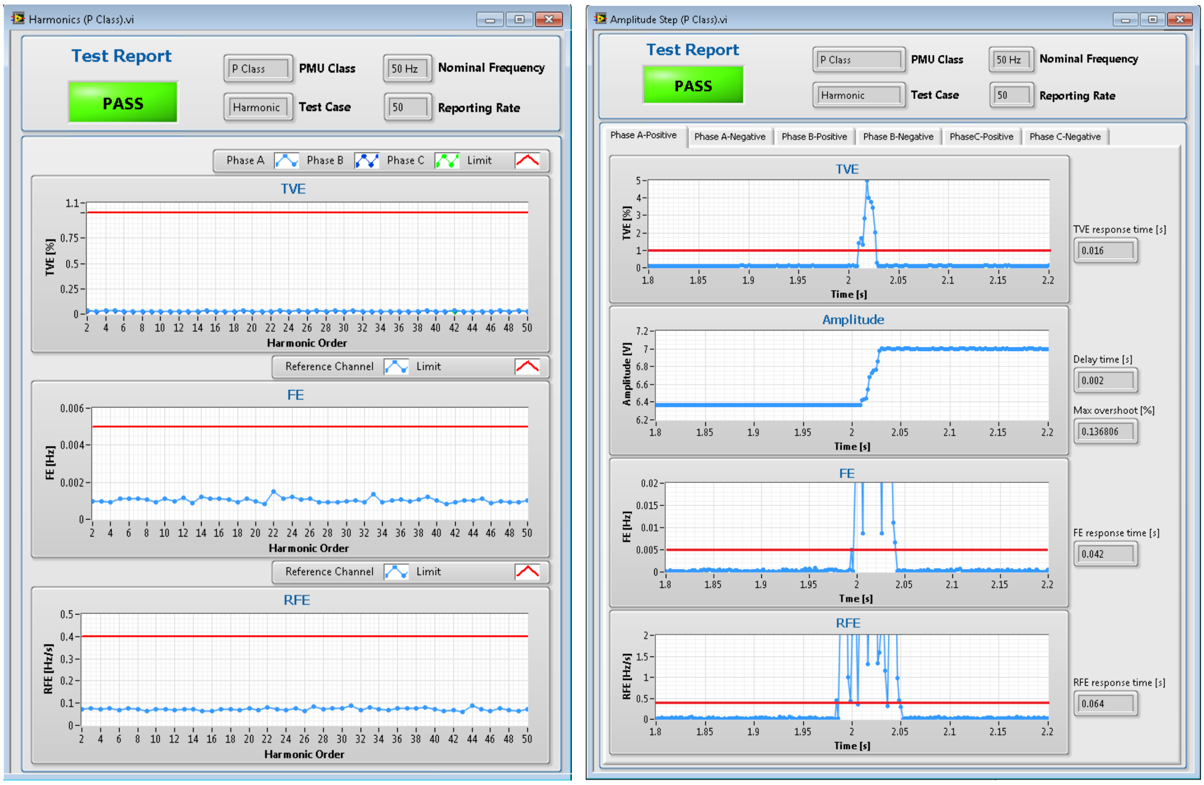
Content

- Amplitude Modulation (M Class)
- Amplitude Step (M Class)
- Frequency Ramp (M Class)
- Harmonics (M Class)
- Latency (M Class)
- Out-of-band Interference (M Class)
- Phase Modulation (M Class)
- Phase Step (M Class)
- Steady Current Magnitude (M Class)
- Steady Frequency (M Class)
- Steady Phase (M Class)
- Steady Voltage Magnitude (M Class)

Amplitude Modulation (M Class)

(a) Top-level Configuration UI

(b) Final Report in HTML Format



Harmonics (P Class).vi

Test Report

PASS

P Class PMU Class

50 Hz Nominal Frequency

Harmonic Test Case

50 Reporting Rate

Amplitude Step (P Class).vi

Test Report

PASS

P Class PMU Class

50 Hz Nominal Frequency

Harmonic Test Case

50 Reporting Rate

TVE response time [s] 0.016

Delay time [s] 0.002

Max overshoot [%] 0.136806

FE response time [s] 0.042

RFE response time [s] 0.064

(c) Report for Harmonic Test Case (d) Report for Amplitude Step Test Case

Figure 3: Examples of User Interface and Generated Compliance Report

4. System Performance Verification

The PMU calibrator needs to be calibrated to a reference standard, and the clause 7.4.4 in IEEE C37.242-2013 describes the relevant typical calibration methods for a PMU calibrator under both steady-state and dynamic conditions. Two methods were used to verify the performance uncertainty of the virtual-instrumentation-based PMU calibrator. The overall system architecture for verifying is shown in Figure 4.

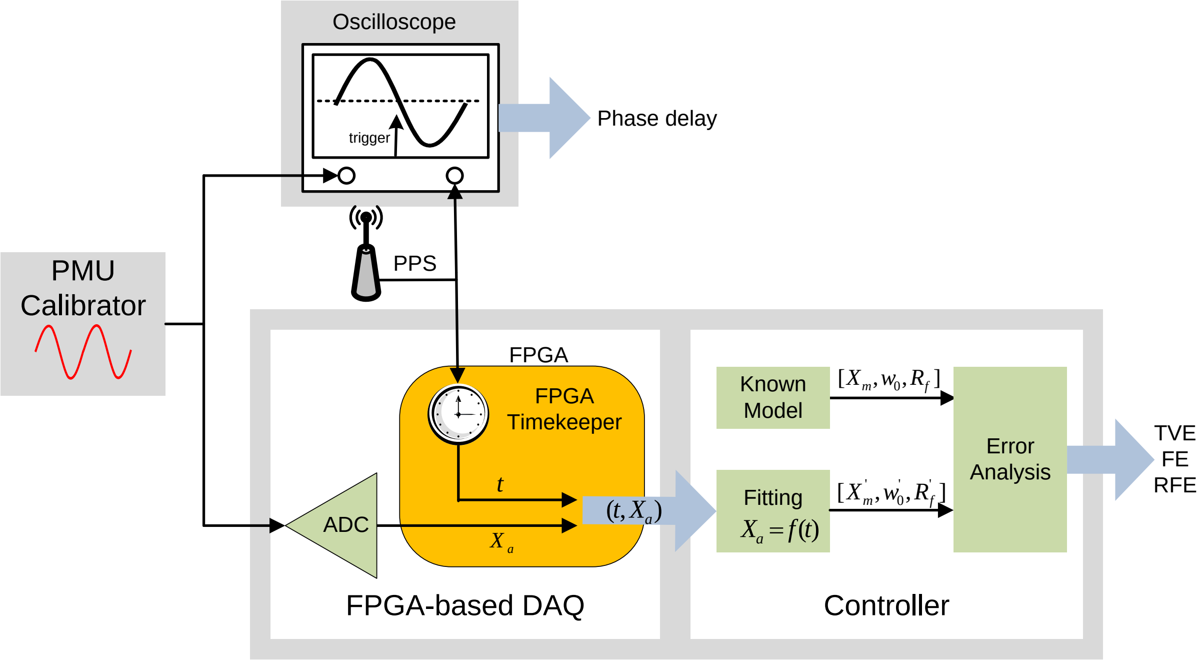


Figure 4 : System Architecture for Verifying Uncertainty of PMU Calibrator

4.1 Uncertainty Verification Using Oscilloscope

Under steady-state output conditions, the output signal phase of the PMU calibrator can be calibrated using standard reference instruments. The method selected uses a high-speed/high-resolution oscilloscope [23] to compare the zero-crossing point of the synchronized sinusoidal output signal with the synchronized PPS trigger signal from a GPS source [6]. According to the verification, the output delay between the trigger edge and the zero-crossing position is less than 1 us, which means 0.3 mrad phase error for a 50 Hz power signal. The phase error can cause only 0.05% TVE under the condition of 0.04% magnitude error [17], which is much less than the allowed error specified in Table 2.

4.2 Uncertainty Verification through Samples Fitting

It may not be possible to measure the uncertainty of output signal with standard calibration instruments during dynamic signal generation. Considering that the signal values follow specific mathematical equations, the verification method is to record the waveforms using data acquisition (DAQ) devices that can determine the absolute time of each sample, and then to estimate the corresponding parameters by fitting recorded synchronized samples to its original mathematical equation [6]. For example, in the case of ramp of frequency enough pairs of sampled values are recorded with their real-time sampled timestamps using FPGA-based DAQ. The recorded samples can be expressed as below.

$$(t_i, X_{a,i}), i = 1,2,..., N \tag{3}$$

In theory, the acquired samples should follow the Equation (4) under the ramping condition.

$$\begin{aligned} X_{a,1} &= f(t_1) = X_m \cos[w_0 t_1 + \pi R_f t_1^{\,2}] \\ X_{a,2} &= f(t_2) = X_m \cos[w_0 t_2 + \pi R_f t_2^{\,2}] \\ &\dots \\ X_{a,N} &= f(t_N) = X_m \cos[w_0 t_N + \pi R_f t_N^{\,2}] \end{aligned} \tag{4}$$

Where $[X_m, w_0, R_f]$ are known user-configured values. Then Levenberg-Marquardt non-linear fitting algorithms [24] are used to determine the set of estimated parameters, $[X_m^{'}, w_0^{'}, R_f^{'}]$ that best fit the set of input data points in Least Squares. Based on the estimated values and known theoretical values of the parameters, the uncertainty of magnitude, phase, frequency and ROCOF are calculated. After applying this procedure to all steady-state and dynamic test conditions, the following typical performance uncertainty of the virtual-instrumentation-based PMU calibrator was obtained:

Table 3. Typical Performance Uncertainty of Virtual-instrumentation-based PMU Calibrator

Test Conditions	TVE (%)	FE (Hz)	RFE (Hz/s)
Steady state	0.05%	0.00005	0.0002
Dynamic-modulation	0.1%	0.0005	0.0005
Dynamic-ramp of frequency	0.1%	0.0005	0.002

5. CONCLUSION

This paper introduces the design and experience developing a PMU calibrator using the virtual instrument platform. As shown in Table 4, virtual instrumentation, enables quick development of a customizable, automated, multi-functional and accurate PMU calibrator. Virtual instrument platform can support accurate real-time configuration and monitoring of all the elements during test signal generation and synchronized phasor data acquisition, so that it can overcome the development difficulties caused by the inherent limitations of PMU measurement process including variable time delays and artifacts in synchronized phasor estimates. All components of the system are integrated into a small-size 3U PXI chassis and are easy to setup. Besides its full compliance with IEEE C37.242-2013, the virtual-instrumentation-based PMU calibrator is fully automated and the testing period is shortened to a few hours. It also achieves the same testing results as traditional instruments, with a fraction of cost and much higher performance.

Table 4. Advantages of Virtual-instrumentation-based PMU Calibrator

Items	**Traditional Methods**	**Solution of This Paper**
System setup	Complex	Simple and small size (all in a 3U chassis)
Execution	Requires proficient operator	Fully automated
Time consumption	Manual: 2~6 weeks per configuration Automated: 6~10 hours per configuration	1.5~2 hours per configuration
Cost	High	Low (based on PXI platform)
Customization	Unchangeable Hardware and closed Software	Modular Hardware and open-source Software
Upgrade flexibility	Difficult	Easy

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