



Verifying Interoperability and Application Performance of PMUs and PMU-Enabled IEDs at the Device and System Level

Final Project Report

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



Verifying Interoperability and Application Performance of PMUs and PMU-Enabled IEDs at the Device and System Level

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Power Systems Engineering Research Center

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Executive Summary

The project report presents a new test methodology for verifying the conformance, interoperability and application performance of Phasor Measurement Units (PMUs), PMU-enabled IEDs and Phasor Data Concentrator (PDCs) at the device and system level. Two types of tests are defined to evaluate the performance of synchrophasor devices verifying two different aspects: *design* and *application*. Discussion of the results from performing the *Design Test* and *Application Test* is also provided. The test platform, such as the test equipment and tools, and the configuration of the device under test, are also included for the purpose of making the procedure repetitive should a third party wish to verify the results.

The tests were performed using a synchrophasor testing and calibration system. The system has an uncertainty of less than 0.08% TVE (Total Vector Error). It consists of a GPS receiver used to synchronize the system to UTC (Coordinated Universal Time), a signal acquisition system used to generate and sample test signals up to 500 kHz, three voltage and current amplifiers connected to PMUs and PMU enabled IEDs providing test signals at typical level, three voltage attenuators and three current shunts. Both GPS signal, time codes (IRIG-B) and IEEE 1588 are available for various synchrophasor devices. A series of software models is developed in LabVIEW for implementing two types of tests. The software is capable of automating test procedures and analyzing test results. A communication network toolbox called “Impairator” is developed and implemented in a newly implemented synchrophasor testbed.

The *Design Test* aims at verifying the *conformance* and *interoperability compliance* of PMUs and PMU-enabled IEDs, time synchronization methods and PDCs against standards. The standards’ *conformance* under specific test conditions was evaluated by comparing the amplitude, phase angle, frequency, and rate of change of frequency (ROCOF) estimates to corresponding reference values. The test conditions, including steady state and dynamic state, are defined in IEEE C37.118-2005, C37.118.1, C37.118.2 and draft “Guide for Phasor Data Concentrator Requirements for Power System Protection, Control, and Monitoring”. The interoperability *compliance* between synchrophasor devices, time clock and PMU, and PMU and PDC, was verified by interchanging equivalent parts. The compliance was evaluated using the function outcome and numerical indices defined in the standards.

- Nine commercial PMUs and PMU-enabled IEDs from eight different vendors were selected to perform the conformance test. From the conformance test results we concluded that most PMUs meet the steady state performance requirement, but all of them failed to provide conformance under some dynamic conditions.
- The interoperability test results indicated that issues between PMUs and time synchronizations options, PMUs and PDCs exist and can be identified using the test method.

The *Application Test* aims at verifying performances of specific applications (fault location and state estimation are selected to perform the application test) under variations of PMUs, time synchronization options, PDCs and communication protocols. The application test results indicate the following:

- Fault location errors using different pairs of PMUs vary from 0.4% to 2.9%, and it has larger errors and uncertainties as the packet loss grows in the communication network. However, this impact may be alleviated by increasing the PMUs' reporting rate.
- The variances of PMU errors and tuning weights can be estimated by the state estimation system using a recursive tuning algorithm. The impact on bad data detection of PMU measurements was investigated. In addition, an improved method was proposed to integrate existing WLS state estimators and enhances the robustness of error detection and identification for PMU measurements.

Future work related to this project should include:

- Development of a virtual PMU testbed to store and play back PMU source data. This method will be able to emulate network with a large number of PMUs while leveraging a small number of physical devices. Such set-up will allow evaluation of the performance of the entire synchrophasor system solution.
- Assessment of cyber security issues in the synchrophasor data transfer. This will entail definition of vulnerabilities, assessment of conformance with cyber security standards and penetration testing to verify cyber security interoperability and impacts of cyber security breaches on application performance.

Project Publications

- [1] Ren, J. and M. Kezunovic, “*An Adaptive Phasor Estimator for Power System Waveforms Containing Transients*”, Accepted by IEEE Transactions on Power Delivery, in press.
- [2] Guan, Y.; M. Kezunovic, and A. Sprintson. *Verifying Interoperability and Application Performance of PDCs in Synchrophasor System Solution*. Accepted by Proceedings of the 43rd North American Power Symposium, Urbana-Champaign, MA, September 9-11, 2012, accepted.
- [3] Ren, J.; M. Kezunovic, and Y. Guan. *Verifying Interoperability and Application Performance of PMUs and PMU-enabled IEDs*. Accepted by Power and Energy Society General Meeting, San Diego, California, July 22-27, 2012.
- [4] Zhang, L. and A. Abur. *Assigning Weights for PMU Measurements: Two Alternative Methods*. Accepted by Power and Energy Society General Meeting, San Diego, California, July 22-27, 2012.
- [5] Zhang, L. and A. Abur. *Impact of Tuning on Bad Data Detection of PMU Measurements*. Accepted by Proceedings of the 2012 IEEE PES Innovative Smart Grid Technologies (ISGT) Conference in Asia, May 21-23, 2012.
- [6] Zhang, L. and A. Abur. *State Estimation Tuning for PMU Measurements*. Accepted by Proceedings of the 43rd North American Power Symposium, Boston, Massachusetts, August 4-6, 2011.
- [7] Ren, J. and M. Kezunovic. *An Improved Fourier Method for Power System Frequency Estimation*. Accepted by Proceedings of the 43rd North American Power Symposium, Boston, Massachusetts, August 4-6, 2011.

Student Dissertations

- [1] Ren, J., *Synchrophasor Measurement using Substation Intelligent Electronic Devices: Algorithms and Test Methodology*. This doctoral dissertation is completed. Graduation from Texas A&M University: December 2011.
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1 Introduction

1.1 Summary of the Statement of Work

The use of synchronized measurements, particularly synchrophasors, has a history of over 30 years of research and development. In the last few years the effort of deploying and demonstrating a variety of applications that can benefit from synchronized measurements has been accelerated through the North American Synchrophasor Initiative (NASPI) and other related industry efforts. Most recently several utilities and regional market operators have developed plans for large scale deployment of such a technology. In the deployment of the Intelligent Electronic Devices (IEDs) for substation synchronized measurement applications, the focus at the moment is on two approaches: a) use of Phasor Measurement Units-PMUs (dedicated high precision recording instruments), and b) use of PMU-enabled IEDs (Digital Fault Recorders-DFRs, Digital Protective Relays-DPRs, Digital Disturbance Recorders-DDRs, etc. that have PMU measurement capability). While the number of PMUs across the USA utility networks is estimated at 250, the number of PMU-enabled IEDs may range in thousands. With the recent investments through American Recovery and Reinvestment Act (ARRA) and other funding sources, the total number of PMUs and PMU-enabled IEDs may increase by an order of magnitude with tens of thousands of such units being installed or enabled in the next 5-10 years. This asset will require costly solutions for substation installation, communications, data integration, and visualization. The total cost of the overall solution may exceed the cost of individual recording devices by several orders of magnitude. With installation of such costly infrastructure, the risks of the asset becoming stranded are real and mitigating measures need to be put in place to avoid such an undesirable (disastrous) outcome.

What makes the risk of the stranded assets outcome real are the expected issues in the synchronized sampling technology implementation:

- Many utilities will need to mix and match PMU solutions from multiple vendors due to various equipment purchasing practices and/or phased expansions of the system solution over an extended period of time;
- In creating system solutions, utilities may have to use PMUs from one vendor, the communication options from another, and data integration concentrators and visualization tools from yet another one;
- Various utility departments may promote, in addition to the stand alone PMUs, the use of PMU enabled IEDs such as DFRs, DDRs and DPRs based on the NERC PRC-002 recommendations, which may create a system solution that combines both PMUs and PMU-enabled IEDs.

While the NASPI efforts have resulted in a guide for testing PMUs, the proposed tests have primarily focused on verifying the static and dynamic performance of PMUs and did not address application performance tests of PMU-enabled IEDs and interoperability tests for system solutions consisting of many diverse types of PMU-capable IEDs. The NASPI effort so far, while useful, does not address how one may verify that:

- Using PMUs from different vendors or mixing PMUs and PMU-enabled IEDs produces consistent accuracy in a system solution;
- Various PMUs and PMU enabled IEDs can work consistently with different Phasor data concentrators and related visualization tools;
- Mixed solutions with PMUs and/or PMU-enabled IEDs will work consistently with various time

The expected benefits of the test methodology and selection of test tools needed to verify operation of PMUs and PMU-enabled IEDs in various power system applications and various measurement infrastructure solutions. The methodology will focus on development and demonstration of application performance and interoperability tests that go beyond the static and dynamic test defined by NASPI. The tools will include the NIST-grade calibrator developed at TAMU and enhance it for running application performance and interoperability tests, as well as the portable test unit recently developed for simultaneous testing of multiple PMUs and/or PMU-enabled IEDs in the field.

1.2 Project Objectives

The objective of this project is to produce the following outcomes:

- Specification of interoperability issues and description of scenarios where such issues may be important to evaluate;
- Specification of the accuracy bounds for PMUs and PMU-enabled IEDs that will result in acceptable error bounds for specific applications (state estimation and fault location);
- Description of test procedures to accomplish the interoperability and accuracy characterization and assessments of PMUs and PMU-enabled IEDs;
- Description of the implementation approach to the test procedures using specific scenarios and specific equipment and/or simulation methods.

1.3 Application Context

Two applications will be discussed as examples used to illustrate the issues and provide procedures for performing the tests and assessing the results. These are the fault location and state estimation applications.

Regarding application performance tests, the accuracy of the final outcome of the calculations will be the criterion.

One of the applications that will benefit from wide-spread availability of PMUs is the fault location. The accuracy of fault location, depending on the algorithm used, may depend on whether the phasors used for the calculation are synchronized or unsynchronized. The results of this part of the project will allow evaluation of how the changes in the accuracy of phasor synchronization affect different types of fault location algorithms.

The other application that will benefit from wide-spread PMU-enabled IEDs is the power system state estimator. An important function of the state estimator is to detect, identify and eliminate bad measurements, thus avoiding biased estimation results. This function is closely affected by the choice of measurement weights. Improper choice of weights will lead to misidentification of good measurement as bad and vice versa. The results of this part of the project will address this issue by presenting a procedure which will allow proper tuning of state estimators that will be using PMU measurements as inputs. The developed tuning procedure is independent of the PMU type or manufacturer in order to facilitate automatic tuning even when one or more PMUs are replaced during operation.

Regarding interoperability tests, the ability to interchange various components of the solution will be the criterion.

The fault location application is sensitive to the types of IEDs needed to implement two-end transmission line solution due to the implementation of the front-end signal processing performed by different types of IEDs. If the IEDs used at the transmission line ends are not from the same vendor, or if they represent a mix of PMUs and PMU-enabled IEDs, then the phasors used from different line ends may end up corresponding to quite a different point in time selected for the phasor calculation. In this application, the communication and data concentrator latency and ability to coordinate the records based on different time-stamps is of interest as well.

The state estimation application is sensitive to time stamping and quality of measurements, as well as ability to differentiate the topology of the power system that the measurements correspond to. The interoperability test will examine the impact of time synchronization and time stamping of synchrophasors used for state estimation due to the communication and data concentrator latency, as well as time synchronization delays that may be caused by loss of the synchronization reference in some parts or the entire electricity grid.

2 Test Classification and Technical Background

2.1 Test Classification

To address the above, this project will develop and perform two categories of tests:

Design Test: Aimed at verifying the conformance performance and interoperability compliance performance of PMUs and PMU-enabled IEDs, time synchronization methods and PDCs against standards. The conformance performance under specific test conditions will be evaluated by comparing the amplitude, phase angle, frequency, and rate of change of frequency (ROCOF) estimates to corresponding theoretical values. The test conditions, including steady state and dynamic state, are consistent with those defined in C37.118-2005 [1] and C37.118.1 (draft) [2]. The functional requirements of PDC are given in the draft “Guide for Phasor Data Concentrator Requirements for Power System Protection, Control and Monitoring” [3]. The interoperability compliance performance between synchrophasor devices, time clock and PMU, PMU and PDC, will be verified by interchanging equivalent parts. The performance will be measured by the function status and numerical indices against requirements defined in standards.

Application Test: Aimed at verifying the performance of specific applications (State estimation and Fault location) with variations of PMUs, PMU-enabled IEDs, PDCs and associated communication network.

2.2 Technical Background

Because the accuracy in both the interoperability and application tests is utilized to assess the impact of how the solution is performing using PMU and PMU-enabled IEDs, the core of the technical approach will be the definition of the accuracy characterization and assessment for both applications used as examples.

2.2.1 Fault Location Accuracy Characterization and Assessment

Transmission line fault location algorithms depend on several factors and thus analysis of the sensitivity of fault location output with those factors changing is crucial in estimating the accuracy of the output. The factors affecting fault location output include: Power system model accuracy, fault type discrimination accuracy, measurement accuracy and algorithm accuracy. Fault location algorithms had been traditionally evaluated considering an error measure proposed in IEEE Standard C37.114 but that does not allow user to estimate the sensitivity of the algorithm under each factor. A variance based global sensitivity analysis method will be used to evaluate accuracy of different phasor measurement based fault location algorithms under changing conditions of time synchronization, time stamping, and communication and data concentrator latency. These experimental results will then guide the user to choose the appropriate fault location algorithm under varying conditions.

2.2.2 State Estimation Accuracy Characterization and Assessment

State estimation solution is a function of the available measurements. One metric that is commonly used to gauge the accuracy of the state estimator is the error variances of estimated states. These values depend not only on the network parameters and measurement configuration but also on the variance of errors associated with the measurements. Hence, it is possible to compute a linear approximation of the sensitivities of the error variances of state estimates to the measurement error variances. These sensitivities will allow formulation of an optimization problem that will provide the required accuracy bounds, i.e. error standard deviations for the considered PMUs and PMU-enabled IEDs in order to maintain a desired set of bounds on the error variances of estimated states. Furthermore, using a given set of these devices, their measurement error variances can be approximately determined by computing their sample variances using large number of repeated measurements. These experimental results will then be used as tuning parameters in the state estimation solution by adjusting the corresponding measurement weights.

3 Part I: Interoperability Test

3.1 Verifying Compliances Performance of PMUs

The conformance under specific test conditions will be evaluated by comparing the total vector error (TVE), amplitude, phase angle, frequency, and rate of change of frequency (ROCOF) estimates to the corresponding reference values. The test conditions including steady-state and dynamic state are consistent with those defined in C37.118-2005 [1] and C37.118.1 (draft) [2]. The mathematical models used to create test signals for steady and dynamic states are given in Table 3.1.

Table 3.1: Test signal models

Test Type		Signal Model	Note
Steady state		$x(t) = X_m \cos(2\pi f t + \varphi)$	X_m : amplitude φ : initial angle f : frequency
Dynamic	Modulation	$x(t) = X_m [1 + k_x \cos(2\pi f_m t)] \cdot \cos[2\pi f_0 t + k_a \cos(2\pi f_m t - \pi)]$	k_x, k_a : amplitude, phase modulation factor f_m : modulation frequency
	Step change	$x(t) = X_m [1 + k_x u(t)] \cdot \cos[2\pi f_0 t + k_a u(t)]$	$u(t)$: unit step function k_x, k_a : amplitude, phase step factor
	Frequency ramp	$x(t) = X_m \cos(2\pi f_0 t + \pi f_d t^2 + \varphi)$	f_0 : nominal frequency f_d : frequency changing rate

3.1.1 Steady State

a. Test Scenarios

The test scenarios for steady state are given in Table 3.2.

Table 3.2: Test scenarios for steady state evaluation

Varying Quantity	Reference Condition	Varying Range	
		Class P	Class M
Voltage amplitude	100 % rated, constant phase and nominal frequency	80 – 120%	10 – 120%
Current amplitude		10 – 200%	10 – 200%
Phase angle	Constant angle	$\pm \pi$ rad	$\pm \pi$ rad
Frequency	Nominal frequency	± 2.0 Hz	$F_s \leq 10$: ± 2.0 Hz; $F_s > 10$: lesser of $\pm F_s/5$ Hz or ± 5 Hz

F_s is phasor reporting rate in frame per second.

b. Test Configurations

The configurations of PMUs and PMU-enabled IEDs under test are given in Appendix A: Table A.1. For those PMUs who require external time clock, the GPS signal and/or IRIG-B/PPS are provided by the reference clock. For others that have dedicated time clock, no additional reference is provided.

3.1.2 Dynamic State

a. Test Scenarios

The test scenarios for modulation, step change and frequency ramp are given in Table 3.3, 3.4 and 2.5 respectively.

Table 3.3: Test scenarios for bandwidth evaluation

Varying Quantity	Reference Condition	Varying Range	
		Class P	Class M
Amplitude and phase angle modulation: $k_x = 0.1$ p.u. $k_a = 0.1$ rad	100 % rated, nominal frequency	Modulation frequency f_m : 0.1 Hz to lesser of $F_s/10$ Hz or 2 Hz	Modulation frequency f_m : 0.1 Hz to lesser of $F_s/5$ Hz or 5 Hz
Phase angle modulation: $k_a = 0.1$ rad	100 % rated, nominal frequency		

F_s is phasor reporting rate in frame per second.

Table 3.4: Test scenarios for step change evaluation

Varying Quantity	Reference Condition	Varying Range	
		Class P	Class M
Amplitude	100 % rated, nominal frequency	$\pm 10\%$	$\pm 10\%$
Phase angle	100 % rated, nominal frequency	$\pm \pi/18$ rad	$\pm \pi/18$ rad

Table 3.5: Test scenarios for frequency ramp evaluation

Varying Quantity	Reference Condition	Varying Range	
		Class P	Class M
Linear frequency ramp: +1.0 Hz/s	100 % rated, nominal frequency	± 2.0 Hz	Lesser of $\pm F_s/5$ Hz or ± 5.0 Hz
Linear frequency ramp: −1.0 Hz/s	100 % rated, nominal frequency		

F_s is phasor reporting rate in frame per second.

b. Test Configurations

The configurations of PMUs and PMU-enabled IEDs under test are given in Appendix A: Table A.1. For those PMUs who require external time clock, the GPS signal and/or IRIG-B/PPS are provided by the reference clock. For others that have dedicated time clock, no additional reference is provided.

3.1.3 Result Analysis and Summary

The test results for conformance performance are given in Table 3.8. The detailed numerical results for each PMU under test are given in Appendix B.1.1.

Table 3.6: Conformance test result summary

PMU	Class	Steady State Test									Dynamic State Test								
		Magnitude Variation			Phase Angle Variation			Frequency Variation			Measurement Bandwidth			Frequency Ramp			Step Change		
		TVE	FE	RFE	TVE	FE	RFE	TVE	FE	RFE	TVE	FE	RFE	TVE	FE	RFE	RT	DT	MO
A	P	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	F	F	F
	M	S	S	S	S	S	S	F	S	S	S	F	S	F	F	F	S	F	F
A-1 *	P	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	F	S	F
	M	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	S	S	F
B	P	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	S	F	S
	M	S	S	S	S	S	S	S	S	S	F	F	S	F	F	F	S	F	S
C	P	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	S	S	S
	M	S	S	S	S	S	S	S	S	S	S	S	S	F	F	F	S	S	S
D	P	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	F	F	F
	M	S	S	S	S	S	S	S	S	S	F	F	S	F	F	F	S	F	F
E	P	S	S	S	S	S	S	S	S	S	S	F	S	S	F	F	F	S	F
	M	S	S	S	S	S	S	F	S	F	F	F	S	S	F	F	S	S	F
F	P	S	S	S	S	S	S	F	S	S	S	F	S	F	F	F	S	S	S
	M	S	S	S	S	S	S	F	S	S	F	F	S	F	F	F	S	S	S

*PMU A-1 is an upgraded firmware of PMU A

TVE: total vector error; FE: frequency error; RFE: rate of change of frequency error;

RT: response time; DT: delay time; MO: maximum over/under shoot

S stands for “Satisfied”; F stands for “Failed”.

The conformance test results are summarized as follows:

- PMU A: This PMU uses external IRIG-B input. The performance is unstable. The phase angle results vary in a large range (from a half to two degrees (1% to 4% TVE accordingly) for each test. Each test case was performed five times and the best result was recorded. According to the new standard [2] test results show that the PMU failed in some cases, see Table B.1.1.3, B.2.1.1 and B.2.1.2. From the frequency ramp test we observe that the rate of change of frequency measured by the PMU has a certain number of multiples (100) of the real value. This may be because the PMU “forgot” to multiply with 100 (as required by the standard C37.118 [1]) before packing ROCOF measurement into data frame.
- PMU A-1: Compared to the unit with old firmware, the performance is stable and the improvement is noticeable. The improvement includes the performance of frequency variation, frequency ramp and step response, see Table B.1.2.3, B.2.2.2 and B.2.2.3. The According to the new standard [2] test results show that the PMU failed in some cases, see Table B.1.1.3, B.2.1.1 and B.2.1.2. The issue of packing the rate of change of frequency measurement into phasor frame has not been improved in this firmware.

- PMU B: This PMU uses a dedicated time receiver which provides time code to PMU for synchronizing outputs while compensating phase errors. The errors of phase angle measurements are quite small. This PMU has the same issue as PMU A that packs the rate of change of frequency measurement (see Table B.2.2.2). This PMU passed the steady state tests, but failed to provide conformance under some dynamic conditions, see Table B.2.2.1, B.2.2.2, and B.2.2.3.
- PMU C: This PMU uses external IRIG-B input. The performance was very stable. It passed the steady state tests and the step test, but failed on some conditions, see Table B.2.3.1, B.2.3.2. This PMU correctly follows the standard in packing the rate of change of frequency into data frame.
- PMU D: This unit has built-in GPS receiver. It has the issue that does not follow the standard in packing ROCOF measurement into phasor, see Table B.2.4.2. This PMU passed the steady state test, but failed to provide conformance under some dynamic conditions, see Table B.2.4.2, B.2.4.2, and B.2.4.3.
- PMU E: This unit has built-in GPS receiver. The communication for sending out phasor data through Ethernet connection was unstable. The connection interrupted frequently while performing tests. This PMU correctly follows the standard in packing the rate of change of frequency into data frame. It failed to provide conformance in class M of frequency variation tests, and some dynamic tests, see Table B.1.5.3, B.2.5.1, B.2.5.2, and B.2.5.3.
- PMU F: This unit uses external IRIG-B input. It has the issue that does not follow the standard in packing ROCOF measurement into phasor, see Table B.2.6.2. This PMU has poor accuracy working under off nominal frequency, see Table B.1.6.3. It failed to provide conformance under some dynamic conditions, see Table B.2.6.1 and B.2.6.2, but it passed the step test.

3.2 Interoperability of PMUs with Time Synchronization Options

3.2.1 Test Description

The interoperability between synchrophasor devices, including the time clock and PMU or PMU-enabled IED, PMU or PMU-enabled IED and PDC, will be verified by interchanging equivalent parts, as described in Table 3.6. The performance will be measured by the functional status and numerical results against standards [1] and [2]. Generally the test load relies on the availability of the PMU, time clock and PDC being tested. The combinations could be enormous for some cases. We reclassify the devices under tests in terms of their features to void invalid combinations. For example, in terms of the type of time source, we categorize PMUs into three classes: a. Direct GPS signal, which has built-in GPS receiver; b. IRIG-B input, which requires external time synchronization source; c. IEEE 1588, which is synchronized through network. Some PMUs may have all three features. The selected steady-state and dynamic state tests will be performed for each combination to generate the numerical results. We assure that the test conditions are consistent so that the test results are comparable.

Table 3.7: Test descriptions for interoperability verification

Object	Configuration	Test Item	Performance Index
Interoperability between the Time clock and PMU or PMU-enabled IED	Direct GPS	Selected Steady state and Dynamic state tests defined in Table 2.2-2.6	Functional status and Numerical performance indices
	IRIG-B / PPS		
	IEEE 1588 v2 PTP		
Interoperability between the PMU or PMU-enabled IED and PDC	Software PDCs		
	Hardware PDCs		

a. Test Scenarios

Four types of scenarios are selected: the amplitude and frequency variations for steady state, and the modulation and frequency ramp for dynamic state. As given in Table 3.7, the tests conditions include the maximum variations for class P and M.

Table 3.8: Test scenarios for interoperability between PMUs and time clock

Scenario	Test Condition		Interchangeable Option
	Class P	Class M	
C1 Amplitude variations	$\pm 20\%$	-90%, +20% for voltage, +100% for current	Direct GPS or Dedicated Receiver IRIG-B / PPS IEEE 1588 v2 PTP
C2 Frequency variations	± 2 Hz	± 5 Hz	
C3 Modulation (combined amplitude and phase)	2 Hz	5 Hz	
C4 Frequency ramp	± 1 Hz/s, ± 2 Hz	± 1 Hz/s, ± 5 Hz	

C1 – C4: stands for the four test scenarios.

b. Test Configurations

Test configuration for synchrophasor units are given in Appendix A: Table A.1. The configuration of synchronization options, such as GPS receivers and Ethernet switches are given in Table A.2.

3.2.2 Result Analysis and Summary

Most PMUs under test have the problem of measuring the rate of change of frequency. We will not consider this performance index in the interoperability test. Test results for the interoperability between PMUs and time synchronizations are given in Table 3.9. The detailed

numerical results for each PMU connected with different synchronization options are given in Appendix B.1.2.

Table 3.9: Interoperability test result summary

Device		Clock A				Clock B				Clock C				Clock D			
		C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
PMU A-1	P	S	S	F	F	N	N	N	N	F	F	F	F	S	S	F	F
	M	S	S	F	F					F	F	F	F	S	S	F	F
PMU B	P	N	N	N	N	S	S	F	F	N	N	N	N	N	N	N	N
	M					S	S	F	F								
PMU C	P	S	S	F	F	N	N	N	N	S	S	F	F	S	S	F	F
	M	S	S	S	F					S	S	F	F	S	S	S	F
PMU F	P	S	F	F	F	N	N	N	N	S	F	F	F	S	F	F	F
	M	S	F	F	F					S	F	F	F	S	F	F	F

C1 - C4: Test scenarios as defined in Table 2.7. P: class P; M: class M.

S stands for “Satisfied”; F stands for “Failed”; N stands for “Not Functional”.

The test results for the interoperability between PMUs and time synchronization options are summarized as follows:

- PMU A-1: This PMU can operate with three time clocks. But it failed to provide conformance when using GPS receiver Clock C while it met performance requirements when using the Clock A and D. We may address that this PMU is not interoperable with Clock C. The PMU was unable to measure frequency correctly during frequency variation and ramp, thus caused large errors in TVE, see Table B.3.3.2. Specific compensations may be applied to the PMU so that it meets the accuracy requirements when using Clock C.
- PMU B: This PMU can only operate with its dedicated GPS receiver Clock B. This may because it uses DCF77 as input time code instead of IRIG-B. This receiver is not compatible with other PMUs.
- PMU C: This PMU can operate with three time clocks. From test results we observe that the performance achieved by using the Clock A and D respectively are comparable. Compared to the results measured by using Clock C, the PMU created larger TVEs than using other clocks, see Table B.3.2.2. We may address that this PMU is not interoperable with Clock C.
- PMU F: This PMU can operate with three time clocks. The performance achieved by using the Clock A, C and D respectively are comparable.

3.3 Verifying Compliances Performance of PDCs

The compliance under specific test conditions will be confirmed by testing the basic/advanced PDC functions defined in "Guide for Phasor Data Concentrator Requirements for Power System Protection, control, and Monitoring" [3], calculating the Data Processing Time, and verifying the amplitudes, phase and TVE in the output data stream meet the requirements defined in C37.118-

2005 [1] and C37.118.1 [2]. In this project, we will primarily focus on verifying if the PDCs under test have some/all of the functions mentioned above and if they are working properly under test conditions.

The test results are given in Table 3.10.

Table 3.10: PDC conformance test result summary

Functions Under Test	PDC A	PDC B	PDC C
Data Alignment	S	S	S
Data Communication	S	S	S
Data Validation	S	S	S
Synchrophasor data transfer protocol support	IEEE C37.118	IEEE C37.118 Comtrade	IEEE C37.118
Synchrophasor data transfer protocols conversion	S	S	S
Format and coordinate conversion	S	S	S
Latency calculation	S	S	S
Reporting rate conversion	S	S	S
Data Buffering	S	S	S
Configuration	S	S	S
Phase and magnitude adjustment	S	S	S
PMU/PDC Performance Monitoring	S	S	S
Data gateway	S	S	S
Data Aggregation	Not well-defined yet, not tested		
Robustness	Not well-defined yet, not tested		
Redundant data handling	S	S	S
Duplicate data handling	Not well-defined yet, not tested		
Data re-transmission request	N	N	N

* S stands for "Satisfied", F stands for "Failed", "N" stands for "Don't have this function".

3.4 Interoperability of PMUs with PDC

The communication network is also considered as an important interchangeable part in the test with various communication protocols and settings [3]. The interoperability between PMUs, PMU-enabled IEDs, PDCs and associated communication network will be verified by interchanging equivalent parts. The performance will be measured by the function status and numerical results by performing the conformance test in 3.1.1. The test conditions are defined below in Table 3.11.

Table 3.11: Test Scenarios for conformance test

PDC under test	PMU	Communication Network	Testing Items	Performance Index
Software PDCs	Reference PMU and PMUs, PMU-enabled IEDs from different vendors	TCP/IP, UDP/IP, UDP/IP multi-casting	Conformance test defined in 3.1.1	Function status and compliance test
		IPv4 and/or IPv6		
Hardware PDCs		Data Protocols (IEEE C37.118-2005, IEEE 1344 etc.)		

The test results are given in Table 3.12.

Table 3.12: Interoperability test result summary

	PMU A	PMU A*	PMU B	PMU C	PMU D	PMU E	PMU F	PMU G	PMU H
PDC A	S	S	S	S	S	S	S	S	S
PDC B	F	F	F	S	S	S	S	S	S
PDC C	S	S	S	F	F	F	F	F	F

* PMU A-1 is an upgraded firmware of PMU A.

** S stands for “Satisfied”; F stands for “Failed”.

*** This PDC requires an additional adapter to support serial port communication.

**** This PDC only supports serial port communication, but it has two Ethernet port available for upgrade to support Ethernet communication

3.5 Interoperability of PMUs, PDCs and Communication Network

3.5.1 Testbed Design

The goal of this thrust is to measure the impact of network impairments, such as delay and packet loss, on the performance of the power system applications such as state estimation and fault location. We have considered a setting in which the PMUs and PDC utilize the IEEE protocol C37.118.2 [4] (Synchrophasor Data Transfer for Power Systems) for communication and control.

We have considered two approaches towards achieving this goal. The first approach is to perform extensive simulations using standard network simulators such as OPNET and NS2. However, building a realistic simulation framework requires full implementation of the C37.118.2, as well as other network protocols in the TCP/IP stack along with a traffic generation module, which should accurately emulate typical traffic patterns of PMU-PDC communication protocols. Implementing a large number of network protocols along with realistic traffic generation represents a significant cost in time and effort. Additionally, testing of this simulation would not provide any insight into industrial implementations and system tolerances of the protocol.

The second option is to create a realistic testbed that includes industrial PMUs and PDCs connected through a communication network. Wide Area Network (WAN) network characteristics are modeled using an impairment generator, referred to as the *impairator*. The *impairator* acts as a ‘bump-in-the-wire’ network device, it is not observable through any network protocol; its role is to emulate an Ethernet cable. With that said the *impairator* has the ability to impart queuing delay (latency), and packet loss according to user defined scripts. In our project, we have adopted the impairment approach to test the performance of PMU applications in real-world scenarios, as well as verify the interoperability of different industrial PMUs.

Figure 3-1 depicts schematic view of the testbed. The testbed includes one or more PMUs and a PDC connected through a local area network (Ethernet). All packets exchanges between the PMUs and the PDC must traverse the *impairator*, which provides the opportunity to experiment with symmetric and asymmetric packet loss and delay.

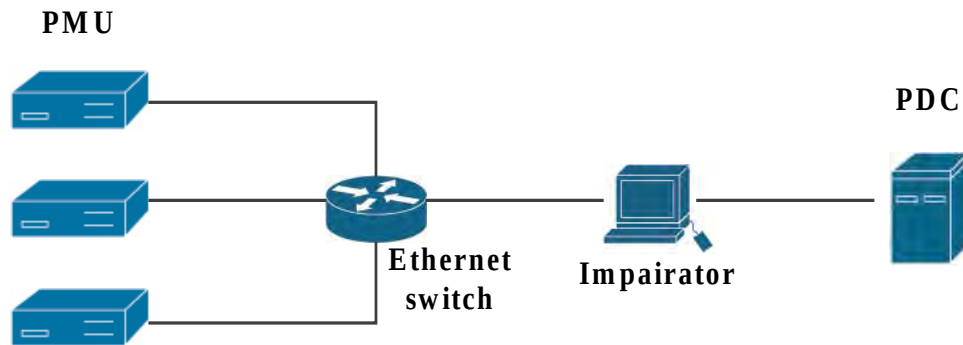


Figure 3.1: Evaluation testbed

3.5.2 Impairator Design and Implementation

The *impairator* was constructed using Click modular router platform [5]. Click is an open source platform that enables fast prototyping of configurable routers. In Click, a router is decomposed into atomic design elements, referred to as *packet processing modules*. The modules have different functionality, such as packet forwarding, packet queuing, and packet classification. Click allows users to describe a router with all of its elements by using a simple configuration script. This architecture allows users to implement new router designs quickly and efficiently by ‘clicking’ several elements together to define their desired functionality.

In our project, the *impairator* unconditionally bridges packets between two Ethernet network interfaces. We supply a Click configuration, which allows for the basic bridging along with controllable symmetric and asymmetric packet loss and delay. For example, when *impairator* receives a packet from PMU to PDC, it can hold the packet for 100ms, before forwarding it to PDC, which results in an observable 100ms delay added to the one-way trip time of the packet.

Figure 3-2 depicts the Click configuration used in this project. Both directions of packet transmission have a “forward with delay” element, which allows for controllable asymmetric packet delay.

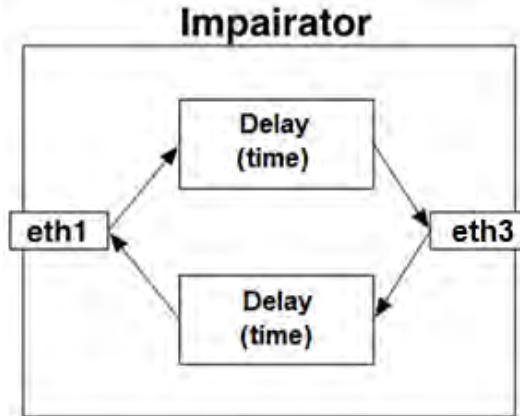


Figure 3.2: Impairator configuration for delays

Figure 3-3 depicts Click configuration for measuring packet losses. Since no packet loss elements are given in Click, the element Discard is implemented by introducing random bit errors. When bit error happens, the packet will be filtered by the network adapter due to a checksum error, which is equivalent to packet loss. The parameter of bit error probability can be calculated from required packet loss probability, which is given by:

$$\text{Bit Error Probability} = 1 - (1 - \text{Packet Loss Probability})^{1/\text{Packet Size}}$$

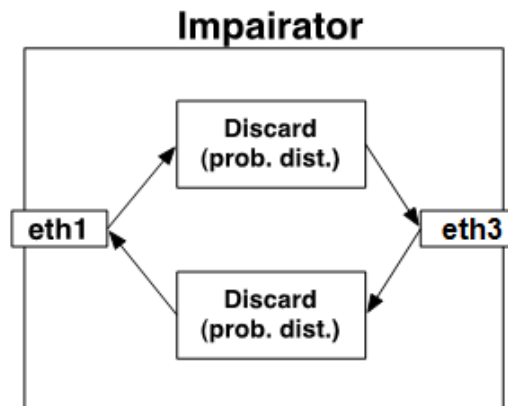


Figure 3.3: Impairator configuration for packet losses.

The scripts for both configurations are given below:

```
FromDevice(eth1)->RandomBitError(p)->ToDevice(eth3)
FromDevice(eth3)->RandomBitError(p)->ToDevice(eth1)
```

Click script for PMU-PDC packet loss case

```
FromDevice(eth1)->Queue->DelayUnqueue(T)->Queue->ToDevice(eth3)
FromDevice(eth3)->Queue->DelayUnqueue(T)->Queue->ToDevice(eth1)
```

Click script for PMU-PDC packet delay case

3.5.3 PDC Data Processing Time Measurement

The next objective was to measure PDC processing latency with respect to C37.118.2 packets. The base network configuration was equivalent to the packet loss and latency tests; however, an addition PDC was added to the environment. In this two-tier configuration, the first tier of PDCs provides an information aggregation function and forwards their summarized data to the top tier PDC. This experiment measured the processing latency of the first tier PDC using the *impairator*. In this test the *impairator* was recording all ingress and egress C37.118.2 packets for the PDC and using their internal identification parameters to calculate processing latency. Figure 3-4 shows network configuration for data processing time management.



Figure 3.4: Network configuration for data processing time management.

The time period measured by this method is actually the sum of PDC processing time, PDC packet send/receive time, *impairator* packet send/receive time, and the time of packet transmission on the wire. Here we assume the send/receive time of a packet is far smaller than PDC processing time. Also, it is obvious that packet transmission time is ignorable. Thus the measured time period is roughly the actual PDC processing time.

To record the time of a packet's arrival and departure through the PDC, we use the open source Packet Capture library PCAP [6]. A capture of each packet both arriving and departing is recorded and then correlated to determine processing latency. PCAP captures packets and marks their arrival or departure time with microsecond granularity. Each packet capture's C37.118.2 header is examined and indexed in an arrival or departure data-structure using the ID header attribute. Processing latency is calculated for each departure packet by finding its corresponding arrival and subtracting its recorded departure and arrival times

3.5.4 Virtual PMU

The method described in the previous section uses industrial PMUs to generate source data. The number of available PMUs limits this experimental setup. This section explores a method to use virtual PMUs to increase the number of components in the testbed network. In particular, using this methodology we will be able to test emulate network with a large number of PMUs while leveraging a small number of physical PMU devices.

A virtual PMU (vPMU) emulates a PMU by generating traffic modeled on the packet capture of a physical PMU. First, a C37.118.2 PMU model is created by capturing a physical PMU's C37.118.2 session with a PDC. Then it is stripped of non-essential protocol data (Ethernet/IP/TCP/UDP). Finally, its C37.118.2 header attributes are made parametric for generic replay. The vPMUs emulate physical PMUs from these PMU session models by instantiating the parametric model with a user-supplied configuration. Packets generated by a vPMU are sent to a PDC just as real PMU data. When received by the PDC, these packets are indecipherable from physical PMUs. This allows us to test large-scale networks without possession of a large number of physical PMUs. The network configuration is given in Figure 3-5:

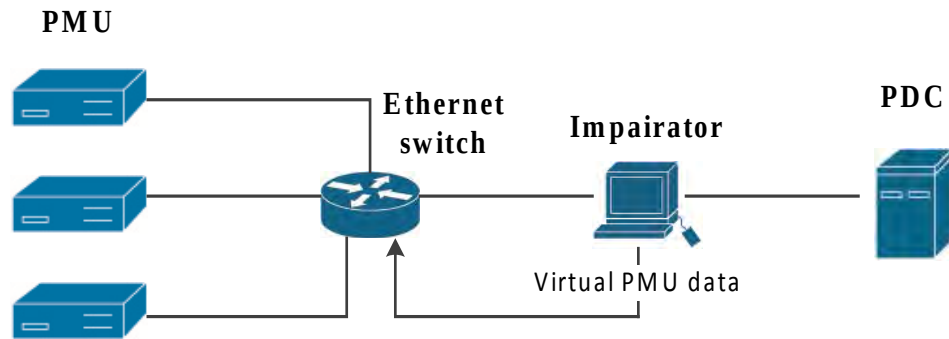


Figure 3.5: Configurations for virtual PMU

4 Part II: Application Performance Test

4.1 Fault Location

a. Fault Location Algorithm

A fault location algorithm using two-end synchronized measurements is selected to perform the application test [7]. As shown in Figure 4.1, a fault occurs on a transmission line. From the equivalent circuit diagram, we have two equations:

$$\dot{V}_S = xZ_L \cdot \dot{I}_S + \dot{V}_f \quad (4-1)$$

$$\dot{V}_R = (1-x)Z_L \cdot \dot{I}_R + \dot{V}_f \quad (4-2)$$

Subtracting (1) from (2) to eliminate $\dot{V}_f$, we obtain the equation for computing location x using two-terminal voltage and current measurements:

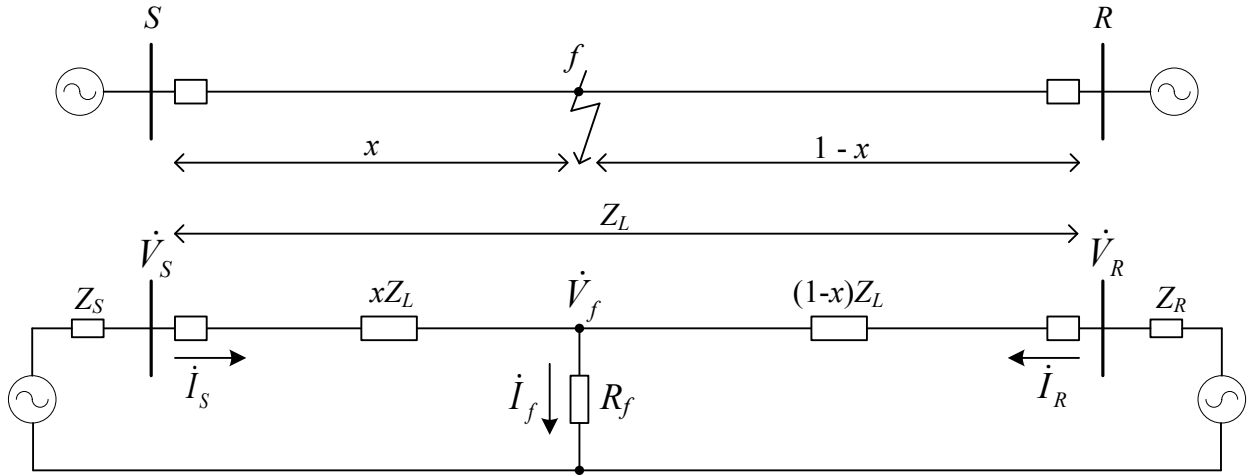


Figure 4.1: One-line diagram and equivalent circuit for a fault on transmission line

b. Test Scenarios

The synchrophasor-based fault location algorithm, as described above, is selected to investigate how different PMUs and PMU-enabled IEDs, time synchronization methods, PDCs and communication protocols affect the application performance. These three elements will be tested individually. The performance will be evaluated by comparing the distance calculated using phasor measurements from PMUs under test to the value calculated using phasor measurements from the reference PMU. The fault disturbances variations may be location and fault type. For phase to ground faults, we set the fault resistance to zero. The test scenarios are summarized in Table 4.1. A 230 kV 4-bus power network is used to simulate various fault scenarios, as shown in Figure 4.2. Transient voltages and currents are generated using ATP/EMTP [8]. The test conditions should be consistent so that the test results are comparable.

Table 4.1 Test scenarios for application test

Target	Test Configuration	Fault Variation
PMU or PMU-enabled IED	Reference time clock, no PDC connected	Location: 10%, 50%, 90%; Type: SLG, LL, LLG, 3L; Resistant: 0 Ω
Time synchronization method	Reference PMU, no PDC connected	
PDC and communication medium	Reference time clock and reference PMU	

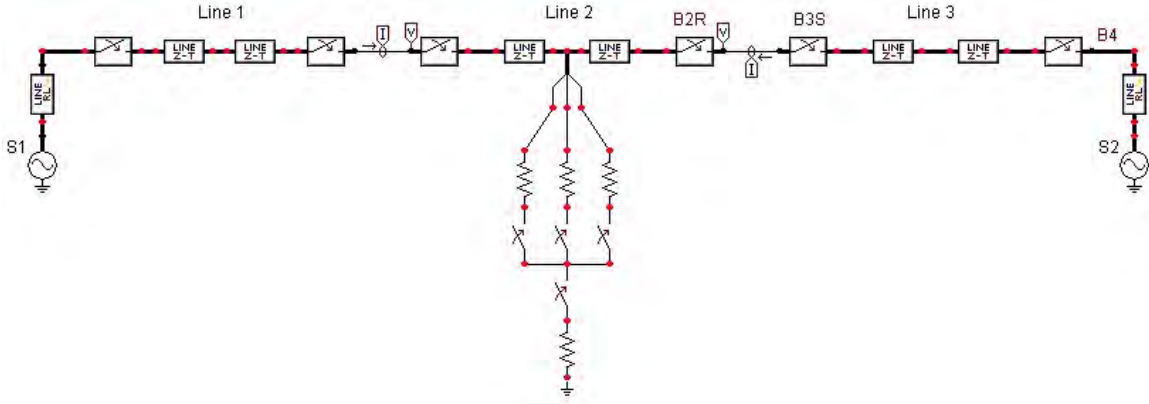


Figure 4.2: A 230 kV 4-bus power network model in ATP/EMTP

c. Test Configurations

Test configurations for synchrophasor units are given in Appendix A: Table A.1. The configurations of synchronization options, such as GPS receivers and Ethernet switches are given in Table A.2.

4.1.1 PMUs and PMU-Enabled IEDs

Three PMUs and PMU-enabled IEDs are selected to perform the application test. The reference GPS receiver is used to synchronize the PMUs at each end, sending end and receiving end, denoted as “S” and “R”. The tests include the configuration of PMUs from the same vendor for both ends and the PMUs from different vendors at each end. The estimated locations and errors for the fault variations defined in Table 3.1 are recorded in Appendix B.2.1. The location error is calculated as follows:

$$l_{Err} = \frac{|l_R - l_M|}{l_R} \times 100\% \quad (4-3)$$

For each set of PMUs, the mean, maximum and minimum values of estimated location errors are recorded. Table 3.2 summarizes the test results.

Table 4.2: Application test results using PMUs and PMU-enabled IEDs

PMU at End S	PMU at End R								
	PMU C			PMU A-1			PMU F		
	Estimated Error (%)			Estimated Error (%)			Estimated Error (%)		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
PMU C	1.448	4.637	0.019	1.454	5.818	0.213	1.449	4.387	0.188
PMU A-1	2.909	8.743	0.167	1.173	10.02	0.055	0.852	6.872	0.076
PMU F	2.571	7.325	0.014	0.473	2.196	0.007	1.018	8.372	2e-4

From the test results, we obtain the conclusions as follows:

- The estimated fault locations under different configurations of PMUs vary in a large range, though the PMUs meet the 1% TVE requirement. The maximum error reaches up to 10% under some fault scenarios.
- For using PMU or PMU-enabled IED from the same vendor at both ends, the accuracy performance for the three devices is consistent.
- For using PMU or PMU-enabled IED from the different vendor at each end, the combination of PMU A-1 and PMU F achieves the best results.

4.1.2 PMUs and Time Synchronizations

Three PMUs and PMU-enabled IEDs and three time synchronization clocks are selected to perform the application test. Each PMU is used at both ends while using different time clocks. The test for using the reference GPS receiver has been performed in Section 3.4.1. The mean, maximum and minimum value of estimated location errors for each configuration of time clocks are recorded, which are given in Appendix B.2.2. Table 4.3, 4.4 and 4.5 summarize the test results.

Table 4.3: Application test results using PMU C and time synchronization clocks

PMU at End S	PMU at End R								
	Clock A			Clock C			Clock D		
	Estimated Error (%)			Estimated Error (%)			Estimated Error (%)		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Clock A	1.448	4.637	0.019	1.520	4.642	0.025	1.573	4.639	0.022
Clock C	1.476	4.628	0.050	1.548	4.633	0.056	1.601	4.630	0.053
Clock D	1.444	4.635	0.046	1.517	4.640	0.052	1.569	4.637	0.048

Table 4.4: Application test results using PMU A-1 and time synchronization clocks

PMU at End S	PMU at End R								
	Clock A			Clock C			Clock D		
	Estimated Error (%)			Estimated Error (%)			Estimated Error (%)		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Clock A	1.173	10.02	0.055	1.853	9.532	0.008	1.249	11.09	0.061
Clock C	1.767	15.67	0.035	2.487	15.16	0.029	1.838	16.77	0.031
Clock D	1.166	9.872	0.068	1.852	9.382	0.040	1.242	10.95	0.046

Table 4.5: Application test results using PMU F and time synchronization clocks

PMU at End S	PMU at End R								
	Clock A			Clock C			Clock D		
	Estimated Error (%)			Estimated Error (%)			Estimated Error (%)		
	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Clock A	1.018	8.372	2e-4	0.768	6.706	0.008	0.633	5.384	0.008
Clock C	0.999	8.901	0.016	0.841	7.242	0.022	0.690	5.918	0.016
Clock D	1.176	10.60	0.013	0.996	8.948	0.008	0.806	7.611	0.009

From the test results, we obtain the following conclusions:

- For each PMU, the estimated fault locations using different time synchronization clocks vary in a large range. The maximum error reaches up to 16.77% for some fault scenarios.
- For PMU C, the accuracy of estimated fault locations using three time clocks is consistent.
- For PMU A-1, the estimation accuracy using Clock A and Clock D is comparable. The estimation errors using Clock C for any end or for both ends are large, compared to using

other two clocks. This is consistent with the interoperability test result, which shows that this PMU is not interoperable with Clock C, as shown in Table 2.9.

The PMU F achieved the best accuracy using Clock A at End S and Clock D at End R, while resulted in the largest error using Clock D at End S and at Clock A End R. The estimation accuracy under other combination of time clocks is comparable.

4.1.3 PMUs, PDCs and Communication Network

A general procedure for performing the communication network test is:

- (1) Generate test signals according to Table 3.1 using ATP and convert the data files into the LabVIEW format [9];
- (2) Feed test signal to PMU A and PMU B, and collect synchrophasor from PDC A. This procedure is automated by the software delicately developed for such test;
- (3) Run the fault location algorithm using collected synchrophasor;
- (4) Record the estimated location and compare to the reference value;
- (5) Change communication network by exchanging a products in the end-to-end solution and repeat the test.

*In Step 2, we use the following procedure:

We use PMU A to capture the sending-end signal at time t_1 , PMU B to capture the receiving-end signal at the t_2 , and "manually" align them by their timestamps, as shown in Figure 4-3. This procedure is to be done by a separate function.

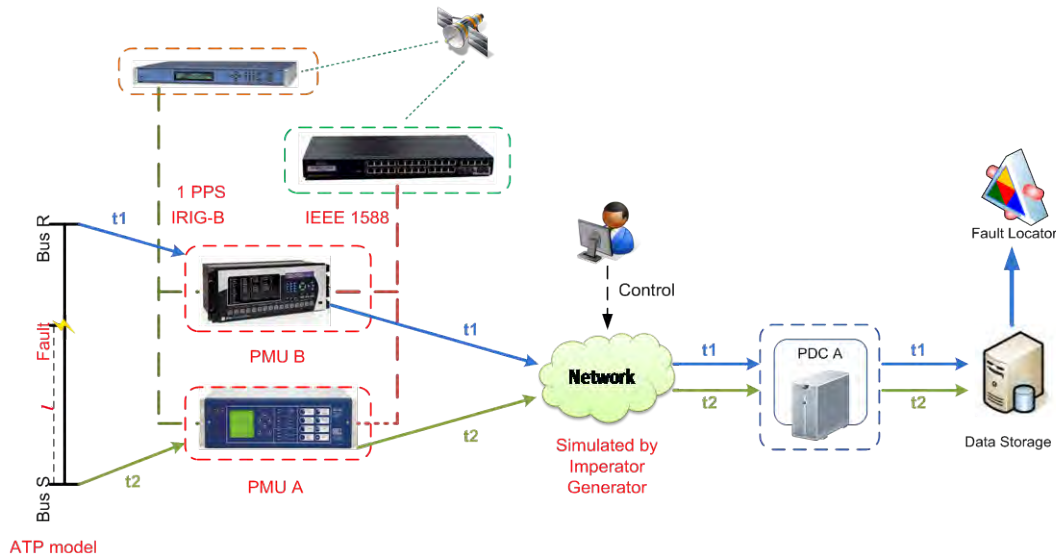


Figure 4.3: Communication network test using one set of signal generator at t_1 and t_2

The test results are given in Table 4.6.

Table 4.6: Impact of communication network data loss on the application test results (PMU reporting rate: 30 sample/s)

Fault Type	Location	Bit Error Rate	Loss Rate	Estimated Error Deviation	No Result
BC	10% (4 miles from the sending end)	0.001%	4.34%	1.567%	0.07%
		0.003%	12.45%	2.713%	1.21%
		0.005%	19.88%	3.963%	4.63%
		0.008%	29.85%	4.660%	12.95%
		0.010%	35.80%	4.965%	19.92%
		0.012%	41.25%	5.242%	28.04%
		0.015%	48.56%	5.492%	40.38%

Table 4.7: Impact of communication network data loss on the application test results (PMU reporting rate: 60 sample/s)

Fault Type	Location	Bit Error Rate	Loss Rate	Estimated Error Deviation	No Result
BC	10% (4 miles from the sending end)	0.001%	4.34%	1.097%	0.00%
		0.003%	12.45%	2.038%	0.02%
		0.005%	19.88%	2.905%	0.21%
		0.008%	29.85%	3.896%	1.70%
		0.010%	35.80%	4.265%	4.33%
		0.012%	41.25%	4.734%	8.01%
		0.015%	48.56%	4.826%	15.81%

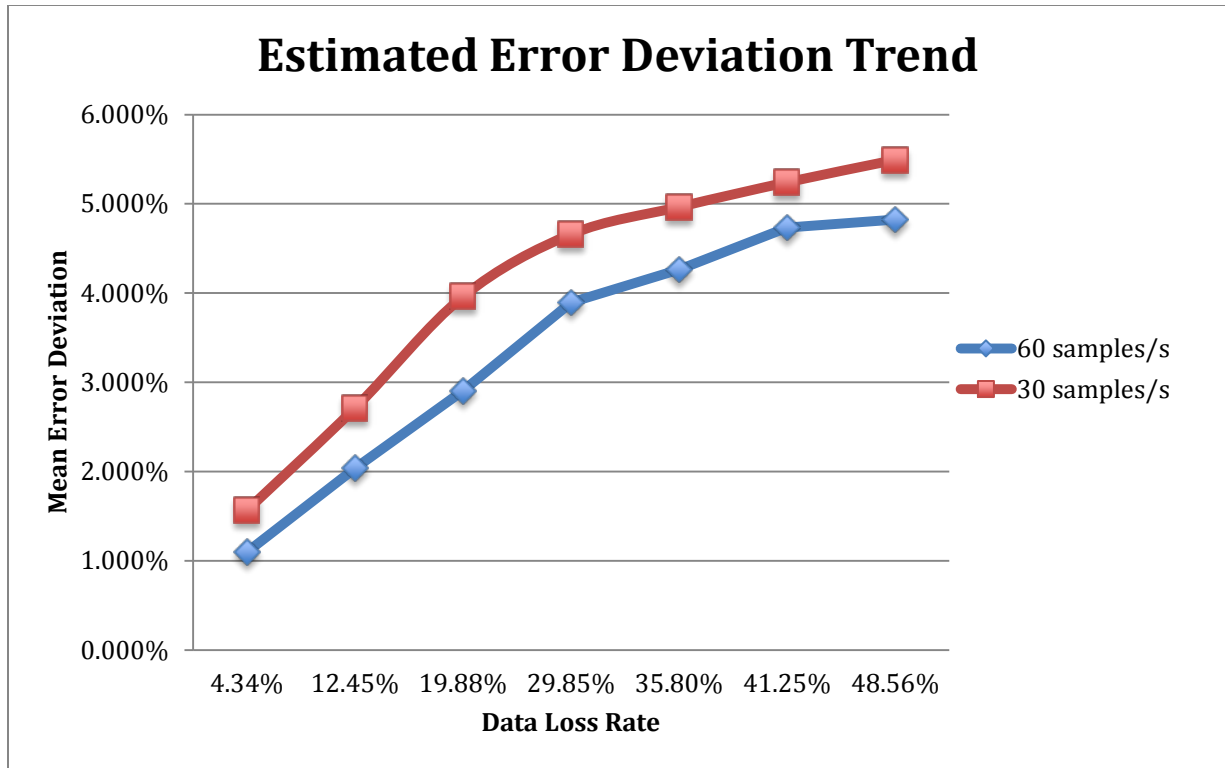


Figure 4.4: Estimated error deviation trend vs. data loss rate

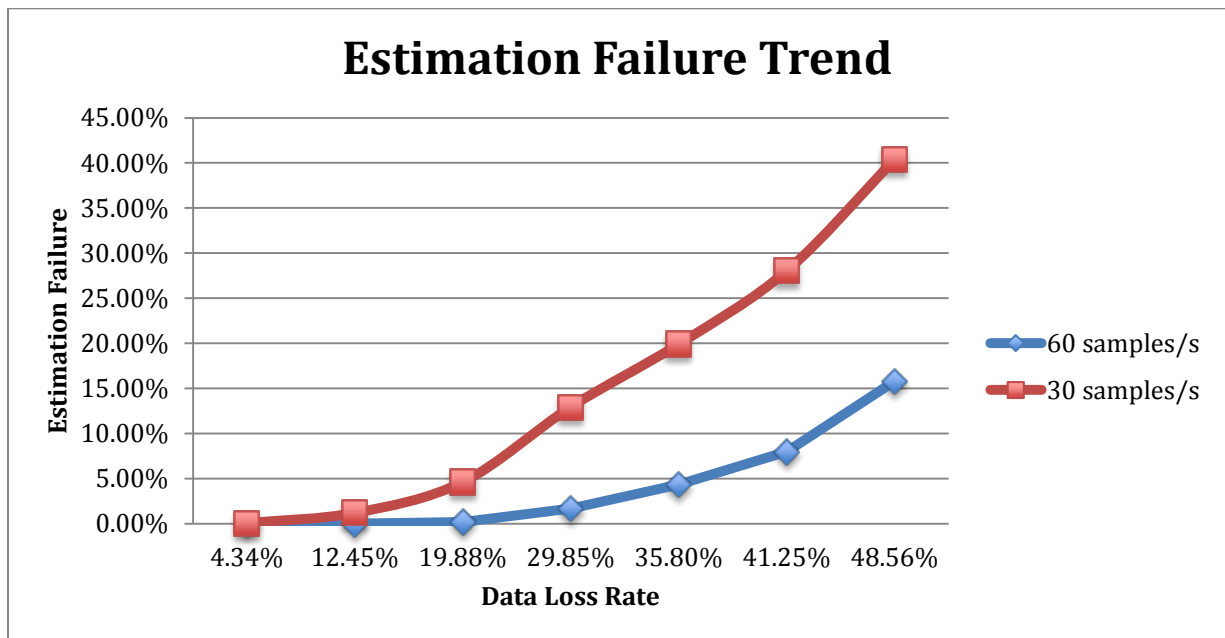


Figure 4.5: Estimation failure trend vs. data loss rate

4.2 State Estimation

A state estimation problem is commonly formulated as an optimization problem which minimizes the least weighted squares of measurement residuals. Hence, an important parameter specified by the users of state estimators is the weight given to each measurement residual when solving this optimization problem. Historically, such weights were assigned based on the accuracy classes of measurements [11], [12]. This may depend on the known or assumed accuracy of the meters used in obtaining the measurement, as well as the errors involved in the chain of measurement devices and transformers between of the point of actual measurement and the digital interface to the computational medium, such as the computer.

The recent trend is using PMU measurements in state estimators along with other conventional measurements [13]-[18]. It brings up the challenge of how to assign measurement weights that will be consistent despite the differences between the various types of measurements used by the estimator. This issue is particularly significant when one or more of the measurements carry errors. Most of the commonly used error detection and identification methods are based on processing of standardized measurement residuals, where the process of standardization involves user assigned measurement weights [19]-[23]. Hence, inconsistently assigned weights may lead to incorrect decisions about the measurements. While some errors may be missed due to their low assigned weights, others may be flagged as bad data due to their very high assigned weights even if they carry statistically insignificant measurement errors.

This section presents a method which can tune the weights associated with the PMU measurements, thus eliminating the need to pre-specify these weights. The approach does not depend on any manufacturer specified data, thus it can be used with different types of PMUs, without the need to address any inter-operability issues

4.2.1 State Estimator Tuning for PMU Measurements

4.2.1.1 Proposed Method

A. Formulation of the problem

In state estimation, the measurement equation is considered as:

$$z = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_m \end{bmatrix} = \begin{bmatrix} h_1(x_1, x_2, \dots, x_n) \\ h_2(x_1, x_2, \dots, x_n) \\ \vdots \\ h_m(x_1, x_2, \dots, x_n) \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_m \end{bmatrix} = h(x) + e \quad (4-4)$$

where

- z measurement vector with dimension of m ;
- x the system state vector with dimension n ;
- e measurement error vector with dimension of m ;
- $h(x)$ nonlinear function of measurement with state vector.

The following basic assumptions are commonly made regarding the measurements:

- 1) The mean of each measurement error is zero:

$$E(e_i) = 0, \quad i = 1, 2, \dots, m \quad (4-5)$$

- 2) Measurement errors are independent so that

$$\text{cov}(e) = E(e \cdot e^T) = R = \begin{bmatrix} \sigma_1^2 & & & \\ & \sigma_2^2 & & \\ & & \ddots & \\ & & & \sigma_m^2 \end{bmatrix} \quad (4-6)$$

where the σ_i is the standard deviation of the error of measurement i , which indicates the accuracy of a measurement.

The weighted least squares estimation method aims to minimize the objective function given by:

$$\begin{aligned} J(x) &= \sum_{i=1}^m [z_i - h_i(x)]^2 \cdot W(i, i) \\ &= [z - h(x)]^T \cdot W \cdot [z - h(x)] \end{aligned} \quad (4-7)$$

where $W = R^{-1}$ is called weight matrix, which is reciprocal of variance matrix. It is normally assumed that the weight matrix is given since the standard deviations of the measurements are known. However, this assumption may not be true, especially for PMUs. Therefore, the objective of the work is to design a self-tuning algorithm to estimate the variances of PMU measurements, whose reciprocals are the weights applied to in state estimation.

Consider the first order approximation to the measurement equation around an initial state x_0 :

$$\Delta z = H \Delta x + e \quad (4-8)$$

where

$$\Delta z = z - h(x_0) \quad (4-9)$$

$$H = \partial h / \partial x \quad (4-10)$$

$$\Delta x = x - x_0 \quad (4-11)$$

Then the incremental change in state vector can be obtained by WLS estimator as follows [11]:

$$\Delta \hat{x} = G^{-1} H^T R^{-1} \Delta z \quad (4-12)$$

where

$$G = H^T R^{-1} H \quad (4-13)$$

The estimated measurement value is given by

$$\Delta \hat{z} = H \Delta \hat{x} = K \Delta z \quad (4-14)$$

where

$$K = H G^{-1} H^T R^{-1} \quad (4-15)$$

Note that K has the property [11]:

$$(I - K)H = 0 \quad (4-16)$$

Then the measurement residuals can be calculated as below:

$$\begin{aligned} r &= \Delta z - \Delta \hat{z} \\ &= (I - K)(H \Delta x + e) \\ &= (I - K)e \\ &= S e \end{aligned} \quad (4-17)$$

where $S = I - K$ is called residual sensitivity matrix.

Using the special property below [11]:

$$S \cdot R \cdot S^T = S \cdot R \quad (4-18)$$

The covariance matrix of measurement residuals can be derived from (14):

$$\begin{aligned} R_r &= cov(r) \\ &= S \cdot cov(e) \cdot S^T \\ &= S \cdot R \cdot S^T \\ &= S \cdot R \end{aligned} \quad (4-19)$$

As shown in (4-6), since R is diagonal, the diagonal elements in (4-9) will be related as follows:

$$R(i, i) = \frac{R_r(i, i)}{S(i, i)} \quad (4-20)$$

where $R(i, i)$, $R_r(i, i)$ and $S(i, i)$ are the i th diagonal element of R , R_r and S respectively. It is noted that the diagonal elements of R_r are just the variances of corresponding measurement residuals.

Equation (4-20) presents the relationship between variances of measurement residuals and variances of measurement errors, whose reciprocals are the weights. It allows the weights of measurements to be tuned through historical data by calculating variances of measurement residuals and sensitivity matrix. This theory has already been used to tune the weights of conventional measurements (including voltage magnitudes, power flows and injections) [24]. In this work, the algorithm will be revised and extended to the case of PMUs. An iterative self-tuning method for PMUs will be presented in the next section.

One way to measure the state estimation accuracy is to use the metric based on the calculated normalized state errors given by [25]:

$$NE = \frac{\|\hat{x} - x_{perfect}\|_2}{\|x_{perfect}\|_2} \quad (4-21)$$

where

$\hat{x}$ estimated state vector;
 $x_{perfect}$ perfect state vector before adding errors.

Normally it is not possible to calculate NE because of lack of information on $x_{perfect}$. However, this will not be an issue when using the power flow solution to synthetically create system measurements for testing. This metric will be computed in order to illustrate the technical benefits of the proposed method on estimation accuracy.

B. Proposed Iterative PMU Tuning Method

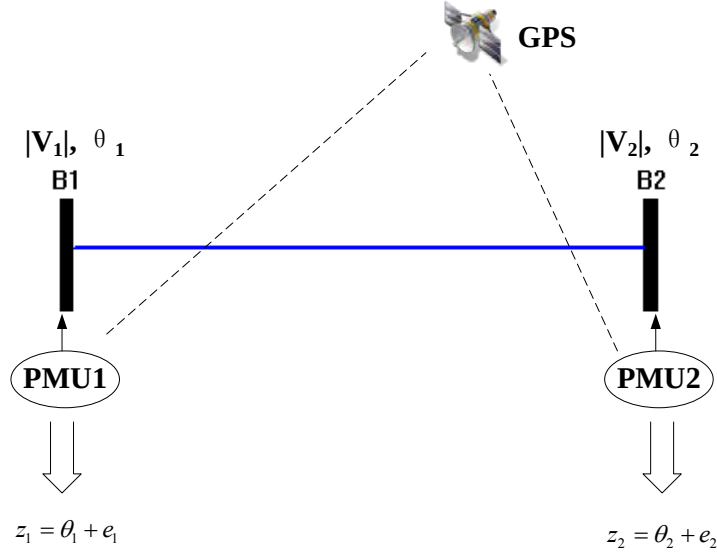


Figure 4.6: PMU measurement in power system

As shown in Figure 4-6, PMUs provide significant benefits as they are deployed in power systems. They measure the phasor angles, which cannot be directly measured by any conventional measurements. As a novel measurement device, the statistical properties of its error may not always be well known. Also, the errors of PMUs of different brands may vary. It is therefore important to design a tuning system, which can determine its error variance, whose reciprocal will be used as the weight in WLS estimator. In this section, an adaptive PMU tuning method will be presented in detail.

It is assumed that no preliminary information about PMUs' error variances exists. Starting with large and equal variances for all PMUs, the tuning method will estimate the variances of measurement errors iteratively according to the procedure outlined below.

- *Step 1:* Take k scans of the system measurements as historical data during a reasonable time period to ensure steady random error variances for all measurements. Note that the network topology and measurement set remain the same during this period.
- *Step 2:* Set up an initial guess of error variance for each PMU. The common value can be set as 1.0 for convenience if no other pre-information provided.
- *Step 3:* Run WLS state estimation for all k snapshots using the same variance as the initial guess in *Step 2*. Calculate all the PMU measurement residuals and their sample variances. Store the variances and corresponding sensitivity matrix.
- *Step 4:* Compute the random error variance of each PMU using the variance of its measurement residuals and sensitivity matrix obtained in *Step 3* based on (4-20).
- *Step 5:* Update the weight of the PMU by the reciprocal of variance calculated in *Step 4*, if the corresponding absolute deviation of this variance value compared to the previous one used in *Step 3* is larger than a threshold. Repeat *Step 3* to *Step 5* until all deviations

are less than threshold or iteration limit has been reached. The weights of PMUs are the reciprocals of these corresponding variances.

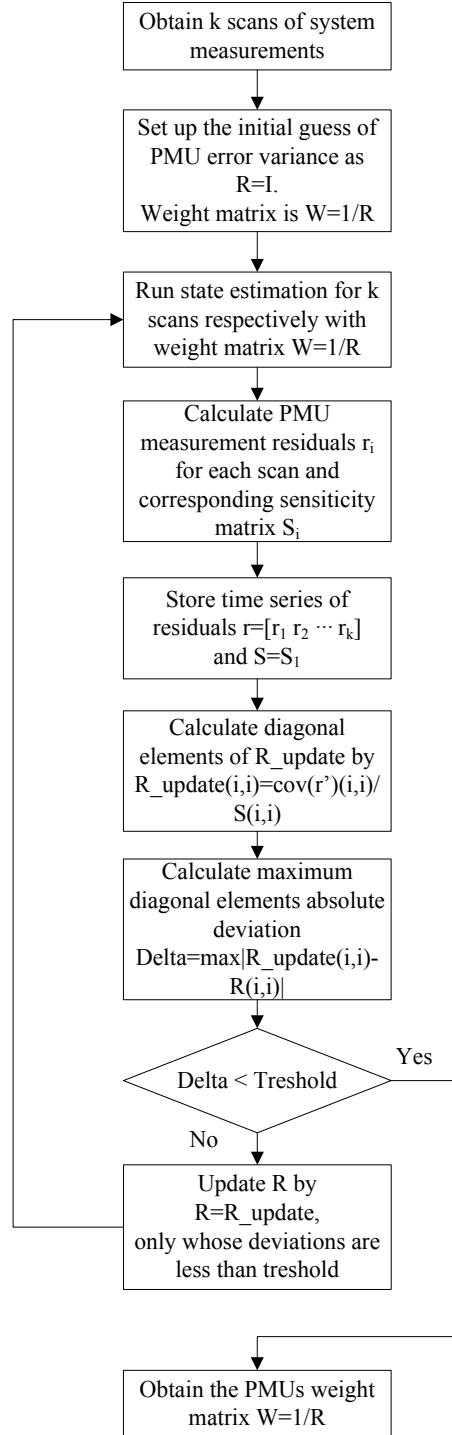


Figure 4.7: Flow chart of the PMU tuning process

The entire process is shown in Figure 4-7. The weights of PMUs are updated recursively at each iteration. As mentioned before, the system topology and measurement set do not change during different scans. Therefore, although the system states may change, during k scans within the same iteration where the weight matrix is the same, the approximation of sensitivity matrix S will remain the same. S will change only if new weights of PMUs are updated for a new iteration. Also, when updating the weights, only those whose absolute deviations from their previously assigned values are larger than a certain threshold will be updated. After this process, the weight matrix of corresponding PMUs will be obtained as results under convergence.

4.2.1.2 Simulation Results

In this section, the PMU tuning method will be implemented and tested on IEEE 14- and 118-bus systems, whose diagrams are shown in Figure 4-8 and Figure 4-9 respectively.

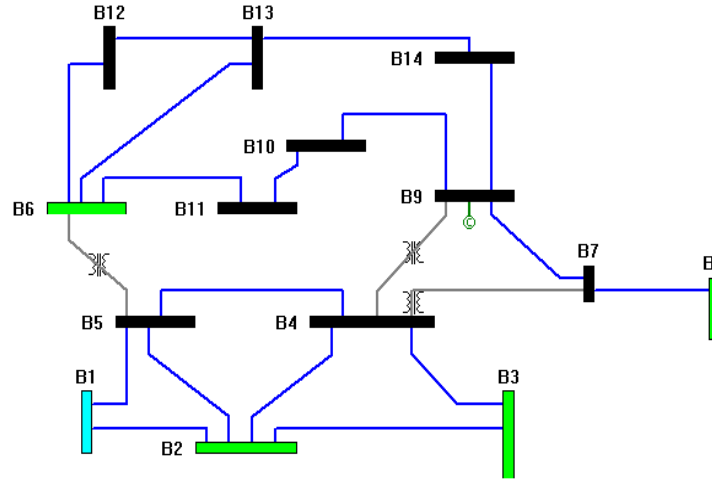


Figure 4.8: IEEE 14-bus system

Table 4.8: Measurement configuration in IEEE 14-bus system

Power Injection	Fully measured
Power Flow	Fully measured
Voltage Magnitude	Fully measured
PMU	At bus 2, 6, 7, 9

In this example, eight measurement scans ($k=8$) are simulated for the system. The measurement configuration is maintained the same during all scans and is shown in Table 4.8. The notation “fully measured” means that each bus is assigned one power injection and one voltage magnitude measurement. Besides, each line is measured by two power flow measurements at its terminal buses. Measurement data of each scan are synthetically created by adding random errors with certain variances to a set perfect measurement value, which is obtained by solving the corresponding power flow problem. The bus loads are slowly varied between different scans and the power flow solutions will reflect these changes. The variances of errors added here will be

used to verify the results of this tuning method. The original PMU weight is set as 1 and the threshold is chosen as 10^{-7} .

Table 4.9: Results of PMU tuning process in IEEE 14-bus system

PMU	$R_{perfect}$	R_{origin}	R_{result}	R_{actual}
θ_2	10^{-6}	1	2.67×10^{-7}	3×10^{-7}
θ_6	10^{-6}	1	5.32×10^{-7}	9×10^{-7}
θ_7	10^{-2}	1	0.0053	0.0052
θ_9	10^{-6}	1	2.78×10^{-6}	1.8×10^{-6}

Table 4.10: Normalized errors of system states in IEEE 14- bus system

Scan Number	NE before tuning	NE after tuning
1	0.0517	0.0039
2	0.2224	0.0030
3	0.1653	0.0042
4	0.0937	0.0052
5	0.0732	0.0048
6	0.0715	0.0024
7	0.0222	0.0044
8	0.0890	0.0039

It has to be clarified that all the conventional measurements and PMUs are tuned in this example. Only the results of PMUs are shown in Table 4.9 after the application of the proposed method. In Table 4.9, $R_{perfect}$ is the variance of the error added when creating synthetic measurement value. R_{origin} is the initial guess of PMU error variance, whose reciprocal is used as weight. R_{result} is the estimated variance of PMU errors after this tuning method. Since only eight scans are carried out, R_{actual} is the actual sample variance of PMU errors, which can be closer to $R_{perfect}$ by increasing the scan number. Note that the error at θ_7 is set higher than others deliberately to test the performance of this method. It is evident from Table 4.9 that although only eight scans are used, and that R_{result} is quite different from R_{origin} , it turns out to be very close to $R_{perfect}$ or R_{actual} including the one corresponding to θ_7 . It can be concluded that the proposed PMU tuning method can successfully estimate the error variances of PMUs with no prior error information. Besides, it can identify different error classes between different PMUs. This will be further elaborated in next section, which will study the impact of these weights on subsequent bad data identification. In addition, normalized errors of state vectors are calculated and shown in Table 4.10 to illustrate the estimation accuracy. These normalized errors of system states have significantly dropped after the tuning procedure for every scan.

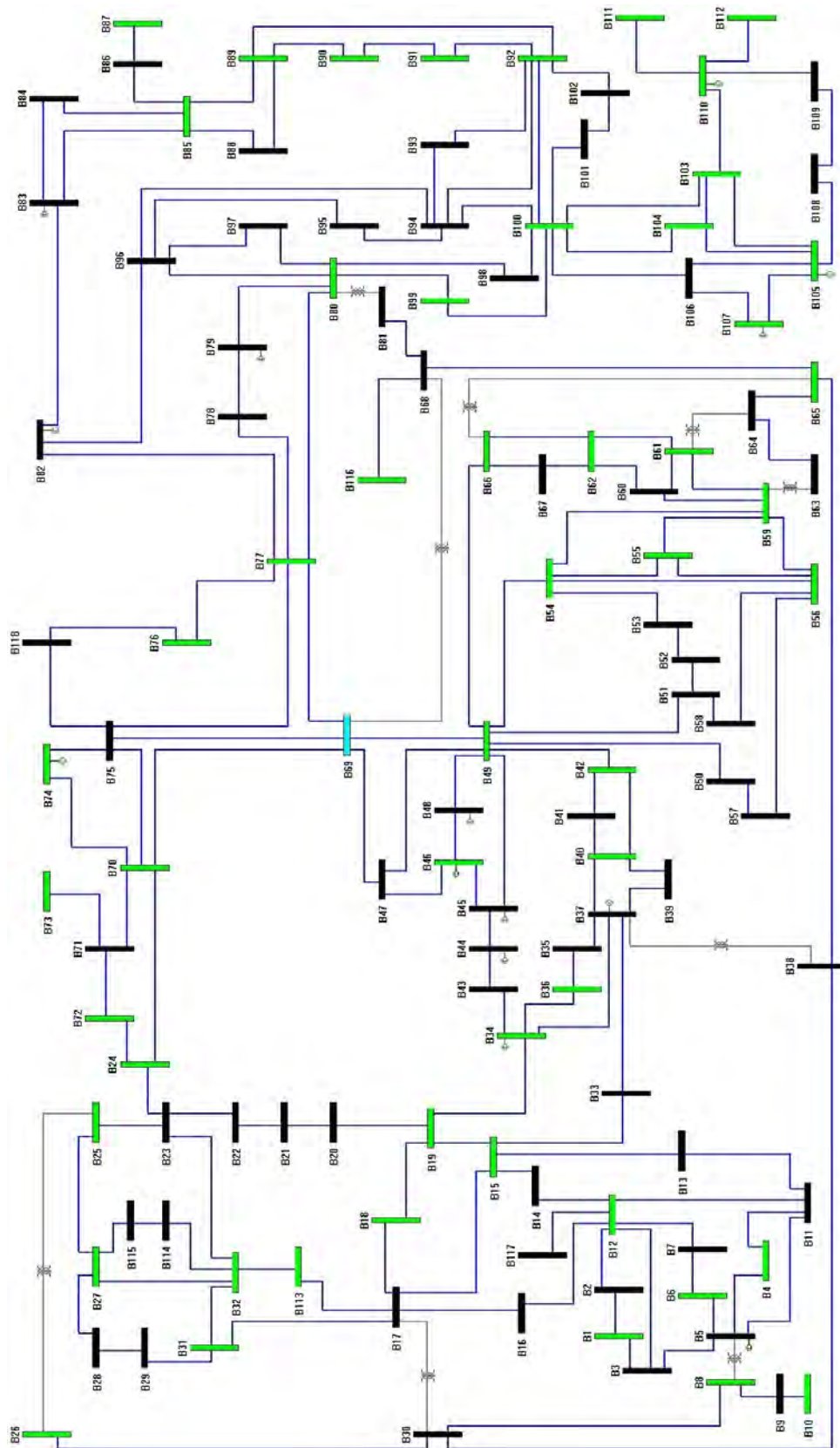


Figure 4.9: Flow chart of the PMU tuning process

Table 4.11: Measurement configuration in IEEE 118-bus system

Power Injection	Fully measured
Power Flow	Fully measured
Voltage Magnitude	Fully measured
PMU	At bus 1, 2, 3, 4, 5, 118

Table 4.12: Results of PMU tuning process in IEEE 118-bus system

PMU	$R_{perfect}$	R_{origin}	R_{result}	R_{actual}
θ_1	10^{-6}	10^{-4}	7.6×10^{-7}	6.0×10^{-7}
θ_2	10^{-6}	10^{-4}	5.7×10^{-7}	9.0×10^{-7}
θ_3	10^{-6}	10^{-4}	6.2×10^{-7}	1.0×10^{-6}
θ_4	10^{-6}	10^{-4}	1.5×10^{-6}	1.4×10^{-6}
θ_5	10^{-6}	10^{-4}	7.0×10^{-7}	5.0×10^{-7}
θ_{118}	10^{-2}	10^{-4}	0.00904	0.00906

The proposed method is also simulated in IEEE 118-bus system, whose diagram is shown in Fig. 4. The measurement setting is shown in Table 4.11, where six PMUs are introduced randomly. Twenty four measurement scans ($k=24$) are applied for this tuning process. The simulation results are provided in Table 4.12. From all these simulations, it can be concluded that the proposed PMU tuning method can successfully estimate the error variances of PMUs with no prior error information. Hence, the technique can be used to improve the system state estimation accuracy substantially. This method is easy to integrate into the existing state estimators. It can also be applied offline for the calibration of PMU measurements.

4.2.1.3 An Alternative Way: Computing Sample Variance Based on Measured Errors

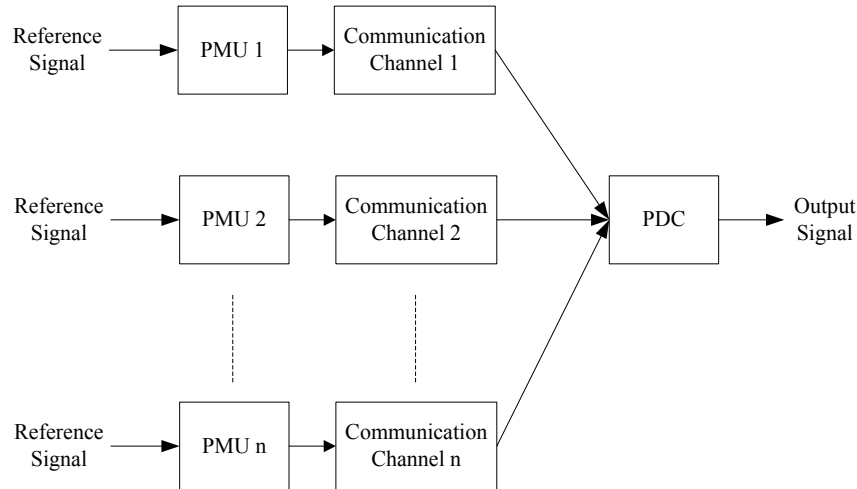


Figure 4.10: Method through calibrating reference signal

An alternative way of determining the accuracy of a PMU measurement system is via a test system in the laboratory with a reference signal. As mentioned before, since the measurement value is finally telemetered to the control center to be used by the state estimator, the measurement system errors include the cumulative errors in PMUs, communication channels and PDCs.

A test system of a typical PMU measurement system is shown in Figure 4-10, which is composed of PMUs, their corresponding communication channels as well as a PDC. A reference signal is chosen for testing the PMU of interest. The output signal of the PMU system with respect to the reference signal is obtained from the output of PDC. For the same reference signal, the test is run as many times as possible to obtain a high enough number of samples to make the sample variance as close to actual as possible. Sample error will be defined as the absolute deviation between each measured output from the PDC and the reference signal. After obtaining all sample errors for the corresponding PMU system, with assumptions of (4-5) and (4-6), its sample error variance can be calculated as follows:

$$var(e) = \frac{1}{n-1} \sum_{i=1}^n [e_i - E(e)]^2 \quad (4-22)$$

where

n sample number;

e_i sample error.

This calculation will be repeated for each PMU under investigation. These two methods provide tools to obtain the accuracies of various types of PMUs and assign weights in state estimator.

Table 4.13 shows the results based on laboratory testing of two PMU systems. The PMU measurement system including PMUs, communication channels as well as PDC that is used for this work is shown in Figure 4-10. A reference voltage signal of known magnitude and angle is applied to two types of PMU systems and tested 100 times respectively. 100 corresponding output signals are obtained separately. 100 sample voltage phase angle values of each PMU measurement system are provided in Table 4.11, comparing to the input reference angle of 9.567 degree. As mentioned, voltage angle shown here is defined as measured output voltage phase angle from the PDC. The unit of the value is degree.

After obtaining all these samples, the error variance of the phase angles measured by the PMU systems can be calculated assuming zero expected errors (zero population mean). The error variance of PMU1 in this simulation is 0.0061 degree², which is equal to 1.86×10⁻⁶ radian². The error variance of PMU2 in this simulation is 0.0218 degree², which is equal to 6.64×10⁻⁶ radian².

However, noted that, as shown in Table 4.10, there seem to be certain bias contained in the results. The sample mean values of measurement errors are 0.0777 degree in PMU1 and 0.1474 degree in PMU2 respectively. They are far from the assumed zero expected errors. Therefore, using (4-22) for calculation, the error variance of PMU1 is 2.60×10⁻⁷ degree², which is equal to 7.90×10⁻¹¹ radian². Similarly, the error variance of PMU2 is 6.89×10⁻⁵ degree², which is equal to 2.10×10⁻⁸ radian². The reasons for the bias may need to be investigated.

If the same types of PMUs are used in the actual system, the results obtained by this method can be compared and validated using the ones obtained by tuning method. It is however noted that, in

this work, the PMU systems tested are not the ones incorporated into the state estimator in tuning method. It can be anticipated that the results from both methods will be consistent if they are applicable in the same power system. These methods provide two distinct ways to quantify accuracies of PMU measurement systems. They can be used to assign consistent weights to the measurements and thus improve the performance of the state estimation.

Table 4.13: Results of PMU accuracy test (values shown in degree)

Test #	1	2	3	4	5	6	7	8	9	10
PMU1	9.645	9.644	9.645	9.645	9.644	9.645	9.645	9.644	9.645	9.645
PMU2	9.71	9.702	9.717	9.724	9.712	9.715	9.711	9.711	9.721	9.697
Test #	11	12	13	14	15	16	17	18	19	20
PMU1	9.645	9.645	9.644	9.645	9.645	9.644	9.645	9.645	9.645	9.645
PMU2	9.714	9.706	9.725	9.72	9.718	9.728	9.73	9.714	9.723	9.714
Test #	21	22	23	24	25	26	27	28	29	30
PMU1	9.645	9.644	9.645	9.645	9.645	9.645	9.645	9.645	9.645	9.645
PMU2	9.705	9.717	9.71	9.704	9.726	9.715	9.72	9.71	9.714	9.702
Test #	31	32	33	34	35	36	37	38	39	40
PMU1	9.644	9.645	9.645	9.644	9.645	9.645	9.644	9.645	9.645	9.644
PMU2	9.7	9.709	9.705	9.718	9.716	9.716	9.724	9.713	9.708	9.709
Test #	41	42	43	44	45	46	47	48	49	50
PMU1	9.645	9.644	9.645	9.645	9.644	9.645	9.645	9.644	9.645	9.645
PMU2	9.696	9.71	9.709	9.718	9.708	9.72	9.723	9.713	9.712	9.717
Test #	51	52	53	54	55	56	57	58	59	60
PMU1	9.644	9.644	9.644	9.644	9.644	9.645	9.644	9.644	9.645	9.644
PMU2	9.718	9.72	9.7	9.721	9.73	9.725	9.717	9.729	9.703	9.709
Test #	61	62	63	64	65	66	67	68	69	70
PMU1	9.645	9.645	9.645	9.645	9.646	9.645	9.645	9.646	9.645	9.645
PMU2	9.721	9.696	9.717	9.708	9.717	9.711	9.723	9.696	9.709	9.719
Test #	71	72	73	74	75	76	77	78	79	80
PMU1	9.645	9.644	9.644	9.645	9.644	9.644	9.645	9.644	9.644	9.645
PMU2	9.712	9.714	9.718	9.724	9.702	9.726	9.721	9.705	9.714	9.716
Test #	81	82	83	84	85	86	87	88	89	90
PMU1	9.645	9.644	9.645	9.645	9.644	9.645	9.645	9.644	9.645	9.645
PMU2	9.709	9.71	9.713	9.726	9.712	9.714	9.712	9.723	9.707	9.713
Test #	91	92	93	94	95	96	97	98	99	100
PMU1	9.644	9.645	9.645	9.644	9.645	9.645	9.644	9.645	9.645	9.644
PMU2	9.71	9.714	9.725	9.736	9.721	9.712	9.7	9.719	9.723	9.722

4.2.1.4 Conclusions

This section presents a recursive PMU tuning algorithm to let the state estimation system estimate the variance of PMU errors and tune its corresponding weight using historical state estimation results. It takes advantages of the state estimator and estimates the accuracies iteratively, which requires access to the results of state estimation for several measurement scans. The method can be used both offline to calibrate PMU measurements and on-line as part of an existing state estimation program to estimate the PMU errors and tune the corresponding weights. The alternative method calculates the accuracies statistically through laboratory tests, in which

the entire measurement chain including all devices and communication links should be taken into account. The results from two methods can be used to validate each other, especially when the test system of second method is practically applied at the state estimator used in first method, in which case the two results should be consistent. The impact of state estimator tuning on bad data processing function will be the subject of next section.

4.2.2 Impact of Tuning on Bad Data Detection of PMU Measurements

Recent increase in the deployment of phasor measurement units (PMUs) in power systems brings up the question of how to choose the right measurement weights for these measurements since such measurements have not been used in state estimators before. Phasor measurements are currently incorporated in state estimators together with other conventional measurements to improve estimation results [13]-[18]. Given the number of different types of PMUs, their weight assignments are to be consistent when several different types of PMUs are used in the same power system. This issue is important particularly when one or more of the PMUs are erroneous. Most state estimators detect and identify measurement errors through the method of calculating normalized measurement residuals, where pre-assigned measurement weights play a key role in the calculations [19]-[23]. Therefore, inaccurate measurement weights may cause biased decisions on the measurements. For example, errors on measurements with low weights may not be detected or good measurements with small errors but with very high weights may be flagged as erroneous.

An on-line tuning method for determining weights for PMU measurements has been developed and preliminary results are documented in Section 4.2.1. The method does not rely on any preliminary information such as manufacturer's data about the measurement devices and determines the weights according to historical data on the measurements over a certain period of time, thus eliminating the need to pre-specify these weights by the user. It can be used with different types of PMUs, addressing the issue of inter-operability as well.

Using accurate weights for measurements, in particular for new PMU measurements is important for successful bad data detection. The objective of this section is to illustrate the benefits of applying the derived tuning process to improve error detection and identification of PMU measurements.

4.2.2.1 Proposed Method

The tuning method presented at [26], as documented in Section 4.2.1, is applied to investigate its technical benefit on bad data processing. This algorithm requires complete access to the results of state estimation for a sequence of measurement scans. Accurate measurement weights of PMUs can be obtained without pre-specifying them before estimation. This is utilized in the proposed method to improve the robustness of bad data detection. The flowchart of the proposed method is shown in Figure 4-11. The detailed explanations are introduced as follows.

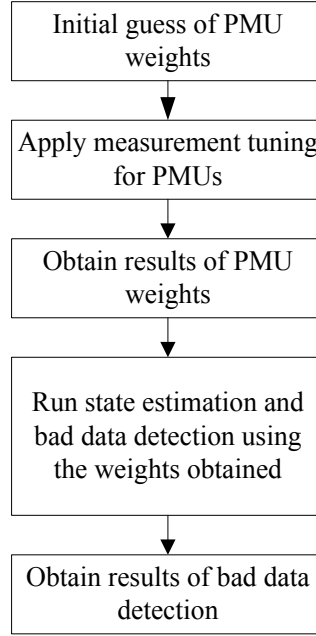


Figure 4.11: Flowchart of robust bad data detection on PMU measurements

- *Step 1:* Take an initial guess of measurement weights for each PMUs instead of pre-specifying this data based on historical accuracy data.
- *Step 2:* Apply the measurement tuning algorithm to PMU measurements and obtain their weights. The algorithm details are reviewed as before.
- *Step 3:* Run state estimation using the weights obtained in *Step 2* for PMUs and bad data detection process. The normalized measurement residual test is performed to detect and identify bad data using the measurement weights obtained in *Step 2* for PMUs.
- *Step 4:* Obtain the robust bad data detection and identification result.

This method can improve the performance of bad data detection of PMU measurements by using the accurate weights obtained by measurement tuning. It is easy to integrate to existing state estimator and enhances the robustness of bad data processing. Simulations results are shown as follows.

4.2.2.2 Simulations

The proposed method has been implemented in the IEEE 14-bus system. Its network diagram is shown in Figure 4-8. The simulation results are presented below.

Table 4.14: Measurement configuration in IEEE 14-bus system

Power Injection	At bus 2, 5, 9, 12
Power Flow	At branch 1-5, 2-3, 2-4, 3-4, 4-7, 4-9, 5-6, 6-12, 6-11, 7-8, 9-14, 9-10, 10-11, 12-13, 13-14
Voltage Magnitude	At bus 2, 3, 4, 5, 6, 8, 9
PMU	At bus 2, 3, 4, 5, 6, 8, 9

In this example, eight measurement scans are obtained for different loading conditions. The measurement configuration is shown in Table 4-14, which corresponds to an observable system. Measurement configuration remains the same for all scans and measurement values are computed synthetically as done in [26]. It is noted that the weights for the conventional measurements are assumed to be already assigned. Only the weights of PMUs are tuned in this example. The initial guess for the error variances of PMUs is randomly set as 0.0001 radian^2 .

Table 4.15: Results of PMU tuning process in IEEE 14-bus system

PMU	$R_{perfect}$	R_{origin}	$R_{results}$	R_{actual}
θ_2	10^{-6}	10^{-4}	2.71×10^{-6}	2.3×10^{-6}
θ_3	10^{-6}	10^{-4}	9.26×10^{-7}	4×10^{-7}
θ_4	10^{-6}	10^{-4}	7.41×10^{-7}	2.4×10^{-6}
θ_5	10^{-6}	10^{-4}	8.42×10^{-7}	1.8×10^{-6}
θ_6	10^{-6}	10^{-4}	2.63×10^{-7}	6×10^{-7}
θ_8	10^{-6}	10^{-4}	3.78×10^{-6}	1.5×10^{-6}
θ_9	10^{-6}	10^{-4}	8.69×10^{-7}	4×10^{-7}

The results of simulations are shown in Table 4.15 after the application of the tuning process. There are seven PMUs are tuned in this example. $R_{perfect}$ is error variance used when adding the random error to perfect phase angle to create synthetic PMU measurement value. R_{origin} is the initial guess of error variance made for PMU. $R_{results}$ is result obtain from tuning process, which is estimated error variance of PMU. R_{actual} is the actual sample variance of PMU errors of these eight scans. With the scan number increased, R_{actual} is anticipated to converge to $R_{perfect}$. As shown in Table 4.15, the error variance of each PMU can be successfully estimated. It can be expected that the results will be more accurate by increasing the number of scans used as well as the measurement redundancy.

After this tuning procedure, the proposed method utilizes the weights of PMUs in bad data detection. Two simulation examples are provided to show its benefits.

Table 4.16: Results of bad data detection of Example 1

Test A (Without tuning)		Test B (With tuning)	
Measurement	r^N	Measurement	r^N
$ V_6 $	2.2279	θ_2	9.7211
θ_2	1.7526	P_2	3.0771
$ V_5 $	1.4297	$ V_6 $	2.9054
Q_{7-8}	1.4206	P_{1-5}	2.7608
$ V_8 $	1.4205	P_{2-3}	2.5233

The first example is to investigate the impact of tuning on bad data detection when PMUs are under weighted. Two cases are presented for comparison with the results shown in Table 4.16 respectively.

Test A: Without tuning process, the initial guess of PMU measurement weight made before is directly used for bad data detection, where the PMUs are with less measurement weights.

Test B: Through the proposed method, the weights of PMU measurements obtained by tuning process are applied for bad data detection.

In this example, an error has been introduced to θ_2 , whose value has been changed from -5.06 to -6.06 degrees. In Test A, the weights of PMUs are set as reciprocals of R_origin in Table 4.15. In Test B, the reciprocal of $R_results$ are assigned as weights of PMUs after tuning. As shown in Table 4.16, without tuning for PMUs, the largest normalized measurement residual is less than 3.0, which is commonly chosen as the threshold as mentioned. It indicates that, without tuning, the measurement error at θ_2 cannot be detected or identified. By contrast, after implementing the proposed method, such error has been successfully detected and identified in Test B, where the normalized residual corresponding to θ_2 is in the top and beyond the threshold. It can be concluded that, under weighting a PMU measurement may cause its bad data undetectable. By tuning the weights of PMUs, the proposed method detects and identifies this error successfully.

The second example is to simulate the scenario when PMU measurements are over weighted and investigate the impact of proposed method. In this example, no measurement error is introduced. All the measurements only have their random noises. Two tests are performed to compare the results with or without measurement tuning.

Test A: Without tuning process, the PMU measurement weight is made as reciprocal of 10^{-8} , which is considered as over weighted.

Test B: The measurement weights of PMUs obtained by tuning, which are R_result in Table 4.17, are used for bad data detection.

Table 4.17: Results of bad data detection of Example 2

Test A (Without tuning)		Test B (With tuning)	
Measurement	r^N	Measurement	r^N
θ_2	5.8195	P_{4-9}	2.4227
θ_5	5.2493	P_{13-14}	1.9625
P_5	4.7343	θ_9	1.7754
P_2	4.6599	P_{6-12}	1.5099
θ_4	3.3441	Q_{2-4}	1.4209

As shown in Table 4.17, in Test A, the largest normalized residual corresponding to θ_2 is beyond the threshold. It indicates that, although there is no measurement error, θ_2 is detected as erroneous incorrectly. However, by assigning accurate weights of PMUs through proposed method, no measurement error is detected in Test B. Therefore, over weighting PMUs may bring up false error detection at certain measurements. This problem can be solved by measurement tuning through the proposed method. It can be concluded that the proposed method improves the robustness of bad data detection and identification of PMUs in state estimation.

4.2.2.3 Conclusions

Previous work on assigning measurement weights of PMU measurements develops a recursive tuning algorithm to let the state estimation system estimate the variances of PMU errors and tune their weights respectively. This section investigates its impact on bad data detection of PMU measurements and presents a systemic method to improve bad data detection of PMU measurements. The proposed method is convenient to integrate to existing WLS state estimators and enhances the robustness of error detection and identification for PMU measurements.

5 Conclusions

A new test methodology for verifying the interoperability and application performance of PMUs and PMU-enabled IEDs at device and system level is proposed in this report paper. Reference signal and test scenarios for two types of tests are described. A reference PMU model and a communication network toolbox called “Impairator” are developed and implemented in a newly implemented synchrophasor testbed. Nine PMUs from eight different vendors, two software PDCs and one hardware PDC, and four commercial GPS receivers providing various types of time synchronization options were used to perform interoperability test, and fault location and state estimation are selected to perform the application tests. The conclusions are summarized as follows:

- Most PMUs satisfied the steady state performance requirement, but none of them meets conformance under all the dynamic conditions; PDCs meet most of the functional requirements in [3].
- The interoperability issues between PMUs, PDCs and time synchronization options can be identified using the test method. The interoperability tests show that the interoperability issues between PMUs and PDCs exist as different PMUs use different communication methods, some use serial port communication only, some use Ethernet communication only while a few support both. At the same time, some PDCs do not support serial port communication while the others only support serial port communication. But this problem may be solved by upgrading or adding additional equipment.
- The communication network toolbox “Impairator” is able to measure the PDC’s data processing time, and generate impairment used in application test. The test results show that the final location will have larger errors and uncertainties as the packet loss grows in the communication network. However this impact may be alleviated by increasing the PMUs’ reporting rate. This method can be further extended to other types of applications, such as state estimation and voltage stability.
- The application test method used for fault location and state estimation can be extended to other types of applications, such as voltage stability etc.

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Appendix A: Test Configurations

The configurations of PMUs and PMU-enabled IEDs for performing the Design tests and Application tests are given in Table A.1. The configurations of time synchronization options are given in Table A.2.

Table A.1: Configurations for PMUs and PMU-enabled IEDs

	Make/Model	Synchro. Method	Comm. Type	Phasors	Proprietary
1	PMU A	IRIG-B/PPS Reference clock	Serial Port	Format: C37.118; Rate: 30 /s; Phasor: Float, Polar; Freq: Float.	Filter: Fast Response
2	PMU A-1	IRIG-B/PPS Reference clock	Serial Port	Format: C37.118; Rate: 30 /s; Phasor: Float, Polar; Freq: Float.	Filter: Fast Response
3	PMU B	IRIG-B/PPS HOPF 6875 (dedicated)	TCP/IP	Format: C37.118; Rate: 30 /s; Phasor: Float, Rectangular; Freq: Float.	N/A
4	PMU C	IRIG-B/PPS Reference clock	TCP/IP	Format: C37.118; Rate: 30 /s; Phasor: Float, Rectangular; Freq: Integer.	Filter: Symm 3-point
5	PMU D	Direct GPS signal	TCP/IP	Format: C37.118; Rate: 60 /s; Phasor: Float, Rectangular Freq: Float.	Time tagging: Center
6	PMU E	Direct GPS signal	TCP/IP	Format: C37.118; Rate: 30 /s; Phasor: Float, Rectangular Freq: Float	N/A

Table A.1: Configurations for PMUs and PMU-enabled IEDs (continued)

#	Make/Model	Synchro. Method	Comm. Type	Phasors	Proprietary
7	PMU F	IRIG-B/PPS Reference clock	TCP/IP	Format: C37.118; Rate: 30 /s; Phasor: Float, Rectangular Freq: Float	N/A

Table A.2: Configurations for time synchronization options

#	Device Type	Make/Model	Sync Mode	Time Source	Proprietary
1	GPS receiver	Clock A	IRIG-B/PPS	GPS	DC shift, IRIG-B000 w/IEEE 1344
2	GPS receiver	Clock B	IRIG-B/DCF77	GPS	DCF77, IEEE 1344
3	GPS receiver	Clock C	IRIG-B	GPS	Unmodulated IRIG-B000
4	Ethernet switch	Clock D	IEEE 1588 v2 PTP	GPS	Ordinary PTP

Appendix B: Test Results

B.1: Design Test

B.1.1: Conformance Test Results

Table B.1.1.1: Steady state – magnitude variation test results for PMU A

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz/s)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.407	0.381	0.383	0.373	0.089	0.037	3.399	1.703	0.066	0.018
	20	0.365	0.348	0.348	0.342	0.066	0.031	0.843	0.593	0.028	0.008
	60	0.524	0.450	0.301	0.296	0.248	0.194	0.442	0.320	0.013	0.004
	80	0.431	0.366	0.284	0.282	0.186	0.131	0.199	0.122	0.007	0.002
	90	0.296	0.281	0.278	0.275	0.058	0.028	0.172	0.104	0.009	0.002
	100	0.314	0.287	0.279	0.276	0.086	0.038	0.328	0.249	0.012	0.003
	110	0.406	0.343	0.272	0.270	0.174	0.118	0.194	0.147	0.007	0.002
	120	0.441	0.372	0.264	0.261	0.204	0.150	0.187	0.125	0.009	0.002
$ I_n $	10	0.810	0.520	0.544	0.349	0.408	0.212	3.399	1.703	0.066	0.018
	20	0.531	0.388	0.303	0.228	0.286	0.176	0.843	0.593	0.028	0.008
	60	0.604	0.541	0.529	0.473	0.214	0.147	0.442	0.320	0.013	0.004
	80	0.541	0.446	0.475	0.402	0.170	0.106	0.199	0.122	0.007	0.002
	90	0.498	0.473	0.490	0.467	0.084	0.035	0.172	0.104	0.009	0.002
	100	0.223	0.155	0.143	0.119	0.106	0.050	0.328	0.249	0.012	0.003
	110	0.308	0.219	0.124	0.108	0.168	0.107	0.194	0.147	0.007	0.002
	120	0.463	0.383	0.242	0.231	0.230	0.174	0.187	0.125	0.009	0.002
	160	0.796	0.699	0.099	0.087	0.453	0.397	0.366	0.131	0.004	0.002
	180	0.639	0.535	0.054	0.043	0.365	0.305	0.198	0.150	0.007	0.002
	200	0.347	0.244	0.070	0.060	0.195	0.135	4.372	1.706	0.008	0.002

Table B.1.1.2: Steady state – phase angle variation test results for PMU A

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz/s)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.491	0.407	0.156	0.149	0.268	0.217	0.788	0.473	0.009	0.006
	-pi/2	0.350	0.274	0.156	0.152	0.181	0.129	0.275	0.165	0.007	0.004
	-pi/6	0.287	0.216	0.155	0.151	0.140	0.085	0.439	0.263	0.008	0.004
	0	0.459	0.375	0.155	0.151	0.248	0.196	0.369	0.221	0.006	0.003
	pi/6	0.448	0.360	0.141	0.136	0.243	0.191	0.422	0.253	0.012	0.002
	pi/2	0.233	0.173	0.143	0.139	0.107	0.053	0.907	0.544	0.010	0.002
	2pi/3	0.298	0.222	0.148	0.144	0.150	0.095	0.625	0.375	0.008	0.003
	pi	0.421	0.334	0.149	0.145	0.226	0.172	0.356	0.214	0.011	0.004
Φ_I	-2pi/3	0.773	0.681	0.527	0.505	0.328	0.260	0.788	0.473	0.009	0.006
	-pi/2	0.636	0.577	0.526	0.498	0.223	0.163	0.275	0.165	0.007	0.004
	-pi/6	0.589	0.552	0.575	0.544	0.110	0.043	0.439	0.263	0.008	0.004
	0	0.598	0.492	0.162	0.132	0.334	0.271	0.369	0.221	0.006	0.003
	pi/6	0.631	0.559	0.571	0.526	0.165	0.101	0.422	0.253	0.012	0.002
	pi/2	0.546	0.511	0.545	0.507	0.074	0.032	0.907	0.544	0.010	0.002
	2pi/3	0.539	0.493	0.520	0.485	0.107	0.040	0.625	0.375	0.008	0.003
	pi	0.699	0.626	0.535	0.507	0.272	0.208	0.356	0.214	0.011	0.004

Table B.1.1.3: Steady state – frequency variation test results for PMU A

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz/s)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	13.00	12.91	1.779	1.770	7.381	7.331	0.262	0.165	0.013	0.004
	-4	5.721	5.632	0.642	0.637	3.257	3.206	0.245	0.191	0.014	0.005
	-3	1.687	1.597	0.367	0.364	0.943	0.891	0.309	0.214	0.001	0.005
	-2	0.854	0.770	0.280	0.278	0.463	0.412	0.201	0.145	0.011	0.004
	-1	0.270	0.241	0.243	0.241	0.071	0.029	0.233	0.151	0.009	0.003
	1	0.584	0.510	0.304	0.303	0.285	0.234	0.221	0.158	0.010	0.003
	2	0.668	0.590	0.325	0.322	0.335	0.283	0.221	0.180	0.010	0.003
	3	0.445	0.427	0.424	0.421	0.082	0.034	0.221	0.184	0.011	0.003
	4	5.118	5.020	0.722	0.718	2.904	2.846	0.229	0.172	0.015	0.004
	5	12.43	12.33	1.874	1.869	7.039	6.982	0.049	0.048	0.013	0.004
F_I	-5	13.09	12.99	1.671	1.650	7.442	7.386	0.262	0.165	0.013	0.004
	-4	5.752	5.645	0.495	0.481	3.284	3.223	0.245	0.191	0.014	0.005
	-3	1.725	1.616	0.230	0.217	0.980	0.918	0.309	0.214	0.001	0.005
	-2	0.854	0.752	0.138	0.122	0.484	0.425	0.201	0.145	0.011	0.004
	-1	0.168	0.115	0.114	0.095	0.076	0.033	0.233	0.151	0.009	0.003
	1	0.634	0.532	0.134	0.117	0.357	0.297	0.221	0.158	0.010	0.003
	2	0.696	0.600	0.170	0.157	0.389	0.332	0.221	0.180	0.010	0.003
	3	0.331	0.276	0.277	0.261	0.108	0.043	0.221	0.184	0.011	0.003
	4	5.245	5.120	0.595	0.571	2.987	2.915	0.229	0.172	0.015	0.004
	5	12.56	12.45	1.801	1.776	7.124	7.061	0.049	0.048	0.013	0.004

Table B.1.2.1: Steady state – magnitude variation test results for PMU A-1

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz/s)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.710	0.683	0.496	0.472	0.296	0.282	0.0	0.0	0.0	0.0
	20	0.592	0.573	0.415	0.406	0.242	0.232	0.240	0.112	0.161	0.052
	60	0.411	0.400	0.334	0.328	0.140	0.131	0.133	0.049	0.036	0.014
	80	0.352	0.348	0.314	0.312	0.092	0.088	0.111	0.031	0.035	0.011
	90	0.362	0.351	0.314	0.310	0.103	0.094	0.114	0.044	0.036	0.011
	100	0.380	0.358	0.298	0.295	0.135	0.116	0.164	0.103	0.027	0.009
	110	0.365	0.345	0.292	0.289	0.127	0.108	0.198	0.109	0.025	0.008
	120	0.316	0.308	0.282	0.280	0.081	0.075	0.072	0.043	0.016	0.005
$ I_n $	10	0.809	0.572	0.503	0.252	0.442	0.284	0.0	0.0	0.0	0.0
	20	0.454	0.373	0.292	0.218	0.240	0.171	0.240	0.112	0.161	0.052
	60	0.239	0.201	0.089	0.057	0.132	0.110	0.133	0.049	0.036	0.014
	80	0.229	0.226	0.218	0.197	0.071	0.053	0.111	0.031	0.035	0.011
	90	0.233	0.217	0.198	0.182	0.081	0.067	0.114	0.044	0.036	0.011
	100	0.176	0.162	0.139	0.118	0.072	0.063	0.164	0.103	0.027	0.009
	110	0.197	0.175	0.156	0.140	0.072	0.060	0.198	0.109	0.025	0.008
	120	0.209	0.198	0.158	0.140	0.089	0.081	0.072	0.043	0.016	0.005
	160	0.228	0.211	0.147	0.132	0.102	0.094	0.076	0.037	0.014	0.006
	180	0.257	0.237	0.172	0.163	0.113	0.098	0.137	0.069	0.015	0.005
	200	0.283	0.270	0.198	0.175	0.159	0.146	0.134	0.070	0.013	0.006

Table B.1.2.2: Steady state – phase angle variation test results for PMU A-1

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz/s)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.357	0.346	0.310	0.306	0.104	0.092	0.103	0.059	0.020	0.009
	-pi/2	0.336	0.330	0.306	0.303	0.079	0.076	0.049	0.023	0.023	0.008
	-pi/6	0.353	0.344	0.309	0.306	0.099	0.089	0.091	0.039	0.021	0.006
	0	0.348	0.340	0.306	0.304	0.094	0.086	0.103	0.043	0.021	0.008
	pi/6	0.353	0.344	0.308	0.305	0.099	0.091	0.107	0.053	0.029	0.009
	pi/2	0.367	0.354	0.311	0.307	0.114	0.100	0.145	0.075	0.022	0.008
	2pi/3	0.352	0.343	0.307	0.304	0.100	0.090	0.107	0.058	0.018	0.007
	pi	0.346	0.340	0.307	0.303	0.095	0.087	0.064	0.025	0.024	0.006
Φ_I	-2pi/3	0.162	0.143	0.126	0.109	0.062	0.053	0.103	0.059	0.020	0.009
	-pi/2	0.225	0.203	0.190	0.171	0.075	0.062	0.049	0.023	0.023	0.008
	-pi/6	0.212	0.195	0.178	0.157	0.083	0.065	0.091	0.039	0.021	0.006
	0	0.248	0.224	0.215	0.190	0.081	0.067	0.103	0.043	0.021	0.008
	pi/6	0.284	0.271	0.259	0.244	0.077	0.066	0.107	0.053	0.029	0.009
	pi/2	0.200	0.174	0.175	0.146	0.064	0.053	0.145	0.075	0.022	0.008
	2pi/3	0.163	0.143	0.120	0.093	0.074	0.062	0.107	0.058	0.018	0.007
	pi	0.189	0.174	0.128	0.111	0.087	0.076	0.064	0.025	0.024	0.006

Table B.1.2.3: Steady state – frequency variation test results for PMU A-1

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz/s)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	0.326	0.311	0.269	0.262	0.108	0.095	0.122	0.062	0.019	0.006
	-4	0.317	0.308	0.273	0.268	0.095	0.086	0.084	0.040	0.020	0.005
	-3	0.341	0.327	0.283	0.278	0.111	0.098	0.125	0.069	0.026	0.009
	-2	0.331	0.323	0.288	0.285	0.094	0.087	0.087	0.031	0.022	0.008
	-1	0.338	0.332	0.296	0.294	0.096	0.088	0.099	0.043	0.017	0.007
	1	0.367	0.355	0.320	0.316	0.103	0.092	0.102	0.061	0.019	0.007
	2	0.376	0.364	0.331	0.328	0.103	0.091	0.107	0.056	0.023	0.009
	3	0.372	0.366	0.341	0.338	0.087	0.081	0.092	0.042	0.016	0.008
	4	0.384	0.377	0.356	0.351	0.085	0.078	0.084	0.032	0.022	0.008
	5	0.405	0.392	0.371	0.365	0.092	0.081	0.114	0.058	0.018	0.006
F_I	-5	0.277	0.254	0.277	0.254	0.019	0.005	0.122	0.062	0.019	0.006
	-4	0.091	0.077	0.088	0.076	0.015	0.005	0.084	0.040	0.020	0.005
	-3	0.111	0.093	0.107	0.087	0.033	0.019	0.125	0.069	0.026	0.009
	-2	0.153	0.132	0.134	0.116	0.047	0.036	0.087	0.031	0.022	0.008
	-1	0.170	0.148	0.138	0.118	0.061	0.051	0.099	0.043	0.017	0.007
	1	0.196	0.181	0.140	0.122	0.085	0.076	0.102	0.061	0.019	0.007
	2	0.237	0.210	0.149	0.131	0.112	0.094	0.107	0.056	0.023	0.009
	3	0.270	0.242	0.164	0.148	0.130	0.110	0.092	0.042	0.016	0.008
	4	0.308	0.289	0.193	0.173	0.145	0.133	0.084	0.032	0.022	0.008
	5	0.405	0.387	0.313	0.293	0.164	0.145	0.114	0.058	0.018	0.006

Table B.1.3.1: Steady state – magnitude variation test results for PMU B

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.270	0.259	0.160	0.150	0.126	0.121	1.801	0.570	0.103	0.045
	20	0.270	0.257	0.163	0.156	0.125	0.117	1.411	0.616	0.113	0.040
	60	0.236	0.220	0.160	0.158	0.101	0.088	1.408	0.558	0.129	0.054
	80	0.219	0.210	0.161	0.158	0.087	0.078	2.025	0.610	0.123	0.050
	90	0.208	0.200	0.159	0.158	0.078	0.070	1.743	0.577	0.151	0.045
	100	0.219	0.210	0.160	0.159	0.086	0.078	1.453	0.587	0.108	0.053
	110	0.175	0.170	0.156	0.155	0.046	0.040	1.606	0.605	0.128	0.037
	120	0.223	0.214	0.156	0.155	0.092	0.085	1.854	0.571	0.204	0.051
$ I_n $	10	0.274	0.260	0.050	0.044	0.155	0.147	1.801	0.570	0.103	0.045
	20	0.267	0.238	0.043	0.021	0.153	0.136	1.411	0.616	0.113	0.040
	60	0.284	0.263	0.029	0.215	0.162	0.150	1.408	0.558	0.129	0.054
	80	0.293	0.274	0.040	0.034	0.167	0.156	2.025	0.610	0.123	0.050
	90	0.303	0.284	0.041	0.033	0.172	0.161	1.743	0.577	0.151	0.045
	100	0.302	0.284	0.085	0.081	0.167	0.157	1.453	0.587	0.108	0.053
	110	0.342	0.328	0.044	0.039	0.195	0.186	1.606	0.605	0.128	0.037
	120	0.318	0.300	0.074	0.072	0.178	0.167	1.854	0.571	0.204	0.051
	160	0.324	0.302	0.057	0.056	0.183	0.170	1.697	0.653	0.143	0.043
	180	0.288	0.271	0.024	0.018	0.165	0.155	1.823	0.515	0.154	0.050
	200	0.312	0.285	0.037	0.034	0.178	0.162	1.595	0.522	0.132	0.045

Table B.1.3.2: Steady state – phase angle variation test results for PMU B

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.209	0.198	0.151	0.150	0.083	0.075	0.969	0.403	0.175	0.040
	-pi/2	0.189	0.180	0.154	0.153	0.063	0.054	1.156	0.355	0.130	0.026
	-pi/6	0.210	0.200	0.157	0.156	0.081	0.072	1.087	0.402	0.110	0.041
	0	0.211	0.205	0.156	0.155	0.082	0.077	1.240	0.496	0.110	0.038
	pi/6	0.180	0.172	0.154	0.153	0.055	0.045	1.381	0.509	0.110	0.040
	pi/2	0.218	0.207	0.157	0.156	0.087	0.077	1.160	0.311	0.118	0.029
	2pi/3	0.209	0.202	0.157	0.155	0.080	0.074	1.076	0.258	0.103	0.029
	pi	0.279	0.270	0.029	0.024	0.160	0.154	1.156	0.488	0.134	0.048
Φ_I	-2pi/3	0.298	0.277	0.050	0.045	0.168	0.156	0.969	0.403	0.175	0.040
	-pi/2	0.533	0.526	0.429	0.425	0.184	0.177	1.156	0.355	0.130	0.026
	-pi/6	0.305	0.290	0.032	0.025	0.174	0.165	1.087	0.402	0.110	0.041
	0	0.294	0.277	0.027	0.024	0.168	0.158	1.240	0.496	0.110	0.038
	pi/6	0.338	0.323	0.023	0.018	0.193	0.185	1.381	0.509	0.110	0.040
	pi/2	0.291	0.277	0.024	0.020	0.166	0.158	1.160	0.311	0.118	0.029
	2pi/3	0.288	0.277	0.018	0.015	0.165	0.158	1.076	0.258	0.103	0.029
	pi	0.223	0.208	0.158	0.156	0.090	0.079	1.156	0.488	0.134	0.048

Table B.1.3.3: Steady state – frequency variation test results for PMU B

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	0.220	0.212	0.143	0.141	0.097	0.090	1.113	0.353	0.090	0.033
	-4	0.235	0.230	0.176	0.175	0.090	0.085	1.320	0.450	0.154	0.042
	-3	0.217	0.209	0.176	0.175	0.074	0.066	1.617	0.471	0.082	0.037
	-2	0.201	0.194	0.176	0.175	0.055	0.048	1.533	0.445	0.119	0.045
	-1	0.194	0.189	0.176	0.175	0.048	0.041	1.652	0.459	0.102	0.032
	1	0.189	0.185	0.175	0.174	0.042	0.036	0.912	0.358	0.101	0.037
	2	0.208	0.195	0.175	0.174	0.065	0.050	1.369	0.463	0.105	0.039
	3	0.213	0.203	0.175	0.173	0.071	0.060	1.190	0.379	0.091	0.031
	4	0.215	0.205	0.175	0.173	0.072	0.062	1.503	0.548	0.082	0.042
	5	0.221	0.206	0.174	0.173	0.078	0.063	2.129	0.513	0.142	0.057
F_I	-5	0.194	0.180	0.036	0.027	0.110	0.102	1.113	0.353	0.090	0.033
	-4	0.224	0.210	0.041	0.034	0.127	0.118	1.320	0.450	0.154	0.042
	-3	0.273	0.256	0.036	0.028	0.156	0.146	0.471	0.082	0.037	1.617
	-2	0.310	0.298	0.036	0.028	0.177	0.170	1.533	0.445	0.119	0.045
	-1	0.341	0.327	0.040	0.035	0.195	0.186	1.652	0.459	0.102	0.032
	1	0.371	0.357	0.050	0.044	0.211	0.203	0.912	0.358	0.101	0.037
	2	0.370	0.348	0.045	0.038	0.210	0.198	1.369	0.463	0.105	0.039
	3	0.354	0.340	0.040	0.033	0.202	0.194	1.190	0.379	0.091	0.031
	4	0.370	0.348	0.049	0.038	0.211	0.198	1.503	0.548	0.082	0.042
	5	0.378	0.358	0.048	0.037	0.215	0.204	2.129	0.513	0.142	0.057

Table B.1.4.1: State – magnitude variation test results for PMU C

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.915	0.788	0.452	0.440	0.455	0.374	0.999	0.033	10.00	0.333
	20	0.877	0.765	0.518	0.509	0.410	0.326	0.0	0.0	0.0	0.0
	60	0.778	0.679	0.442	0.430	0.367	0.301	0.0	0.0	0.0	0.0
	80	0.763	0.622	0.415	0.406	0.367	0.270	0.0	0.0	0.0	0.0
	90	0.688	0.586	0.408	0.395	0.320	0.246	0.999	0.166	10.00	1.00
	100	0.678	0.579	0.393	0.382	0.320	0.248	0.0	0.0	0.0	0.0
	110	0.679	0.573	0.387	0.378	0.320	0.245	0.0	0.0	0.0	0.0
	120	0.635	0.533	0.376	0.366	0.298	0.221	0.0	0.0	0.0	0.0
$ I_n $	10	0.929	0.906	0.766	0.688	0.455	0.381	0.999	0.033	10.00	0.333
	20	0.909	0.851	0.794	0.760	0.291	0.216	0.0	0.0	0.0	0.0
	60	0.805	0.753	0.706	0.695	0.236	0.162	0.0	0.0	0.0	0.0
	80	0.756	0.699	0.658	0.646	0.222	0.147	0.0	0.0	0.0	0.0
	90	0.712	0.664	0.626	0.616	0.205	0.136	0.999	0.166	10.00	1.00
	100	0.755	0.700	0.645	0.635	0.232	0.165	0.0	0.0	0.0	0.0
	110	0.696	0.650	0.607	0.597	0.207	0.143	0.0	0.0	0.0	0.0
	120	0.705	0.648	0.599	0.590	0.224	0.149	0.0	0.0	0.0	0.0
	160	0.549	0.449	0.587	0.580	0.250	0.179	0.0	0.0	0.0	0.0
	180	0.787	0.705	0.634	0.621	0.268	0.188	0.999	0.133	10.00	0.333
	200	0.837	0.777	0.684	0.672	0.285	0.221	0.999	0.133	10.00	0.333

Table B.1.4.2: Steady state – phase angle variation test results for PMU C

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.761	0.613	0.403	0.391	0.370	0.269	0.0	0.0	0.0	0.0
	-pi/2	0.643	0.565	0.380	0.375	0.298	0.241	0.0	0.0	0.0	0.0
	-pi/6	0.719	0.630	0.394	0.385	0.350	0.285	0.0	0.0	0.0	0.0
	0	0.677	0.592	0.391	0.381	0.319	0.258	0.0	0.0	0.0	0.0
	pi/6	0.695	0.599	0.402	0.388	0.335	0.260	0.0	0.0	0.0	0.0
	pi/2	0.683	0.596	0.397	0.386	0.319	0.258	0.0	0.0	10.00	1.00
	2pi/3	0.722	0.589	0.403	0.393	0.344	0.250	0.0	0.0	0.0	0.0
	pi	0.674	0.588	0.390	0.381	0.320	0.255	0.0	0.0	0.0	0.0
Φ_I	-2pi/3	0.799	0.728	0.670	0.660	0.259	0.173	0.0	0.0	0.0	0.0
	-pi/2	0.739	0.691	0.644	0.633	0.212	0.155	0.0	0.0	0.0	0.0
	-pi/6	0.836	0.766	0.684	0.674	0.280	0.206	0.0	0.0	0.0	0.0
	0	0.750	0.706	0.654	0.644	0.221	0.160	0.0	0.0	0.0	0.0
	pi/6	0.796	0.738	0.685	0.671	0.247	0.173	0.0	0.0	0.0	0.0
	pi/2	0.717	0.671	0.633	0.621	0.206	0.140	0.0	0.0	10.00	1.00
	2pi/3	0.810	0.739	0.696	0.686	0.240	0.152	0.0	0.0	0.0	0.0
	pi	0.714	0.673	0.634	0.624	0.201	0.138	0.0	0.0	0.0	0.0

Table B.1.4.3: Steady state – frequency variation test results for PMU C

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	0.674	0.585	0.413	0.401	0.312	0.242	0.0	0.0	10.00	1.667
	-4	0.651	0.562	0.405	0.391	0.296	0.230	0.999	0.033	10.00	1.333
	-3	0.693	0.614	0.406	0.393	0.324	0.269	0.0	0.0	10.00	1.333
	-2	0.672	0.590	0.406	0.395	0.311	0.250	0.0	0.0	10.00	1.00
	-1	0.713	0.615	0.406	0.394	0.338	0.270	0.0	0.0	10.00	0.666
	1	0.700	0.612	0.402	0.389	0.333	0.269	0.0	0.0	0.0	0.0
	2	0.706	0.605	0.394	0.384	0.342	0.266	0.0	0.0	0.0	0.0
	3	0.720	0.623	0.401	0.391	0.346	0.277	0.0	0.0	0.0	0.0
	4	0.725	0.612	0.390	0.377	0.351	0.275	0.0	0.0	0.0	0.0
	5	0.776	0.621	0.405	0.392	0.381	0.275	0.0	0.0	0.0	0.0
F_I	-5	0.794	0.743	0.693	0.677	0.236	0.172	0.0	0.0	10.00	1.667
	-4	0.818	0.763	0.713	0.699	0.240	0.171	0.999	0.033	10.00	1.333
	-3	0.764	0.711	0.662	0.624	0.235	0.170	0.0	0.0	10.00	1.333
	-2	0.810	0.759	0.701	0.688	0.249	0.180	0.0	0.0	10.00	1.00
	-1	0.760	0.713	0.651	0.638	0.235	0.180	0.0	0.0	10.00	0.666
	1	0.760	0.711	0.647	0.634	0.242	0.181	0.0	0.0	0.0	0.0
	2	0.767	0.704	0.649	0.632	0.251	0.173	0.0	0.0	0.0	0.0
	3	0.715	0.658	0.616	0.604	0.221	0.145	0.0	0.0	0.0	0.0
	4	0.773	0.709	0.653	0.638	0.246	0.172	0.0	0.0	0.0	0.0
	5	0.746	0.673	0.630	0.616	0.242	0.151	0.0	0.0	0.0	0.0

Table B.1.5.1: Steady state – magnitude variation test results for PMU D

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.744	0.724	0.374	0.364	0.373	0.358	0.816	0.318	1.075	0.384
	20	0.650	0.631	0.385	0.378	0.302	0.289	0.420	0.157	0.730	0.176
	60	0.527	0.511	0.392	0.389	0.202	0.189	0.179	0.055	0.218	0.083
	80	0.512	0.495	0.384	0.380	0.195	0.182	0.145	0.054	0.215	0.066
	90	0.508	0.488	0.377	0.374	0.195	0.179	0.206	0.058	0.209	0.065
	100	0.498	0.480	0.371	0.367	0.192	0.177	0.210	0.061	0.184	0.059
	110	0.497	0.478	0.369	0.365	0.192	0.176	0.233	0.065	0.220	0.068
	120	0.494	0.472	0.365	0.361	0.191	0.174	0.214	0.080	0.294	0.092
$ I_n $	10	0.916	0.838	0.824	0.771	0.260	0.186	0.816	0.318	1.075	0.384
	20	0.721	0.684	0.656	0.633	0.184	0.149	0.420	0.157	0.730	0.176
	60	0.707	0.687	0.602	0.587	0.216	0.204	0.179	0.055	0.218	0.083
	80	0.654	0.642	0.561	0.552	0.200	0.188	0.145	0.054	0.215	0.066
	90	0.654	0.640	0.563	0.555	0.195	0.182	0.206	0.058	0.209	0.065
	100	0.507	0.498	0.501	0.493	0.053	0.041	0.210	0.061	0.184	0.059
	110	0.603	0.593	0.559	0.552	0.134	0.124	0.233	0.065	0.220	0.068
	120	0.633	0.620	0.576	0.570	0.151	0.139	0.214	0.080	0.294	0.092
	160	0.592	0.585	0.550	0.546	0.131	0.120	0.164	0.064	0.225	0.074
	180	0.587	0.576	0.532	0.528	0.143	0.133	0.198	0.057	0.179	0.054
	200	0.573	0.564	0.536	0.532	0.117	0.105	0.194	0.065	0.207	0.070

Table B.1.5.2: Steady state – phase angle variation test results for PMU D

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.492	0.475	0.374	0.369	0.184	0.171	0.186	0.054	0.282	0.070
	-pi/2	0.495	0.398	0.373	0.369	0.187	0.174	0.183	0.072	0.205	0.077
	-pi/6	0.478	0.466	0.370	0.367	0.175	0.164	0.145	0.046	0.254	0.076
	0	0.498	0.479	0.371	0.367	0.191	0.175	0.259	0.078	0.197	0.063
	pi/6	0.492	0.476	0.371	0.368	0.187	0.173	0.198	0.061	0.178	0.060
	pi/2	0.489	0.476	0.373	0.369	0.183	0.172	0.152	0.053	0.174	0.076
	2pi/3	0.493	0.476	0.371	0.369	0.185	0.173	0.175	0.060	0.252	0.054
	pi	0.486	0.473	0.373	0.368	0.182	0.170	0.133	0.046	0.271	0.078
Φ_I	-2pi/3	0.440	0.436	0.440	0.436	0.011	0.005	0.186	0.054	0.282	0.070
	-pi/2	0.397	0.391	0.370	0.364	0.090	0.081	0.183	0.072	0.205	0.077
	-pi/6	0.394	0.386	0.392	0.384	0.037	0.022	0.145	0.046	0.254	0.076
	0	0.698	0.682	0.590	0.582	0.215	0.204	0.259	0.078	0.197	0.063
	pi/6	0.675	0.662	0.581	0.575	0.200	0.188	0.198	0.061	0.178	0.060
	pi/2	0.608	0.596	0.560	0.551	0.140	0.130	0.152	0.053	0.174	0.076
	2pi/3	0.493	0.483	0.460	0.463	0.105	0.095	0.175	0.060	0.252	0.054
	pi	0.456	0.446	0.402	0.398	0.126	0.115	0.133	0.046	0.271	0.078

Table B.1.5.3: Steady state – frequency variation test results for PMU D

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	0.511	0.490	0.376	0.372	0.198	0.182	0.263	0.079	0.375	0.105
	-4	0.507	0.486	0.374	0.371	0.196	0.180	0.194	0.076	0.345	0.104
	-3	0.510	0.488	0.375	0.371	0.199	0.181	0.248	0.079	0.226	0.073
	-2	0.501	0.483	0.373	0.370	0.192	0.178	0.202	0.076	0.246	0.085
	-1	0.501	0.481	0.374	0.369	0.192	0.177	0.240	0.667	0.260	0.080
	1	0.474	0.463	0.368	0.365	0.173	0.163	0.164	0.059	0.291	0.089
	2	0.496	0.477	0.370	0.367	0.190	0.174	0.206	0.074	0.241	0.092
	3	0.495	0.477	0.371	0.367	0.190	0.175	0.313	0.109	0.385	0.111
	4	0.483	0.468	0.366	0.363	0.182	0.169	0.206	0.572	0.280	0.911
	5	0.494	0.475	0.369	0.365	0.190	0.174	0.267	0.079	0.180	0.060
F_I	-5	0.865	0.848	0.823	0.810	0.158	0.144	0.263	0.079	0.375	0.105
	-4	0.599	0.586	0.526	0.516	0.172	0.159	0.194	0.076	0.345	0.104
	-3	0.554	0.539	0.510	0.500	0.133	0.116	0.248	0.079	0.226	0.073
	-2	0.480	0.468	0.469	0.458	0.070	0.056	0.202	0.076	0.246	0.085
	-1	0.435	0.428	0.435	0.428	0.012	0.005	0.240	0.667	0.260	0.080
	1	0.489	0.479	0.473	0.465	0.078	0.066	0.164	0.059	0.291	0.089
	2	0.504	0.492	0.486	0.475	0.086	0.074	0.206	0.074	0.241	0.092
	3	0.551	0.541	0.506	0.497	0.137	0.122	0.313	0.109	0.385	0.111
	4	0.544	0.530	0.500	0.489	0.131	0.117	0.206	0.572	0.280	0.911
	5	0.569	0.550	0.512	0.498	0.150	0.134	0.267	0.079	0.180	0.060

Table B.1.6.1: Steady state – magnitude variation test results for PMU E

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.704	0.578	0.250	0.246	0.383	0.300	0.0	0.0	0.0	0.0
	20	0.633	0.600	0.230	0.161	0.337	0.331	0.0	0.0	0.0	0.0
	60	0.622	0.620	0.150	0.149	0.345	0.345	0.0	0.0	0.0	0.0
	80	0.632	0.615	0.150	0.140	0.352	0.343	0.0	0.0	0.0	0.0
	90	0.632	0.617	0.141	0.140	0.353	0.344	0.0	0.0	0.0	0.0
	100	0.625	0.619	0.147	0.133	0.348	0.346	0.0	0.0	0.0	0.0
	110	0.626	0.622	0.142	0.132	0.349	0.348	0.0	0.0	0.0	0.0
	120	0.627	0.625	0.136	0.134	0.351	0.350	0.0	0.0	0.0	0.0
$ I_n $	10	0.499	0.426	0.497	0.422	0.035	0.032	0.0	0.0	0.0	0.0
	20	0.451	0.406	0.451	0.406	0.011	0.008	0.0	0.0	0.0	0.0
	60	0.415	0.411	0.415	0.411	0.010	0.004	0.0	0.0	0.0	0.0
	80	-/407	0.406	0.406	0.406	0.012	0.011	0.0	0.0	0.0	0.0
	90	0.405	0.403	0.402	0.402	0.017	0.015	0.0	0.0	0.0	0.0
	100	0.412	0.404	0.411	0.402	0.023	0.021	0.0	0.0	0.0	0.0
	110	0.409	0.407	0.407	0.405	0.027	0.023	0.0	0.0	0.0	0.0
	120	0.407	0.406	0.404	0.403	0.030	0.027	0.0	0.0	0.0	0.0
	160	0.412	0.411	0.406	0.405	0.040	0.039	0.0	0.0	10.0	0.667
	180	0.415	0.414	0.407	0.406	0.046	0.045	0.0	0.0	10.0	0.333
	200	0.417	0.416	0.407	0.406	0.051	0.050	0.0	0.0	10.0	0.333

Table B.1.6.2: Steady state – phase angle variation test results for PMU E

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.639	0.630	0.138	0.135	0.357	0.352	0.0	0.0	0.0	0.0
	-pi/2	0.633	0.621	0.148	0.134	0.355	0.347	0.0	0.0	0.0	0.0
	-pi/6	0.639	0.632	0.138	0.135	0.357	0.354	0.0	0.0	0.0	0.0
	0	0.625	0.619	0.149	0.134	0.348	0.346	0.0	0.0	0.0	0.0
	pi/6	0.634	0.631	0.150	0.140	0.353	0.352	0.0	0.0	0.0	0.0
	pi/2	0.633	0.620	0.134	0.134	0.355	0.347	0.0	0.0	0.0	0.0
	2pi/3	0.632	0.628	0.141	0.137	0.353	0.351	0.0	0.0	0.0	0.0
	pi	0.633	0.621	0.147	0.133	0.355	0.347	0.0	0.0	10.0	0.667
Φ_I	-2pi/3	0.408	0.407	0.406	0.405	0.024	0.024	0.0	0.0	0.0	0.0
	-pi/2	0.403	0.402	0.402	0.401	0.022	0.021	0.0	0.0	0.0	0.0
	-pi/6	0.408	0.407	0.406	0.405	0.024	0.024	0.0	0.0	0.0	0.0
	0	0.404	0.403	0.402	0.401	0.022	0.018	0.0	0.0	0.0	0.0
	pi/6	0.408	0.407	0.406	0.405	0.022	0.022	0.0	0.0	0.0	0.0
	pi/2	0.403	0.402	0.402	0.401	0.023	0.021	0.0	0.0	0.0	0.0
	2pi/3	0.408	0.407	0.406	0.406	0.022	0.021	0.0	0.0	0.0	0.0
	pi	0.411	0.403	0.409	0.401	0.023	0.022	0.0	0.0	10.0	0.667

Table B.1.6.3: Steady state – frequency variation test results for PMU E

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	1.615	1.603	0.131	0.126	0.923	0.916	0.999	0.533	20.0	7.667
	-4	1.418	1.406	0.135	0.127	0.809	0.803	0.999	0.533	20.0	4.667
	-3	1.221	1.209	0.133	0.126	0.696	0.689	0.999	0.699	10.0	1.667
	-2	0.967	0.943	0.140	0.129	0.488	0.480	0.999	0.699	10.0	1.333
	-1	0.837	0.822	0.134	0.124	0.474	0.466	0.999	0.666	10.0	1.667
	1	0.449	0.436	0.132	0.123	0.248	0.240	0.999	0.566	10.0	2.667
	2	0.265	0.251	0.140	0.127	0.133	0.124	0.999	0.699	10.0	5.333
	3	0.144	0.133	0.142	0.131	0.019	0.012	0.999	0.433	20.0	6.000
	4	0.240	0.227	0.150	0.140	0.109	0.102	0.999	0.399	40.0	2.333
	5	0.402	0.395	0.140	0.131	0.217	0.213	0.999	0.499	20.0	6.667
F_I	-5	1.080	1.075	0.010	0.006	0.619	0.616	0.999	0.533	20.0	7.667
	-4	0.817	0.865	0.005	0.002	0.499	0.496	0.999	0.533	20.0	4.667
	-3	0.665	0.657	0.008	0.004	0.381	0.376	0.999	0.699	10.0	1.667
	-2	0.467	0.456	0.007	0.002	0.268	0.261	0.999	0.699	10.0	1.333
	-1	0.253	0.247	0.008	0.003	0.145	0.142	0.999	0.666	10.0	1.667
	1	0.431	0.424	0.398	0.391	0.099	0.094	0.999	0.566	10.0	2.667
	2	0.554	0.547	0.403	0.397	0.219	0.215	0.999	0.699	10.0	5.333
	3	0.711	0.706	0.404	0.398	0.337	0.334	0.999	0.433	20.0	6.000
	4	0.893	0.888	0.413	0.408	0.455	0.452	0.999	0.399	40.0	2.333
	5	0.998	0.993	0.009	0.006	0.572	0.569	0.999	0.499	20.0	6.667

Table B.1.7.1: Steady state – magnitude variation test results for PMU F

Variation (%)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE (e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $	10	0.615	0.405	0.543	0.227	0.330	0.174	3.294	2.278	3.984	1.534
	20	0.541	0.390	0.391	0.269	0.242	0.157	2.525	0.841	1.904	0.725
	60	0.493	0.426	0.379	0.322	0.198	0.158	0.954	0.329	0.872	0.232
	80	0.491	0.430	0.383	0.336	0.176	0.153	0.698	0.287	0.563	0.213
	90	0.479	0.433	0.389	0.340	0.176	0.153	0.438	0.172	0.311	0.144
	100	0.495	0.460	0.412	0.373	0.175	0.154	0.518	0.227	0.496	0.165
	110	0.477	0.453	0.395	0.369	0.164	0.150	0.328	0.128	0.508	0.136
	120	0.488	0.458	0.403	0.373	0.174	0.152	0.316	0.107	0.169	0.067
$ I_n $	10	0.867	0.441	0.774	0.247	0.493	0.176	3.294	2.278	3.984	1.534
	20	0.566	0.301	0.470	0.158	0.298	0.134	2.525	0.841	1.904	0.725
	60	0.385	0.259	0.172	0.070	0.220	0.139	0.954	0.329	0.872	0.232
	80	0.374	0.281	0.175	0.089	0.210	0.148	0.698	0.287	0.563	0.213
	90	0.368	0.287	0.157	0.095	0.192	0.154	0.438	0.172	0.311	0.144
	100	0.327	0.262	0.093	0.050	0.185	0.147	0.518	0.227	0.496	0.165
	110	0.338	0.279	0.107	0.059	0.186	0.156	0.328	0.128	0.508	0.136
	120	0.314	0.282	0.183	0.117	0.170	0.150	0.316	0.107	0.169	0.067
	160	0.327	0.270	0.102	0.055	0.184	0.151	0.236	0.109	0.254	0.118
	180	0.448	0.417	0.354	0.318	0.168	0.155	0.267	0.089	0.176	0.059
	200	0.307	0.274	0.133	0.086	0.171	0.148	0.202	0.079	0.235	0.076

Table B.1.7.2: Steady state – phase angle variation test results for PMU F

Variation (rad)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE(e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Φ_V	-2pi/3	0.470	0.430	0.378	0.336	0.165	0.154	0.438	0.121	0.428	0.132
	-pi/2	0.473	0.435	0.377	0.345	0.164	0.152	0.438	0.157	0.425	0.146
	-pi/6	0.470	0.434	0.381	0.341	0.167	0.153	0.354	0.144	0.398	0.175
	0	0.468	0.430	0.370	0.340	0.165	0.151	0.415	0.136	0.389	0.135
	pi/6	0.461	0.437	0.380	0.345	0.174	0.154	0.431	0.154	0.327	0.109
	pi/2	0.456	0.432	0.367	0.340	0.169	0.152	0.431	0.188	0.394	0.136
	2pi/3	0.461	0.430	0.372	0.340	0.171	0.151	0.347	0.151	0.336	0.133
	pi	0.460	0.436	0.371	0.345	0.168	0.153	0.408	0.140	0.473	0.146
Φ_I	-2pi/3	0.355	0.274	0.091	0.036	0.200	0.155	0.438	0.121	0.428	0.132
	-pi/2	0.359	0.267	0.123	0.036	0.198	0.150	0.438	0.157	0.425	0.146
	-pi/6	0.417	0.325	0.241	0.185	0.208	0.152	0.354	0.144	0.398	0.175
	0	0.334	0.284	0.208	0.100	0.188	0.151	0.415	0.136	0.389	0.135
	pi/6	0.369	0.299	0.200	0.113	0.193	0.157	0.431	0.154	0.327	0.109
	pi/2	0.353	0.280	0.134	0.071	0.191	0.154	0.431	0.188	0.394	0.136
	2pi/3	0.329	0.280	0.159	0.083	0.182	0.152	0.347	0.151	0.336	0.133
	pi	0.541	0.452	0.431	0.358	0.218	0.156	0.408	0.140	0.473	0.146

Table B.1.7.3: Steady state – frequency variation test results for PMU F

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (e-3Hz)		RFE(e-3Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
F_V	-5	26.90	26.87	0.834	0.807	15.41	15.39	0.377	0.169	0.453	0.146
	-4	21.58	21.55	0.410	0.386	12.36	12.35	0.500	0.124	0.473	0.169
	-3	16.26	16.22	0.102	0.064	9.318	9.296	0.618	0.211	0.481	0.180
	-2	10.94	10.91	0.197	0.162	6.267	6.248	0.454	0.160	0.343	0.133
	-1	5.632	5.598	0.313	0.294	3.222	3.203	0.576	0.193	0.384	0.124
	1	5.085	5.057	0.316	0.294	2.909	2.893	0.458	0.139	0.295	0.140
	2	10.41	10.37	0.184	0.158	5.962	5.942	0.442	0.173	0.364	0.139
	3	15.72	15.69	0.114	0.067	9.006	8.989	0.450	0.177	0.316	0.154
	4	21.04	21.01	0.440	0.394	12.05	12.04	0.740	0.197	0.783	0.185
	5	26.37	26.34	0.833	0.802	15.10	15.08	0.328	0.153	0.306	0.115
F_I	-5	26.95	26.87	1.307	1.216	15.42	15.38	0.377	0.169	0.453	0.146
	-4	21.64	21.55	0.831	0.760	12.39	12.34	0.500	0.124	0.473	0.169
	-3	16.31	16.23	0.481	0.384	9.343	9.298	0.618	0.211	0.481	0.180
	-2	11.01	10.91	0.278	0.186	6.305	6.250	0.454	0.160	0.343	0.133
	-1	5.633	5.582	0.162	0.061	3.227	3.198	0.576	0.193	0.384	0.124
	1	5.135	5.065	0.129	0.041	2.942	2.902	0.458	0.139	0.295	0.140
	2	10.44	10.37	0.273	0.202	5.980	5.942	0.442	0.173	0.364	0.139
	3	15.79	15.70	0.586	0.457	9.045	8.993	0.450	0.177	0.316	0.154
	4	21.14	21.03	0.857	0.781	12.11	12.04	0.740	0.197	0.783	0.185
	5	26.44	26.35	1.251	1.116	15.14	15.09	0.328	0.153	0.306	0.115

Table B.2.1.1: Dynamic state – measurement bandwidth test results for PMU A

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE(Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.576	0.329	0.345	0.272	0.264	0.101	0.002	0.001	0.005	0.002
	0.5	0.361	0.308	0.265	0.257	0.149	0.093	0.018	0.011	0.156	0.099
	1	0.328	0.299	0.302	0.282	0.099	0.049	0.061	0.381	0.624	0.398
	2	0.756	0.629	0.372	0.282	0.411	0.318	0.182	0.118	0.251	0.160
	3	0.867	0.594	0.582	0.282	0.492	0.260	0.350	0.225	5.665	3.675
	4	1.284	0.698	1.051	0.435	0.560	0.288	0.498	0.317	10.110	6.441
	5	2.569	0.748	1.641	0.884	1.364	0.546	0.727	0.481	15.758	10.498
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.679	0.622	0.421	0.398	0.289	0.225	0.002	0.001	0.005	0.002
	0.5	0.360	0.229	0.215	0.108	0.196	0.112	0.018	0.011	0.156	0.099
	1	0.221	0.120	0.168	0.098	0.092	0.034	0.061	0.381	0.624	0.398
	2	0.333	0.158	0.228	0.093	0.162	0.066	0.182	0.118	0.251	0.160
	3	0.847	0.575	0.523	0.198	0.485	0.287	0.350	0.225	5.665	3.675
	4	1.155	0.705	0.878	0.423	0.588	0.299	0.498	0.317	10.11	6.441
	5	2.813	1.595	1.635	0.888	1.489	0.617	0.727	0.481	15.76	10.50
Volt. $k_x=0$ $k_a=0.1$	0.1	0.642	0.555	0.314	0.264	0.336	0.278	0.001	0.001	0.005	0.002
	0.5	0.429	0.361	0.256	0.252	0.197	0.146	0.016	0.010	0.155	0.099
	1	0.617	0.539	0.289	0.283	0.315	0.262	0.059	0.037	0.623	0.398
	2	0.736	0.600	0.302	0.281	0.389	0.303	0.197	0.125	2.513	1.599
	3	0.883	0.577	0.336	0.280	0.481	0.281	0.349	0.225	5.665	3.675
	4	1.061	0.562	0.434	0.287	0.563	0.264	0.534	0.340	10.11	6.441
	5	1.545	0.937	0.411	0.288	0.854	0.509	0.727	0.481	15.75	10.45
Curr. $k_x=0$ $k_a=0.1$	0.1	0.557	0.452	0.138	0.088	0.316	0.253	0.001	0.001	0.005	0.002
	0.5	0.391	0.291	0.097	0.086	0.219	0.159	0.016	0.010	0.155	0.099
	1	0.645	0.546	0.279	0.164	0.347	0.297	0.059	0.037	0.623	0.398
	2	0.647	0.449	0.149	0.062	0.369	0.254	0.197	0.125	2.513	1.599
	3	0.834	0.447	0.269	0.137	0.476	0.235	0.349	0.225	5.665	3.675
	4	1.133	0.539	0.359	0.159	0.624	0.280	0.534	0.340	10.11	6.441
	5	1.559	0.916	0.254	0.153	0.882	0.515	0.727	0.481	15.75	10.45

Table B.2.1.2: Dynamic state – frequency ramp test results for PMU A

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	0.632	0.507	0.433	0.378	0.307	0.173	0.096	0.092	0.990	0.990
	-1.0	0.668	0.483	0.373	0.334	0.341	0.179	0.105	0.102	0.990	0.990
Curr. $\pm 2\text{Hz}$	1.0	0.488	0.319	0.487	0.206	0.224	0.117	0.096	0.092	0.990	0.990
	-1.0	0.992	0.682	0.794	0.583	0.405	0.184	0.105	0.102	0.990	0.990
Volt. $\pm 5\text{Hz}$	1.0	11.49	3.008	2.280	0.838	6.453	1.627	0.099	0.084	0.990	0.990
	-1.0	12.85	3.490	1.786	0.655	7.289	1.932	0.126	0.112	0.990	0.990
Curr. $\pm 5\text{Hz}$	1.0	11.64	2.978	2.172	0.658	6.550	1.645	0.099	0.084	0.990	0.990
	-1.0	12.88	3.472	1.678	0.471	7.321	1.960	0.126	0.112	0.990	0.990

Table B.2.1.3: Dynamic state – step change test results for PMU A

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	48.074	25.624	11.242	2.852
	-10	48.073	24.460	11.296	2.823
$ I_n $	+10	34.004	18.873	11.448	2.441
	-10	36.348	22.504	11.475	2.826
Φ_V	+pi/18	60.566	15.154	11.717	3.911
	-pi/18	50.083	16.416	11.169	5.642
Φ_I	+pi/18	56.433	24.939	11.733	3.765
	-pi/18	44.260	14.070	11.413	5.229

Table B.2.2.1: Dynamic state – measurement bandwidth test results for PMU A-1

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE(Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.348	0.339	0.303	0.301	0.098	0.089	0.0006	0.0004	0.005	0.004
	0.5	0.349	0.338	0.309	0.304	0.094	0.086	0.013	0.008	0.155	0.099
	1	0.356	0.341	0.322	0.307	0.091	0.086	0.051	0.032	0.623	0.397
	2	0.378	0.343	0.330	0.305	0.105	0.089	0.194	0.120	2.507	1.596
	3	0.422	0.342	0.368	0.305	0.127	0.087	0.366	0.231	5.655	3.664
	4	0.506	0.346	0.423	0.305	0.165	0.087	0.554	0.340	10.07	6.437
	5	0.636	0.363	0.506	0.305	0.246	0.109	0.553	0.380	15.75	10.49
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.325	0.310	0.284	0.267	0.102	0.090	0.0006	0.0004	0.005	0.004
	0.5	0.352	0.314	0.327	0.284	0.086	0.075	0.013	0.008	0.155	0.099
	1	0.391	0.325	0.357	0.280	0.124	0.092	0.051	0.032	0.623	0.397
	2	0.379	0.301	0.350	0.257	0.127	0.086	0.194	0.120	2.507	1.596
	3	0.315	0.247	0.299	0.162	0.156	0.100	0.366	0.231	5.655	3.664
	4	0.459	0.344	0.424	0.211	0.235	0.138	0.554	0.340	10.07	6.437
	5	0.382	0.259	0.354	0.141	0.219	0.100	0.553	0.380	15.75	10.49
Volt. $k_x=0$ $k_a=0.1$	0.1	0.345	0.338	0.305	0.303	0.093	0.086	0.0005	0.0003	0.005	0.004
	0.5	0.346	0.338	0.306	0.303	0.092	0.087	0.013	0.008	0.155	0.099
	1	0.366	0.353	0.317	0.308	0.106	0.098	0.051	0.032	0.623	0.387
	2	0.368	0.353	0.319	0.309	0.109	0.097	0.193	0.120	2.507	1.596
	3	0.366	0.347	0.321	0.306	0.122	0.091	0.366	0.231	5.654	3.665
	4	0.398	0.353	0.337	0.305	0.158	0.092	0.553	0.341	10.08	6.437
	5	0.460	0.376	0.373	0.310	0.210	0.101	0.549	0.380	15.78	10.49
Curr. $k_x=0$ $k_a=0.1$	0.1	0.278	0.256	0.251	0.230	0.077	0.064	0.0005	0.0003	0.005	0.004
	0.5	0.304	0.292	0.284	0.273	0.074	0.059	0.013	0.008	0.155	0.099
	1	0.445	0.388	0.394	0.324	0.152	0.122	0.051	0.032	0.623	0.387
	2	0.498	0.407	0.384	0.267	0.213	0.175	0.193	0.120	2.507	1.596
	3	0.317	0.194	0.126	0.065	0.174	0.103	0.366	0.231	5.654	3.665
	4	0.261	0.130	0.161	0.068	0.137	0.059	0.553	0.341	10.08	6.437
	5	0.390	0.235	0.204	0.147	0.210	0.095	0.549	0.380	15.78	10.49

Table B.2.2.2: Dynamic state – frequency ramp test results for PMU A-1

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	0.381	0.354	0.368	0.338	0.106	0.052	0.083	0.083	0.990	0.989
	-1.0	0.496	0.401	0.309	0.296	0.232	0.152	0.083	0.083	0.990	0.990
Curr. $\pm 2\text{Hz}$	1.0	0.651	0.442	0.286	0.079	0.341	0.245	0.083	0.083	0.990	0.989
	-1.0	0.285	0.148	0.285	0.091	0.127	0.057	0.083	0.083	0.990	0.990
Volt. $\pm 5\text{Hz}$	1.0	0.847	0.461	0.636	0.430	0.320	0.079	0.084	0.083	0.990	0.990
	-1.0	0.811	0.435	0.306	0.236	0.460	0.198	0.084	0.083	0.990	0.990
Curr. $\pm 5\text{Hz}$	1.0	0.904	0.520	0.356	0.247	0.472	0.212	0.084	0.083	0.990	0.990
	-1.0	0.812	0.209	0.317	0.083	0.465	0.099	0.084	0.083	0.990	0.990

Table B.2.2.3: Dynamic state – step change test results for PMU A-1

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	37.005	2.464	11.005	3.076
	-10	45.708	2.457	11.097	3.012
$ I_n $	+10	33.770	2.501	11.397	2.856
	-10	42.019	2.478	10.585	3.193
Φ_V	+pi/18	49.035	2.460	11.348	2.829
	-pi/18	43.478	2.487	10.868	3.348
Φ_I	+pi/18	44.094	2.389	10.696	3.132
	-pi/18	44.588	2.643	11.247	2.842

Table B.2.3.1: Dynamic state – measurement bandwidth test results for PMU B

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.197	0.177	0.138	0.125	0.082	0.072	0.001	0.0004	0.005	0.002
	0.5	0.470	0.263	0.443	0.208	0.122	0.076	0.007	0.004	0.156	0.100
	1	0.760	0.439	0.719	0.360	0.231	0.110	0.023	0.014	0.624	0.398
	2	1.550	1.044	1.248	0.693	0.676	0.378	0.091	0.058	2.510	1.601
	3	6.668	2.277	4.293	1.513	2.924	0.947	0.213	0.182	5.672	3.664
	4	6.957	3.157	4.621	1.590	2.994	1.511	0.765	0.354	10.09	6.432
	5	5.669	1.593	5.005	1.948	2.626	1.423	0.827	0.536	15.74	10.47
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.296	0.281	0.029	0.020	0.169	0.161	0.001	0.0004	0.005	0.002
	0.5	0.402	0.332	0.294	0.172	0.202	0.156	0.007	0.004	0.156	0.100
	1	0.774	0.552	0.707	0.342	0.435	0.214	0.023	0.014	0.624	0.398
	2	2.607	1.208	2.681	0.794	1.389	0.451	0.091	0.058	2.510	1.601
	3	5.377	1.847	3.642	1.254	2.502	0.748	0.213	0.182	5.672	3.664
	4	8.954	3.170	6.091	1.581	3.856	1.524	0.765	0.354	10.09	6.432
	5	5.603	3.388	4.976	1.936	2.894	1.435	0.827	0.536	15.74	10.47
Volt. $k_x=0$ $k_a=0.1$	0.1	0.233	0.222	0.162	0.161	0.096	0.088	0.001	0.0005	0.005	0.002
	0.5	0.274	0.221	0.164	0.161	0.128	0.085	0.007	0.004	0.156	0.099
	1	0.453	0.272	0.173	0.164	0.242	0.112	0.024	0.014	0.624	0.398
	2	1.206	0.694	0.176	0.162	0.684	0.378	0.092	0.058	2.510	1.601
	3	5.123	1.669	0.175	0.162	2.934	0.943	0.213	0.181	5.672	3.664
	4	6.085	2.620	0.243	0.176	3.485	1.495	0.567	0.245	10.09	6.437
	5	5.138	2.689	0.331	0.182	2.942	1.524	0.911	0.460	15.75	10.48
Curr. $k_x=0$ $k_a=0.1$	0.1	0.464	0.450	0.365	0.359	0.164	0.155	0.001	0.0005	0.005	0.002
	0.5	0.499	0.448	0.357	0.351	0.201	0.158	0.007	0.004	0.156	0.099
	1	0.863	0.561	0.338	0.214	0.465	0.296	0.024	0.014	0.624	0.398
	2	1.378	0.774	0.417	0.341	0.761	0.379	0.092	0.058	2.510	1.601
	3	5.342	1.724	0.417	0.296	3.057	0.954	0.213	0.181	5.672	3.664
	4	6.685	2.627	0.289	0.181	3.830	1.496	0.567	0.245	10.09	6.437
	5	5.463	2.724	0.444	0.283	3.127	1.542	0.911	0.460	15.75	10.48

Table B.2.3.2: Dynamic state – frequency ramp test results for PMU B

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	0.532	0.403	0.185	0.170	0.286	0.2090	0.039	0.036	0.991	0.991
	-1.0	0.858	0.715	0.173	0.159	0.485	0.399	0.038	0.037	0.991	0.991
Curr. $\pm 2\text{Hz}$	1.0	0.998	0.893	0.534	0.323	0.588	0.473	0.039	0.036	0.991	0.991
	-1.0	0.797	0.476	0.624	0.362	0.321	0.160	0.038	0.037	0.991	0.991
Volt. $\pm 5\text{Hz}$	1.0	0.952	0.559	0.381	0.253	0.499	0.284	0.037	0.036	0.991	0.991
	-1.0	1.245	0.854	0.157	0.086	0.713	0.485	0.038	0.036	0.991	0.991
Curr. $\pm 5\text{Hz}$	1.0	1.352	1.001	0.534	0.252	0.774	0.551	0.037	0.036	0.991	0.991
	-1.0	1.163	0.651	0.790	0.424	0.626	0.267	0.038	0.036	0.991	0.991

Table B.2.3.3: Dynamic state – step change test results for PMU B

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	24.827	18.213	0.0116	0.0230
	-10	24.940	18.212	0.0126	0.0187
$ I_n $	+10	24.877	18.193	0.284	0.321
	-10	25.530	18.172	0.352	0.290
Φ_V	+pi/18	19.690	16.668	0.155	0.172
	-pi/18	19.707	16.671	0.183	0.193
Φ_I	+pi/18	19.749	16.667	0.226	0.197
	-pi/18	19.782	16.668	0.182	0.143

Table B.2.4.1: Dynamic state – measurement bandwidth test results for PMU C

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.666	0.560	0.385	0.378	0.313	0.234	0.001	0.0004	0.009	0.003
	0.5	0.686	0.568	0.392	0.378	0.327	0.241	0.007	0.003	0.092	0.029
	1	0.720	0.616	0.431	0.392	0.336	0.270	0.015	0.009	0.374	0.235
	2	0.863	0.609	0.552	0.383	0.415	0.248	0.121	0.041	2.786	1.831
	3	1.079	0.662	0.731	0.382	0.555	0.255	0.127	0.081	7.944	5.135
	4	1.555	0.914	0.998	0.499	0.809	0.388	0.232	0.148	15.06	9.60
	5	1.706	1.019	1.294	0.657	0.828	0.335	0.191	0.095	20.25	13.54
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.698	0.637	0.608	0.595	0.214	0.125	0.001	0.0004	0.009	0.003
	0.5	0.738	0.680	0.627	0.615	0.230	0.162	0.007	0.003	0.092	0.029
	1	0.850	0.762	0.842	0.753	0.134	0.061	0.015	0.009	0.374	0.235
	2	0.912	0.778	0.880	0.754	0.211	0.098	0.121	0.041	2.786	1.831
	3	1.078	0.760	0.931	0.611	0.476	0.217	0.127	0.081	7.944	5.135
	4	1.496	0.978	1.282	0.720	0.611	0.340	0.232	0.148	15.06	9.60
	5	1.641	1.067	1.596	0.831	0.634	0.309	0.191	0.095	20.25	13.54
Volt. $k_x=0$ $k_a=0.1$	0.1	0.685	0.587	0.390	0.381	0.328	0.254	0.001	0.0003	0.008	0.003
	0.5	0.703	0.585	0.389	0.380	0.344	0.253	0.007	0.002	0.092	0.029
	1	0.707	0.612	0.403	0.385	0.337	0.271	0.015	0.008	0.370	0.228
	2	0.808	0.597	0.399	0.387	0.408	0.253	0.053	0.033	2.691	1.715
	3	1.068	0.630	0.409	0.393	0.568	0.249	0.114	0.073	7.854	5.072
	4	1.494	0.810	0.444	0.411	0.825	0.373	0.204	0.132	14.91	9.499
	5	1.476	0.797	0.439	0.398	0.818	0.363	0.163	0.090	20.38	13.64
Curr. $k_x=0$ $k_a=0.1$	0.1	0.733	0.676	0.628	0.617	0.228	0.153	0.001	0.0003	0.008	0.003
	0.5	0.755	0.684	0.628	0.615	0.251	0.162	0.007	0.002	0.092	0.029
	1	0.859	0.769	0.846	0.752	0.191	0.077	0.015	0.008	0.370	0.228
	2	0.932	0.803	0.906	0.788	0.168	0.074	0.053	0.033	2.691	1.715
	3	1.060	0.828	0.856	0.755	0.408	0.171	0.114	0.073	7.854	5.072
	4	1.348	0.997	0.867	0.769	0.634	0.335	0.204	0.132	14.91	9.499
	5	1.467	0.911	0.706	0.640	0.761	0.332	0.163	0.090	20.38	13.64

Table B.2.4.2: Dynamic state – frequency ramp test results for PMU C

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	0.684	0.504	0.415	0.397	0.325	0.176	0.020	0.013	0.040	0.005
	-1.0	0.906	0.713	0.414	0.392	0.470	0.338	0.022	0.014	0.020	0.011
Curr. $\pm 2\text{Hz}$	1.0	0.892	0.664	0.892	0.642	0.199	0.078	0.020	0.013	0.040	0.005
	-1.0	0.966	0.748	0.852	0.584	0.448	0.253	0.022	0.014	0.020	0.011
Volt. $\pm 5\text{Hz}$	1.0	0.732	0.523	0.607	0.472	0.308	0.113	0.021	0.012	0.030	0.004
	-1.0	1.206	0.757	0.387	0.307	0.680	0.390	0.027	0.015	0.020	0.011
Curr. $\pm 5\text{Hz}$	1.0	0.951	0.711	0.904	0.698	0.183	0.061	0.021	0.012	0.030	0.004
	-1.0	1.241	0.805	0.850	0.527	0.651	0.328	0.021	0.012	0.020	0.004

Table B.2.4.3: Dynamic state – step change test results for PMU C

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	23.593	0.073	0.272	0.386
	-10	19.316	0.123	0.216	0.106
$ I_n $	+10	24.132	0.014	0.276	0.317
	-10	18.046	0.252	0.352	0.289
Φ_V	+pi/18	23.672	0.218	0.290	0.364
	-pi/18	24.999	0.128	0.512	0.441
Φ_I	+pi/18	24.781	0.258	0.520	0.500
	-pi/18	25.144	0.089	0.525	0.331

Table B.2.5.1: Dynamic state – measurement bandwidth test results for PMU D

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.439	0.421	0.322	0.305	0.179	0.167	0.0003	0.0001	0.005	0.002
	0.5	0.749	0.492	0.686	0.363	0.191	0.166	0.005	0.003	0.155	0.098
	1	1.084	0.592	1.038	0.478	0.269	0.163	0.022	0.014	0.622	0.396
	2	1.726	0.990	1.668	0.850	0.466	0.211	0.086	0.055	2.491	1.588
	3	2.417	1.556	2.296	1.237	0.799	0.413	0.191	0.121	5.611	3.545
	4	3.265	2.233	2.890	1.642	1.265	0.701	0.332	0.212	9.991	6.372
	5	4.130	3.003	3.516	2.031	1.821	1.070	0.507	0.319	15.64	9.748
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.527	0.506	0.486	0.467	0.125	0.112	0.0003	0.0001	0.005	0.002
	0.5	0.819	0.495	0.818	0.492	0.045	0.028	0.005	0.003	0.155	0.098
	1	1.195	0.580	1.195	0.568	0.078	0.032	0.022	0.014	0.622	0.396
	2	1.883	0.986	1.882	0.893	0.310	0.161	0.086	0.055	2.491	1.588
	3	2.456	1.532	2.398	1.254	0.657	0.378	0.191	0.121	5.611	3.545
	4	3.322	2.217	3.088	1.660	1.078	0.671	0.332	0.212	9.991	6.372
	5	4.162	2.974	3.162	2.024	1.688	1.050	0.507	0.319	15.64	9.748
Volt. $k_x=0$ $k_a=0.1$	0.1	0.479	0.465	0.369	0.364	0.178	0.166	0.0003	0.0001	0.005	0.002
	0.5	0.495	0.467	0.369	0.364	0.191	0.166	0.006	0.003	0.155	0.098
	1	0.638	0.484	0.433	0.374	0.291	0.171	0.022	0.014	0.622	0.396
	2	0.911	0.556	0.422	0.370	0.474	0.210	0.086	0.055	2.491	1.588
	3	1.468	0.840	0.428	0.371	0.810	0.414	0.191	0.121	5.611	3.545
	4	2.229	1.306	0.396	0.372	1.260	0.701	0.333	0.212	9.990	6.372
	5	3.198	1.919	0.422	0.378	1.819	1.067	0.506	0.320	15.64	9.748
Curr. $k_x=0$ $k_a=0.1$	0.1	0.568	0.558	0.531	0.523	0.126	0.112	0.0003	0.0001	0.005	0.002
	0.5	0.576	0.556	0.534	0.524	0.133	0.106	0.006	0.003	0.155	0.098
	1	0.675	0.562	0.578	0.497	0.222	0.145	0.022	0.014	0.622	0.396
	2	1.223	0.987	1.002	0.890	0.463	0.202	0.086	0.055	2.491	1.588
	3	1.281	0.932	0.725	0.592	0.639	0.389	0.191	0.121	5.611	3.545
	4	2.061	1.371	0.661	0.592	1.121	0.680	0.333	0.212	9.990	6.372
	5	2.909	1.942	0.657	0.568	1.632	1.048	0.506	0.320	15.64	9.748

Table B.2.5.2: Dynamic state – frequency ramp test results for PMU D

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	0.776	0.480	0.427	0.358	0.373	0.17	0.035	0.035	0.990	0.990
	-1.0	0.665	0.478	0.459	0.362	0.302	0.165	0.035	0.035	0.990	0.990
Curr. $\pm 2\text{Hz}$	1.0	0.857	0.611	0.852	0.570	0.350	0.098	0.035	0.035	0.990	0.990
	-1.0	0.738	0.524	0.735	0.488	0.201	0.094	0.035	0.035	0.990	0.990
Volt. $\pm 5\text{Hz}$	1.0	1.307	0.667	0.593	0.432	0.725	0.275	0.035	0.034	0.990	0.990
	-1.0	0.767	0.429	0.409	0.303	0.426	0.156	0.035	0.035	0.990	0.990
Curr. $\pm 5\text{Hz}$	1.0	1.258	0.664	0.848	0.566	0.620	0.164	0.035	0.034	0.990	0.990
	-1.0	0.875	0.550	0.584	0.454	0.536	0.143	0.035	0.035	0.990	0.990

Table B.2.5.3: Dynamic state – step change test results for PMU D

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	15.905	10.460	0.109	0.0484
	-10	22.348	10.456	0.0986	0.0205
$ I_n $	+10	16.134	10.474	0.169	0.215
	-10	25.637	10.468	0.272	0.146
Φ_V	+pi/18	59.295	10.318	40.640	0.0633
	-pi/18	56.020	10.321	41.609	0.202
Φ_I	+pi/18	58.908	10.417	41.492	0.542
	-pi/18	62.394	10.285	41.522	0.493

Table B.2.6.1: Dynamic state – measurement bandwidth test results for PMU E

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.645	0.630	0.178	0.164	0.358	0.348	0.001	0.0008	0.013	0.005
	0.5	0.663	0.589	0.141	0.085	0.380	0.333	0.012	0.007	0.065	0.027
	1	0.998	0.691	0.634	0.374	0.524	0.323	0.047	0.030	0.325	0.190
	2	1.915	1.168	1.138	0.660	0.987	0.498	0.176	0.116	2.306	1.384
	3	3.103	1.908	1.677	1.003	1.590	0.873	0.355	0.224	6.903	4.384
	4	4.357	2.586	2.190	1.326	2.174	1.245	0.543	0.352	14.22	8.717
	5	5.173	3.013	2.718	1.616	2.543	1.445	0.690	0.450	22.56	14.81
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.445	0.435	0.442	0.432	0.029	0.026	0.001	0.0008	0.013	0.005
	0.5	0.398	0.215	0.487	0.210	0.053	0.023	0.012	0.007	0.065	0.027
	1	0.914	0.543	0.901	0.479	0.194	0.109	0.047	0.030	0.325	0.190
	2	1.648	1.154	1.418	0.758	0.661	0.428	0.176	0.116	2.306	1.384
	3	2.786	1.848	1.938	1.077	1.274	0.795	0.355	0.224	6.903	4.384
	4	3.993	2.530	2.440	1.363	1.835	1.192	0.543	0.352	14.22	8.717
	5	4.850	2.998	2.967	1.616	2.205	1.428	0.690	0.450	22.56	14.81
Volt. $k_x=0$ $k_a=0.1$	0.1	0.640	0.626	0.138	0.129	0.359	0.351	0.001	0.0008	0.007	0.004
	0.5	0.667	0.593	0.138	0.123	0.377	0.333	0.013	0.007	0.062	0.027
	1	0.932	0.583	0.152	0.130	0.528	0.324	0.046	0.030	0.320	0.191
	2	1.740	0.893	0.154	0.135	0.994	0.499	0.175	0.117	2.136	1.395
	3	2.842	1.560	0.164	0.136	1.625	0.887	0.353	0.227	7.023	4.475
	4	3.908	2.239	0.163	0.140	2.238	1.278	0.551	0.360	14.35	8.933
	5	4.590	2.607	0.194	0.147	2.628	1.490	0.711	0.464	22.76	15.28
Curr. $k_x=0$ $k_a=0.1$	0.1	0.404	0.399	0.402	0.397	0.026	0.023	0.001	0.0008	0.007	0.004
	0.5	0.405	0.394	0.403	0.391	0.053	0.024	0.013	0.007	0.062	0.027
	1	0.522	0.450	0.406	0.496	0.197	0.109	0.046	0.030	0.320	0.191
	2	1.252	0.881	0.412	0.399	0.677	0.433	0.175	0.117	2.136	1.395
	3	2.306	1.500	0.424	0.404	1.301	0.811	0.353	0.227	7.023	4.475
	4	3.355	2.197	0.435	0.409	1.907	1.223	0.551	0.360	14.35	8.933
	5	4.048	2.618	0.460	0.415	2.305	1.475	0.711	0.464	22.76	15.28

Table B.2.6.2: Dynamic state – frequency ramp test results for PMU E

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	0.998	0.986	0.155	0.133	0.633	0.560	0.078	0.074	0.24	0.041
	-1.0	0.322	0.243	0.147	0.121	0.170	0.118	0.082	0.078	0.24	0.035
Curr. $\pm 2\text{Hz}$	1.0	0.661	0.562	0.419	0.400	0.296	0.225	0.078	0.074	0.24	0.041
	-1.0	0.631	0.528	0.408	0.390	0.277	0.202	0.082	0.078	0.24	0.035
Volt. $\pm 5\text{Hz}$	1.0	0.975	0.875	0.344	0.191	0.615	0.485	0.078	0.069	0.22	0.070
	-1.0	0.896	0.324	0.143	0.075	0.513	0.174	0.082	0.075	0.24	0.075
Curr. $\pm 5\text{Hz}$	1.0	0.809	0.569	0.602	0.459	0.364	0.172	0.078	0.069	0.22	0.070
	-1.0	0.705	0.460	0.410	0.335	0.360	0.165	0.082	0.075	0.24	0.075

Table B.2.6.3: Dynamic state – step change test results for PMU E

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	17.571	-7.930	0.215	0.0173
	-10	17.920	-7.931	0.114	0.0874
$ I_n $	+10	15.263	-7.908	0.1393	0.0069
	-10	17.003	-7.916	0.1322	0.951
Φ_V	+pi/18	108.039	-7.945	0.296	10.122
	-pi/18	158.721	-7.954	0.326	10.260
Φ_I	+pi/18	125.364	-7.931	0.316	10.089
	-pi/18	132.267	-7.948	0.245	10.290

Table B.2.7.1: Dynamic state – measurement bandwidth test results for PMU F

Variation (Hz)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $k_x=0.1$ $k_a=0.1$	0.1	0.400	0.374	0.318	0.300	0.151	0.128	0.0007	0.0004	0.005	0.004
	0.5	0.816	0.672	0.617	0.510	0.317	0.251	0.0145	0.0091	0.155	0.099
	1	1.200	0.570	0.892	0.414	0.477	0.221	0.056	0.035	0.623	0.398
	2	1.970	1.006	1.423	0.713	0.758	0.396	0.201	0.128	2.507	1.598
	3	2.629	1.481	1.883	1.047	1.063	0.598	0.372	0.240	5.667	3.667
	4	3.395	1.956	2.430	1.380	1.372	0.792	0.522	0.333	10.08	6.43
	5	3.901	2.369	2.733	1.663	1.603	0.966	0.524	0.349	15.73	10.49
Curr. $k_x=0.1$ $k_a=0.1$	0.1	0.322	0.257	0.179	0.130	0.164	0.126	0.0007	0.0004	0.005	0.004
	0.5	0.660	0.476	0.340	0.165	0.355	0.253	0.0145	0.0091	0.155	0.099
	1	1.162	0.587	0.990	0.451	0.394	0.197	0.056	0.035	0.623	0.398
	2	1.739	0.988	1.127	0.685	0.758	0.396	0.201	0.128	2.507	1.598
	3	2.335	1.444	1.695	1.015	0.969	0.585	0.372	0.240	5.667	3.667
	4	3.096	1.959	2.189	1.379	1.348	0.785	0.522	0.333	10.08	6.43
	5	3.641	2.368	2.566	1.645	1.595	0.967	0.524	0.349	15.73	10.49
Volt. $k_x=0$ $k_a=0.1$	0.1	0.423	0.404	0.362	0.338	0.148	0.126	0.0008	0.0004	0.005	0.004
	0.5	0.667	0.561	0.360	0.342	0.324	0.253	0.0144	0.0088	0.155	0.095
	1	0.895	0.544	0.385	0.344	0.473	0.216	0.055	0.035	0.624	0.384
	2	1.389	0.801	0.384	0.344	0.774	0.394	0.201	0.134	2.506	1.571
	3	1.892	1.081	0.369	0.340	1.068	0.571	0.372	0.247	5.666	3.701
	4	2.401	1.385	0.378	0.342	1.364	0.758	0.523	0.328	10.08	6.614
	5	2.820	1.677	0.385	0.342	1.605	0.923	0.524	0.337	15.74	10.67
Curr. $k_x=0$ $k_a=0.1$	0.1	0.301	0.240	0.178	0.103	0.153	0.124	0.0008	0.0004	0.005	0.004
	0.5	0.577	0.460	0.179	0.113	0.318	0.246	0.0144	0.0088	0.155	0.095
	1	0.776	0.407	0.299	0.160	0.420	0.206	0.055	0.035	0.624	0.384
	2	1.218	0.730	0.325	0.193	0.689	0.394	0.201	0.134	2.506	1.571
	3	1.826	1.048	0.306	0.211	1.045	0.576	0.372	0.247	5.666	3.701
	4	2.282	1.461	0.637	0.530	1.266	0.759	0.523	0.328	10.08	6.614
	5	2.809	1.699	0.467	0.371	1.598	0.932	0.524	0.337	15.74	10.67

Table B.2.7.2: Dynamic state – frequency ramp test results for PMU F

Variation (Hz/Sec)		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
Volt. $\pm 2\text{Hz}$	1.0	10.02	7.514	0.306	0.250	5.742	4.303	0.092	0.092	0.990	0.990
	-1.0	10.55	8.044	0.308	0.235	6.044	4.607	0.092	0.091	0.990	0.990
Curr. $\pm 2\text{Hz}$	1.0	10.12	7.532	0.244	0.092	5.797	4.315	0.092	0.092	0.990	0.990
	-1.0	10.53	8.072	0.357	0.114	6.031	4.624	0.092	0.091	0.990	0.990
Volt. $\pm 5\text{Hz}$	1.0	26.31	15.58	0.548	0.215	15.07	8.926	0.092	0.092	0.990	0.089
	-1.0	26.88	16.12	0.949	0.318	15.39	9.232	0.092	0.092	0.990	0.990
Curr. $\pm 5\text{Hz}$	1.0	26.33	15.58	0.736	0.253	15.08	8.929	0.092	0.092	0.990	0.089
	-1.0	26.66	16.11	1.217	0.389	15.26	9.232	0.092	0.092	0.990	0.990

Table B.2.7.3: Dynamic state – step change test results for PMU F

Variation (%/rad)		Positive Sequence Voltage V_1 / Current I_1			
		Response time (ms)	Delay time (ms)	Max overshoot (%)	Max undershoot (%)
$ V_n $	+10	17.922	8.487	0.427	0.174
	-10	17.566	8.515	0.224	0.158
$ I_n $	+10	17.173	8.503	0.437	1.122
	-10	17.586	8.446	0.738	0.485
Φ_V	+pi/18	18.542	8.513	0.123	0.106
	-pi/18	18.781	8.507	0.224	0.196
Φ_I	+pi/18	18.703	8.510	0.270	0.053
	-pi/18	18.551	8.527	0.509	0.480

B.1.2: Interoperability Test Results

Table B.3.1.1: Interoperability test – PMU B and Clock B

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.205	0.198	0.159	0.157	0.076	0.068	1.335 e-3	0.538 e-3	0.136 e-3	0.044 e-3
	-20	0.233	0.221	0.163	0.160	0.096	0.087	2.033 e-3	0.639 e-3	0.125 e-3	0.042 e-3
	-90	0.631	0.610	0.175	0.161	0.348	0.337	0.0	0.0	0.0	0.0
$ I_n $ (%)	+20	0.302	0.290	0.024	0.021	0.173	0.166	1.335 e-3	0.538 e-3	0.136 e-3	0.044 e-3
	-20	0.297	0.283	0.021	0.016	0.170	0.161	2.033 e-3	0.639 e-3	0.125 e-3	0.042 e-3
	-90	0.634	0.568	0.587	0.520	0.154	0.131	0.0	0.0	0.0	0.0
	+100	0.323	0.204	0.076	0.032	0.175	0.154	0.002	6.874 e-3	1.213 e-4	5.072 e-5
F_V (Hz)	+2.0	0.226	0.218	0.167	0.164	0.088	0.083	1.377 e-3	0.457 e-3	0.105 e-3	0.037 e-3
	-2.0	0.241	0.228	0.166	0.164	0.100	0.091	1.327 e-3	0.448 e-3	0.137 e-3	0.047 e-3
	+5.0	0.215	0.209	0.173	0.171	0.075	0.069	1.098 e-3	4.675 e-4	1.094 e-4	3.891 e-5
	-5.0	0.230	0.222	0.172	0.170	0.089	0.081	1.468 e-3	4.200 e-4	1.142 e-4	3.894 e-5
F_I (Hz)	+2.0	0.332	0.321	0.015	0.011	0.190	0.184	1.377 e-3	0.457 e-3	0.105 e-3	0.037 e-3
	-2.0	0.367	0.356	0.257	0.253	0.151	0.144	1.327 e-3	0.448 e-3	0.137 e-3	0.047 e-3
	+5.0	0.455	0.438	0.208	0.197	0.233	0.224	1.098 e-3	4.675 e-4	1.094 e-4	3.891 e-5
	-5.0	0.311	0.300	0.193	0.187	0.142	0.134	1.468 e-3	4.200 e-4	1.142 e-4	3.894 e-5
V, f_m (Hz)	2.0	1.550	1.059	1.243	0.685	0.692	0.399	0.092	0.058	2.510	1.572
	5.0	5.670	3.347	4.132	1.870	2.901	1.510	0.914	0.460	15.75	10.66
I, f_m (Hz)	2.0	2.602	1.266	1.974	0.806	1.370	0.472	0.092	0.058	2.510	1.572
	5.0	6.006	3.322	5.102	1.842	3.186	1.482	0.914	0.460	15.75	10.66
V, df (Hz)	+2.0	0.542	0.424	0.188	0.171	0.294	0.221	0.037	0.036	0.991	0.991
	-2.0	0.786	0.665	0.178	0.161	0.441	0.370	0.038	0.036	0.991	0.991
	+5.0	0.921	0.529	0.392	0.235	0.477	0.270	0.038	0.036	0.991	0.991
	-5.0	1.102	0.821	0.177	0.114	0.685	0.464	0.038	0.037	0.991	0.991
I, df (Hz)	+2.0	0.870	0.852	0.097	0.067	0.377	0.287	0.037	0.036	0.991	0.991
	-2.0	0.382	0.240	0.205	0.084	0.214	0.124	0.038	0.036	0.991	0.991
	+5.0	1.473	1.012	0.489	0.301	0.801	0.552	0.038	0.036	0.991	0.991
	-5.0	0.863	0.471	0.422	0.213	0.482	0.226	0.038	0.037	0.991	0.991

Table B.3.2.1: Interoperability test – PMU C and Clock A

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.582	0.455	0.069	0.063	0.331	0.258	0.0	0.0	0.0	0.0
	-20	0.612	0.586	0.109	0.102	0.403	0.330	0.0	0.0	0.0	0.0
	-90	0.905	0.705	0.134	0.125	0.513	0.397	4.597 e-4	2.855 e-4	0.01	0.007
$ I_n $ (%)	+20	0.506	0.386	0.125	0.116	0.282	0.210	0.0	0.0	0.0	0.0
	-20	0.531	0.405	0.166	0.156	0.292	0.213	0.0	0.0	0.0	0.0
	-90	0.933	0.773	0.538	0.439	0.470	0.361	4.597 e-4	2.855 e-4	0.01	0.007
	+100	0.650	0.570	0.447	0.432	0.282	0.210	0.0	0.0	0.0	0.0
F_V (Hz)	+2.0	0.677	0.526	0.088	0.082	0.384	0.298	0.0	0.0	0.0	0.0
	-2.0	0.636	0.512	0.088	0.084	0.361	0.289	0.0	0.0	0.0	0.0
	+5.0	0.743	0.550	0.092	0.084	0.422	0.311	0.0	0.0	0.0	0.0
	-5.0	0.600	0.445	0.091	0.086	0.340	0.250	9.994 e-4	7.138 e-5	0.01	0.002
F_I (Hz)	+2.0	0.519	0.378	0.141	0.131	0.286	0.202	0.0	0.0	0.0	0.0
	-2.0	0.546	0.427	0.170	0.160	0.301	0.226	0.0	0.0	0.0	0.0
	+5.0	0.608	0.476	0.347	0.339	0.289	0.188	0.0	0.0	0.0	0.0
	-5.0	0.646	0.538	0.406	0.399	0.290	0.205	9.994 e-4	7.138 e-5	0.01	0.002
V, f_m (Hz)	2.0	0.801	0.530	0.242	0.123	0.458	0.288	0.120	0.041	2.766	1.830
	5.0	2.212	1.061	1.057	0.676	1.130	0.405	0.246	0.103	21.74	13.95
I, f_m (Hz)	2.0	0.637	0.406	0.424	0.278	0.295	0.150	0.120	0.041	2.766	1.830
	5.0	2.376	1.088	1.470	0.704	1.211	0.371	0.246	0.103	21.74	13.95
V, df (Hz)	+2.0	0.592	0.371	0.109	0.086	0.336	0.207	0.010	0.012	0.010	0.002
	-2.0	0.905	0.663	0.089	0.077	0.517	0.377	0.024	0.014	0.030	0.013
	+5.0	0.673	0.330	0.287	0.143	0.370	0.162	0.021	0.012	0.03	0.002
	-5.0	0.946	0.713	0.103	0.054	0.551	0.407	0.026	0.015	0.04	0.011
I, df (Hz)	+2.0	0.524	0.440	0.496	0.381	0.233	0.119	0.010	0.012	0.010	0.002
	-2.0	0.940	0.668	0.480	0.367	0.489	0.313	0.024	0.014	0.030	0.013
	+5.0	0.781	0.608	0.781	0.584	0.282	0.076	0.021	0.012	0.03	0.002
	-5.0	0.978	0.709	0.562	0.345	0.593	0.343	0.026	0.015	0.04	0.011

Table B.3.2.2: Interoperability test – PMU C and Clock B

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.621	0.486	0.074	0.063	0.353	0.276	0.0	0.0	0.0	0.0
	-20	0.684	0.557	0.109	0.102	0.387	0.314	0.0	0.0	0.0	0.0
	-90	0.827	0.680	0.121	0.110	0.470	0.384	9.994 e-4	1.071 e-4	0.0	0.0
$ I_n $ (%)	+20	0.531	0.399	0.159	0.150	0.292	0.211	0.0	0.0	0.0	0.0
	-20	0.496	0.382	0.165	0.156	0.270	0.198	0.0	0.0	0.0	0.0
	-90	0.965	0.795	0.633	0.560	0.444	0.322	9.994 e-4	1.071 e-4	0.0	0.0
	+100	0.660	0.582	0.468	0.455	0.274	0.204	0.0	0.0	0.0	0.0
F_V (Hz)	+2.0	0.686	0.517	0.089	0.083	0.390	0.292	0.0	0.0	0.0	0.0
	-2.0	0.677	0.514	0.097	0.088	0.384	0.290	0.0	0.0	0.0	0.0
	+5.0	0.733	0.531	0.084	0.079	0.417	0.301	0.0	0.0	0.0	0.0
	-5.0	0.618	0.440	0.093	0.087	0.350	0.247	9.994 e-4	3.570 e-5	0.01	0.002
F_I (Hz)	+2.0	0.547	0.384	0.152	0.143	0.301	0.203	0.0	0.0	0.0	0.0
	-2.0	0.510	0.368	0.162	0.148	0.279	0.193	0.0	0.0	0.0	0.0
	+5.0	0.643	0.511	0.428	0.420	0.275	0.161	0.0	0.0	0.0	0.0
	-5.0	0.648	0.526	0.402	0.392	0.295	0.198	9.994 e-4	3.570 e-5	0.01	0.002
V, f_m (Hz)	2.0	0.853	0.535	0.240	0.124	0.468	0.291	0.121	0.041	2.766	1.829
	5.0	2.142	1.053	1.038	0.672	1.091	0.409	0.883	0.167	21.78	13.45
I, f_m (Hz)	2.0	0.716	0.406	0.280	0.145	0.378	0.202	0.121	0.041	2.766	1.829
	5.0	2.192	1.061	1.418	0.693	1.225	0.357	0.883	0.167	21.78	13.45
V, df (Hz)	+2.0	0.644	0.382	0.084	0.077	0.366	0.214	0.010	0.012	0.010	0.001
	-2.0	0.927	0.662	0.090	0.075	0.530	0.376	0.023	0.015	0.020	0.012
	+5.0	0.678	0.346	0.287	0.142	0.375	0.172	0.021	0.012	0.01	0.002
	-5.0	1.196	0.728	0.112	0.054	0.682	0.415	0.025	0.015	0.04	0.011
I, df (Hz)	+2.0	0.501	0.257	0.136	0.126	0.276	0.127	0.010	0.012	0.010	0.001
	-2.0	0.919	0.643	0.545	0.372	0.484	0.291	0.023	0.015	0.020	0.012
	+5.0	0.730	0.492	0.688	0.468	0.241	0.069	0.021	0.012	0.01	0.002
	-5.0	1.108	0.696	0.504	0.299	0.606	0.349	0.025	0.015	0.04	0.011

Table B.3.2.3: Interoperability test – PMU C and Clock D

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.718	0.546	0.086	0.074	0.408	0.310	0.0	0.0	0.0	0.0
	-20	0.800	0.624	0.121	0.112	0.453	0.351	0.0	0.0	0.0	0.0
	-90	0.876	0.728	0.116	0.111	0.498	0.412	9.994 e-4	1.428 e-4	0.0	0.0
$ I_n $ (%)	+20	0.758	0.684	0.588	0.580	0.278	0.204	0.0	0.0	0.0	0.0
	-20	0.760	0.694	0.610	0.604	0.270	0.191	0.0	0.0	0.0	0.0
	-90	0.976	0.842	0.713	0.642	0.465	0.401	9.994 e-4	1.428 e-4	0.0	0.0
	+100	0.773	0.646	0.522	0.510	0.331	0.224	0.0	0.0	0.0	0.0
F_V (Hz)	+2.0	0.735	0.574	0.099	0.089	0.418	0.325	0.0	0.0	0.0	0.0
	-2.0	0.676	0.548	0.100	0.091	0.383	0.310	0.0	0.0	0.0	0.0
	+5.0	0.723	0.569	0.086	0.080	0.411	0.322	0.0	0.0	0.0	0.0
	-5.0	0.569	0.444	0.082	0.080	0.322	0.250	0.0	0.0	0.01	0.004
F_I (Hz)	+2.0	0.580	0.413	0.230	0.221	0.307	0.198	0.0	0.0	0.0	0.0
	-2.0	0.536	0.428	0.200	0.192	0.287	0.218	0.0	0.0	0.0	0.0
	+5.0	0.695	0.592	0.468	0.459	0.297	0.211	0.0	0.0	0.0	0.0
	-5.0	0.598	0.502	0.362	0.351	0.276	0.204	0.0	0.0	0.01	0.004
V, f_m (Hz)	2.0	0.891	0.572	0.249	0.120	0.490	0.314	0.121	0.041	2.766	1.832
	5.0	1.620	0.977	1.016	0.672	0.860	0.348	0.195	0.095	20.18	13.73
I, f_m (Hz)	2.0	0.841	0.561	0.567	0.415	0.374	0.195	0.121	0.041	2.766	1.832
	5.0	1.603	0.970	1.310	0.659	0.740	0.294	0.195	0.095	20.18	13.73
V, df (Hz)	+2.0	0.694	0.410	0.107	0.092	0.394	0.229	0.209	0.013	0.010	0.002
	-2.0	0.969	0.734	0.107	0.090	0.553	0.417	0.226	0.014	0.040	0.013
	+5.0	0.667	0.350	0.287	0.144	0.364	0.174	0.021	0.012	0.04	0.003
	-5.0	1.169	0.724	0.108	0.053	0.667	0.413	0.026	0.015	0.03	0.012
I, df (Hz)	+2.0	0.557	0.452	0.525	0.391	0.203	0.124	0.209	0.013	0.010	0.002
	-2.0	0.865	0.575	0.262	0.117	0.494	0.320	0.226	0.014	0.040	0.013
	+5.0	0.807	0.549	0.784	0.518	0.290	0.087	0.021	0.012	0.04	0.003
	-5.0	1.067	0.698	0.529	0.372	0.594	0.326	0.026	0.015	0.03	0.012

Table B.3.3.1: Interoperability test – PMU A-1 and Clock A

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.338	0.325	0.293	0.290	0.096	0.084	0.152 e-3	0.073 e-3	0.017 e-3	0.007 e-3
	-20	0.375	0.363	0.314	0.310	0.119	0.109	0.103 e-3	0.052 e-3	0.026 e-3	0.011 e-3
	-90	0.730	0.711	0.482	0.463	0.320	0.308	0.0	0.0	0.0	0.0
$ I_n $ (%)	+20	0.208	0.193	0.114	0.104	0.102	0.093	0.152 e-3	0.073 e-3	0.017 e-3	0.007 e-3
	-20	0.165	0.137	0.075	0.052	0.093	0.072	0.103 e-3	0.052 e-3	0.026 e-3	0.011 e-3
	-90	0.882	0.692	0.401	0.273	0.484	0.360	0.0	0.0	0.0	0.0
	+100	0.400	0.382	0.290	0.267	0.163	0.156	2.288 e-5	8.174 e-7	1.384 e-5	4.944 e-7
F_V (Hz)	+2.0	0.359	0.351	0.323	0.320	0.090	0.083	0.064 e-3	0.037 e-3	0.016 e-3	0.005 e-3
	-2.0	0.326	0.318	0.282	0.278	0.094	0.088	0.103 e-3	0.044 e-3	0.025 e-3	0.010 e-3
	+5.0	0.389	0.382	0.363	0.358	0.084	0.077	7.629 e-5	3.269 e-5	2.317 e-5	7.285 e-6
	-5.0	0.304	0.295	0.260	0.253	0.094	0.086	8.392 e-5	4.087 e-5	2.117 e-5	8.726 e-6
F_I (Hz)	+2.0	0.205	0.184	0.083	0.062	0.113	0.099	0.064 e-3	0.037 e-3	0.016 e-3	0.005 e-3
	-2.0	0.080	0.054	0.036	0.016	0.044	0.029	0.103 e-3	0.044 e-3	0.025 e-3	0.010 e-3
	+5.0	0.435	0.418	0.360	0.340	0.150	0.138	7.629 e-5	3.269 e-5	2.317 e-5	7.285 e-6
	-5.0	0.246	0.228	0.245	0.225	0.034	0.022	8.392 e-5	4.087 e-5	2.117 e-5	8.726 e-6
V, f_m (Hz)	2.0	0.368	0.337	0.327	0.299	0.105	0.089	0.194	0.120	2.507	1.596
	5.0	0.615	0.348	0.490	0.287	0.245	0.107	0.553	0.370	15.76	10.68
I, f_m (Hz)	2.0	0.764	0.667	0.701	0.590	0.227	0.177	0.194	0.120	2.507	1.596
	5.0	0.432	0.264	0.416	0.172	0.184	0.084	0.553	0.370	15.76	10.68
V, df (Hz)	+2.0	0.369	0.345	0.353	0.332	0.093	0.047	0.083	0.083	0.990	0.990
	-2.0	0.468	0.386	0.309	0.288	0.217	0.144	0.083	0.083	0.990	0.990
	+5.0	0.797	0.451	0.621	0.422	0.286	0.076	0.084	0.083	0.990	0.990
	-5.0	0.747	0.426	0.303	0.232	0.424	0.195	0.084	0.083	0.990	0.990
I, df (Hz)	+2.0	0.734	0.576	0.643	0.494	0.280	0.163	0.083	0.083	0.990	0.990
	-2.0	0.643	0.465	0.643	0.450	0.146	0.055	0.083	0.083	0.990	0.990
	+5.0	1.067	0.556	0.597	0.338	0.506	0.246	0.084	0.083	0.990	0.990
	-5.0	0.606	0.327	0.466	0.253	0.326	0.093	0.084	0.083	0.990	0.990

Table B.3.3.2: Interoperability test – PMU A-1 and Clock C

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	2.293	2.240	0.295	0.292	1.303	1.272	0.0	0.0	0.0	0.0
	-20	3.829	2.113	0.315	0.309	2.187	1.184	0.0	0.0	0.0	0.0
	-90	3.321	1.919	0.942	0.574	1.859	1.014	0.0	0.0	0.0	0.0
$ I_n $ (%)	+20	2.047	1.964	0.500	0.487	1.137	1.090	0.0	0.0	0.0	0.0
	-20	3.467	1.950	0.493	0.469	1.967	1.059	0.0	0.0	0.0	0.0
	-90	3.107	1.765	0.479	0.299	1.778	0.980	0.0	0.0	0.0	0.0
	+100	3.434	1.931	0.289	0.280	1.961	1.083	0.0	0.0	0.0	0.0
F_V (Hz)	+2.0	2.028	1.967	0.377	0.374	1.142	1.106	2.0	2.0	0.0	0.0
	-2.0	1.493	1.433	0.334	0.332	0.834	0.799	2.0	2.0	0.0	0.0
	+5.0	2.967	1.672	0.802	0.696	1.650	0.837	5.0	5.0	0.0	0.0
	-5.0	1.592	1.546	0.599	0.592	0.847	0.818	5.0	5.0	0.0	0.0
F_I (Hz)	+2.0	1.765	1.685	0.613	0.595	0.950	0.903	2.0	2.0	0.0	0.0
	-2.0	1.360	1.284	0.532	0.509	0.720	0.675	2.0	2.0	0.0	0.0
	+5.0	3.371	1.650	0.856	0.775	1.880	0.797	5.0	5.0	0.0	0.0
	-5.0	1.498	1.432	0.595	0.578	0.795	0.751	5.0	5.0	0.0	0.0
V, f_m (Hz)	2.0	2.526	2.442	0.320	0.302	1.436	1.388	0.199	0.126	2.513	1.603
	5.0	2.420	2.045	0.474	0.290	1.354	1.157	0.433	0.278	15.71	10.66
I, f_m (Hz)	2.0	2.294	2.180	0.639	0.550	1.277	1.208	0.199	0.126	2.513	1.603
	5.0	2.016	1.656	0.562	0.313	1.126	0.930	0.433	0.278	15.71	10.66
V, df (Hz)	+2.0	18.29	15.71	0.454	0.356	10.48	8.999	1.899	1.449	1.0	1.0
	-2.0	15.15	15.05	0.332	0.318	8.681	8.622	1.899	1.449	1.0	1.0
	+5.0	44.97	9.946	2.679	0.567	25.77	5.635	4.899	2.949	1.0	1.0
	-5.0	1.787	1.061	0.429	0.362	1.009	0.548	4.900	2.950	1.0	1.0
I, df (Hz)	+2.0	17.91	15.38	0.374	0.168	10.26	8.815	1.899	1.449	1.0	1.0
	-2.0	14.93	14.74	0.335	0.173	8.555	8.446	1.899	1.449	1.0	1.0
	+5.0	44.71	9.948	2.659	0.483	25.62	5.653	4.899	2.949	1.0	1.0
	-5.0	2.085	1.142	0.451	0.252	1.177	0.622	4.900	2.950	1.0	1.0

Table B.3.3.3: Interoperability test – PMU A-1 and Clock D

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.332	0.323	0.290	0.288	0.093	0.083	1.564 e-4	6.185 e-5	1.810 e-5	5.648 e-6
	-20	0.382	0.365	0.309	0.306	0.128	0.113	2.212 e-4	7.356 e-5	2.808 e-5	1.112 e-5
	-90	0.927	0.579	0.881	0.543	0.310	0.089	0.0	0.0	0.0	0.0
$ I_n $ (%)	+20	0.231	0.215	0.166	0.152	0.099	0.086	1.564 e-4	6.185 e-5	1.810 e-5	5.648 e-6
	-20	0.602	0.580	0.585	0.562	0.096	0.082	2.212 e-4	7.356 e-5	2.808 e-5	1.112 e-5
	-90	0.987	0.662	0.671	0.274	0.516	0.333	0.0	0.0	0.0	0.0
	+100	0.261	0.243	0.230	0.210	0.081	0.070	1.945 e-4	8.460 e-5	2.514 e-5	8.576 e-6
F_V (Hz)	+2.0	0.379	0.361	0.322	0.318	0.115	0.097	2.784 e-4	8.556 e-5	3.018 e-5	8.956 e-6
	-2.0	0.335	0.323	0.280	0.277	0.109	0.095	1.678 e-4	6.839 e-5	3.590 e-5	1.152 e-5
	+5.0	0.582	0.548	0.571	0.537	0.079	0.061	2.212 e-4	7.711 e-5	2.288 e-5	7.949 e-6
	-5.0	0.455	0.418	0.423	0.385	0.106	0.091	2.746 e-4	1.218 e-4	2.517 e-5	8.419 e-6
F_I (Hz)	+2.0	0.281	0.263	0.143	0.128	0.142	0.132	2.784 e-4	8.556 e-5	3.018 e-5	8.956 e-6
	-2.0	0.527	0.511	0.522	0.508	0.042	0.028	1.678 e-4	6.839 e-5	3.590 e-5	1.152 e-5
	+5.0	0.364	0.323	0.334	0.283	0.104	0.088	2.212 e-4	7.711 e-5	2.288 e-5	7.949 e-6
	-5.0	0.264	0.222	0.225	0.191	0.080	0.064	2.746 e-4	1.218 e-4	2.517 e-5	8.419 e-6
V, f_m (Hz)	2.0	0.390	0.342	0.329	0.298	0.120	0.096	0.194	0.125	2.507	1.568
	5.0	0.789	0.484	0.697	0.445	0.265	0.103	0.553	0.370	15.75	10.68
I, f_m (Hz)	2.0	0.326	0.232	0.305	0.180	0.119	0.079	0.194	0.125	2.507	1.568
	5.0	0.887	0.698	0.844	0.543	0.388	0.219	0.553	0.370	15.75	10.68
V, df (Hz)	+2.0	0.377	0.352	0.345	0.331	0.121	0.057	0.084	0.083	0.990	0.989
	-2.0	0.485	0.405	0.304	0.291	0.225	0.159	0.083	0.083	0.990	0.990
	+5.0	0.788	0.448	0.624	0.420	0.275	0.075	0.084	0.083	0.990	0.990
	-5.0	0.778	0.444	0.302	0.234	0.441	0.207	0.083	0.083	0.990	0.990
I, df (Hz)	+2.0	0.510	0.330	0.304	0.130	0.279	0.168	0.084	0.083	0.990	0.989
	-2.0	0.698	0.503	0.683	0.489	0.191	0.053	0.083	0.083	0.990	0.990
	+5.0	1.104	0.662	0.776	0.532	0.473	0.215	0.084	0.083	0.990	0.990
	-5.0	0.677	0.297	0.372	0.168	0.381	0.118	0.083	0.083	0.990	0.990

Table B.3.4.1: Interoperability test – PMU F and Clock A

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.482	0.462	0.399	0.379	0.162	0.150	4.425 e-4	1.535 e-4	3.181 e-4	1.167 e-4
	-20	0.493	0.465	0.414	0.376	0.181	0.156	6.446 e-4	2.004 e-4	4.348 e-4	1.901 e-4
	-90	0.698	0.391	0.426	0.232	0.362	0.160	3.604 e-3	1.799 e-3	3.000 e-3	9.542 e-4
$ I_n $ (%)	+20	0.347	0.291	0.205	0.128	0.180	0.148	4.425 e-4	1.535 e-4	3.181 e-4	1.167 e-4
	-20	0.694	0.623	0.619	0.556	0.192	0.158	6.446 e-4	2.004 e-4	4.348 e-4	1.901 e-4
	-90	0.722	0.388	0.632	0.248	0.404	0.145	3.604 e-3	1.799 e-3	3.000 e-3	9.542 e-4
	+100	0.388	0.351	0.266	0.238	0.170	0.147	4.844 e-4	1.816 e-4	4.165 e-4	1.591 e-4
F_V (Hz)	+2.0	10.04	10.37	0.236	0.197	5.962	5.943	5.989 e-4	1.957 e-4	3.753 e-4	1.609 e-4
	-2.0	10.93	10.89	0.235	0.201	6.261	6.244	4.997 e-4	1.783 e-4	4.623 e-4	1.649 e-4
	+5.0	26.37	26.34	0.794	0.762	15.10	15.09	4.196 e-4	1.534 e-4	3.936 e-4	1.453 e-4
	-5.0	26.89	26.87	0.792	0.763	15.40	15.39	4.082 e-4	1.895 e-4	3.364 e-4	1.209 e-4
F_I (Hz)	+2.0	10.44	10.37	0.483	0.400	5.978	5.938	5.989 e-4	1.957 e-4	3.753 e-4	1.609 e-4
	-2.0	10.97	10.91	0.459	0.382	6.286	6.247	4.997 e-4	1.783 e-4	4.623 e-4	1.649 e-4
	+5.0	26.78	27.64	0.896	0.679	15.21	15.13	4.082 e-4	1.895 e-4	3.364 e-4	1.209 e-4
	-5.0	26.96	26.87	1.074	0.976	15.44	15.39	4.082 e-4	1.895 e-4	3.364 e-4	1.209 e-4
V, f_m (Hz)	2.0	1.983	0.989	1.477	0.706	0.762	0.393	0.200	0.133	2.507	1.570
	5.0	3.913	2.270	2.762	1.591	1.594	0.926	0.524	0.337	15.73	10.68
I, f_m (Hz)	2.0	2.074	1.024	1.591	0.743	0.764	0.389	0.200	0.133	2.507	1.570
	5.0	3.854	2.276	2.691	1.603	1.585	0.925	0.524	0.337	15.73	10.68
V, df (Hz)	+2.0	10.06	7.517	0.338	0.283	5.766	4.304	0.092	0.091	0.990	0.990
	-2.0	10.54	8.042	0.342	0.278	6.039	4.605	0.092	0.092	0.990	0.990
	+5.0	26.31	15.58	0.504	0.215	15.07	8.925	0.092	0.092	0.990	0.989
	-5.0	26.91	16.11	0.890	0.311	15.41	9.231	0.092	0.091	0.990	0.990
I, df (Hz)	+2.0	10.01	7.541	0.671	0.494	5.731	4.310	0.092	0.091	0.990	0.990
	-2.0	10.55	8.084	0.650	0.473	6.041	4.623	0.092	0.092	0.990	0.990
	+5.0	26.33	15.58	0.808	0.279	15.08	8.929	0.092	0.092	0.990	0.989
	-5.0	26.69	16.12	1.221	0.395	15.28	9.231	0.092	0.091	0.990	0.990

Table B.3.4.2: Interoperability test – PMU F and Clock C

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.482	0.464	0.402	0.377	0.167	0.154	3.586 e-4	1.531 e-4	2.907 e-4	8.158 e-5
	-20	0.471	0.420	0.380	0.335	0.194	0.144	6.332 e-4	2.189 e-4	4.394 e-4	1.779 e-4
	-90	0.701	0.442	0.616	0.311	0.310	0.157	3.001 e-3	1.642 e-3	3.318 e-3	1.486 e-2
$ I_n $ (%)	+20	0.382	0.298	0.217	0.141	0.180	0.149	3.586 e-4	1.531 e-4	2.907 e-4	8.158 e-5
	-20	0.426	0.335	0.307	0.119	0.230	0.175	6.332 e-4	2.189 e-4	4.394 e-4	1.779 e-4
	-90	0.904	0.480	0.757	0.297	0.500	0.186	3.001 e-3	1.642 e-3	3.318 e-3	1.486 e-2
	+100	0.365	0.327	0.226	0.184	0.178	0.154	4.234 e-4	1.856 e-4	3.982 e-4	1.214 e-4
F_V (Hz)	+2.0	10.39	10.36	0.225	0.196	5.955	5.936	5.340 e-4	1.254 e-4	2.517 e-4	8.664 e-5
	-2.0	10.95	10.91	0.231	0.196	6.272	6.249	4.806 e-4	1.509 e-4	4.257 e-4	1.432 e-4
	+5.0	26.35	26.33	0.810	0.770	15.10	15.08	3.814 e-4	1.199 e-4	2.517 e-4	1.365 e-4
	-5.0	26.91	26.87	0.796	0.756	15.41	15.39	5.340 e-4	1.716 e-4	4.417 e-4	1.583 e-4
F_I (Hz)	+2.0	10.43	10.36	0.127	0.064	5.974	5.937	5.340 e-4	1.254 e-4	2.517 e-4	8.664 e-5
	-2.0	10.98	10.91	0.148	0.803	6.293	6.252	4.806 e-4	1.509 e-4	4.257 e-4	1.432 e-4
	+5.0	26.43	26.33	0.978	0.886	15.13	15.08	3.814 e-4	1.199 e-4	2.517 e-4	1.365 e-4
	-5.0	27.01	26.87	0.918	0.801	15.47	15.39	5.340 e-4	1.716 e-4	4.417 e-4	1.583 e-4
V, f_m (Hz)	2.0	1.987	0.986	1.455	0.704	0.776	0.393	0.200	0.133	2.507	1.570
	5.0	3.919	2.268	2.753	1.589	1.598	0.925	0.524	0.337	15.74	10.68
I, f_m (Hz)	2.0	1.768	0.978	1.167	0.686	0.783	0.391	0.200	0.133	2.507	1.570
	5.0	3.876	2.268	2.724	1.581	1.600	0.927	0.524	0.337	15.74	10.68
V, df (Hz)	+2.0	10.03	7.506	0.352	0.287	5.748	4.298	0.092	0.092	0.990	0.989
	-2.0	10.56	8.055	0.344	0.276	6.052	4.612	0.092	0.092	0.990	0.990
	+5.0	26.31	15.57	0.506	0.218	15.07	8.921	0.092	0.092	0.990	0.990
	-5.0	26.89	16.12	0.924	0.312	15.40	9.236	0.092	0.092	0.990	0.990
I, df (Hz)	+2.0	9.997	7.502	0.246	0.078	5.728	4.298	0.092	0.092	0.990	0.989
	-2.0	10.46	8.036	0.146	0.052	5.995	4.605	0.092	0.092	0.990	0.990
	+5.0	26.34	15.58	0.613	0.231	15.09	8.925	0.092	0.092	0.990	0.990
	-5.0	26.72	16.12	1.060	0.333	15.30	9.235	0.092	0.092	0.990	0.990

Table B.3.4.3: Interoperability test – PMU F and Clock D

Variation		Positive Sequence Voltage V_1 / Current I_1									
		TVE (%)		Amp Err (%)		Angle Err (deg)		FE (Hz)		RFE (Hz)	
		Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean
$ V_n $ (%)	+20	0.501	0.475	0.400	0.378	0.185	0.167	2.975 e-4	1.308 e-4	2.655 e-4	1.093 e-4
	-20	0.518	0.473	0.407	0.375	0.187	0.165	3.929 e-4	1.706 e-4	4.211 e-4	1.629 e-4
	-90	0.725	0.421	0.714	0.290	0.268	0.156	2.883 e-3	1.107 e-3	3.723 e-3	1.420 e-3
$ I_n $ (%)	+20	0.390	0.324	0.241	0.171	0.193	0.157	2.975 e-4	1.308 e-4	2.655 e-4	1.093 e-4
	-20	0.404	0.304	0.164	0.091	0.223	0.165	3.929 e-4	1.706 e-4	4.211 e-4	1.629 e-4
	-90	0.949	0.526	0.831	0.273	0.505	0.223	2.883 e-3	1.107 e-3	3.723 e-3	1.420 e-3
	+100	0.438	0.409	0.325	0.299	0.183	0.159	3.967 e-4	1.456 e-4	4.692 e-4	1.281 e-4
F_V (Hz)	+2.0	10.38	10.34	0.224	0.199	5.946	5.928	3.738 e-4	1.580 e-4	4.921 e-4	1.629 e-4
	-2.0	10.95	10.92	0.222	0.194	6.275	6.259	4.196 e-4	1.745 e-4	3.754 e-4	1.449 e-4
	+5.0	26.35	26.32	0.800	0.764	15.09	15.07	5.188 e-4	2.054 e-4	4.394 e-4	1.596 e-4
	-5.0	26.92	26.88	0.799	0.767	15.42	15.40	7.172 e-4	1.715 e-4	2.975 e-4	1.383 e-4
F_I (Hz)	+2.0	10.40	10.35	0.124	0.067	5.960	5.931	3.738 e-4	1.580 e-4	4.921 e-4	1.630 e-4
	-2.0	10.99	10.93	0.117	0.045	6.298	6.260	4.196 e-4	1.745 e-4	3.754 e-4	1.449 e-4
	+5.0	26.47	26.33	1.051	0.974	15.16	15.07	5.188 e-4	2.054 e-4	4.394 e-4	1.596 e-4
	-5.0	28.98	26.76	1.132	0.875	15.57	15.32	7.172 e-4	1.715 e-4	2.975 e-4	1.383 e-4
V, f_m (Hz)	2.0	2.011	0.986	1.476	0.703	0.783	0.394	0.200	0.134	2.506	1.570
	5.0	3.940	2.273	2.745	1.591	1.624	0.929	0.524	0.337	15.73	10.69
I, f_m (Hz)	2.0	2.047	1.035	1.669	0.734	0.686	0.388	0.200	0.134	2.506	1.570
	5.0	3.802	2.809	2.513	1.598	1.640	0.926	0.524	0.337	15.73	10.69
V, df (Hz)	+2.0	9.998	7.481	0.348	0.290	5.727	4.283	0.092	0.091	0.990	0.990
	-2.0	10.54	8.068	0.337	0.276	6.036	4.620	0.092	0.092	0.990	0.990
	+5.0	26.29	15.56	0.499	0.216	15.06	8.913	0.092	0.091	0.990	0.990
	-5.0	26.88	16.14	0.905	0.308	15.39	9.244	0.092	0.091	0.990	0.990
I, df (Hz)	+2.0	9.930	7.512	0.775	0.615	5.680	4.292	0.092	0.091	0.990	0.990
	-2.0	10.51	8.049	0.608	0.414	6.024	4.605	0.092	0.092	0.990	0.990
	+5.0	26.26	15.56	0.880	0.294	15.04	8.916	0.092	0.091	0.990	0.990
	-5.0	26.76	16.14	0.834	0.322	15.32	9.245	0.092	0.091	0.990	0.990

B.2: Application Tests

B.2.1: PMUs and PMU-Enabled IEDs

The estimated locations under different fault scenarios using reference phasors and DUT's phasors respectively, and the location errors for each configuration of PMUs at two ends are given in the following tables.

Table B.4.1.1: Application test – PMU C at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0956	0.0946	1.0145
	AG	0.0569	0.0577	1.3726
	BC	0.0856	0.0817	4.5405
	BCG	0.0896	0.0870	2.9325
50	ABC	0.4996	0.4986	0.1864
	AG	0.4989	0.4950	0.7766
	BC	0.4994	0.4974	0.4066
	BCG	0.4996	0.4979	0.3360
90	ABC	0.9244	0.9672	4.6371
	AG	0.9642	0.9550	0.9556
	BC	0.9341	0.9322	0.2034
	BCG	0.9300	0.9298	0.0190

Table B.4.1.2: Application test – PMU C at S and PMU A-1 at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0944	0.0948	0.4200
	AG	0.0550	0.0582	5.8182
	BC	0.0795	0.0831	4.4559
	BCG	0.0852	0.0863	1.2273
50	ABC	0.4995	0.4984	0.2130
	AG	0.4834	0.4971	2.8407
	BC	0.4938	0.4972	0.6737
	BCG	0.4955	0.4974	0.3978
90	ABC	0.9242	0.9221	0.2294
	AG	0.9500	0.9561	0.6413
	BC	0.9292	0.9321	0.3088
	BCG	0.9264	0.9285	0.2218

Table B.4.1.3: Application test – PMU C at S and PMU F at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0940	0.0936	0.4760
	AG	0.0547	0.0571	4.3875
	BC	0.0782	0.0815	4.2691
	BCG	0.0844	0.0859	1.6985
50	ABC	0.4986	0.4976	0.2010
	AG	0.4777	0.4957	3.7645
	BC	0.4928	0.4953	0.5094
	BCG	0.4951	0.4968	0.3511
90	ABC	0.9242	0.9222	0.2126
	AG	0.9445	0.9547	1.0802
	BC	0.9284	0.9308	0.2557
	BCG	0.9263	0.9280	0.1884

Table B.4.1.4: Application test – PMU A-1 at S and PMU C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0957	0.0961	0.4498
	AG	0.0549	0.0597	8.7432
	BC	0.0906	0.0833	8.0440
	BCG	0.0932	0.0894	4.0986
50	ABC	0.5004	0.4995	0.1677
	AG	0.5144	0.4956	3.6466
	BC	0.5049	0.4991	1.1546
	BCG	0.5035	0.4994	0.8164
90	ABC	0.9251	0.9676	4.5977
	AG	0.9787	0.9563	2.2874
	BC	0.9398	0.9346	0.5597
	BCG	0.9344	0.9312	0.3430

Table B.4.1.5: Application test – PMU A-1 at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0946	0.0964	1.8960
	AG	0.0547	0.0602	10.024
	BC	0.0846	0.0848	0.2181
	BCG	0.0888	0.0887	0.1587
50	ABC	0.5002	0.4993	0.1945
	AG	0.4989	0.4977	0.2324
	BC	0.4994	0.4989	0.0936
	BCG	0.4995	0.4990	0.1010
90	ABC	0.9250	0.9225	0.2614
	AG	0.9645	0.9574	0.7405
	BC	0.9349	0.9344	0.0548
	BCG	0.9308	0.9299	0.1046

Table B.4.1.6: Application test – PMU A-1 at S and PMU F at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0941	0.0951	0.9961
	AG	0.0553	0.0591	6.8716
	BC	0.0833	0.0832	0.0757
	BCG	0.0881	0.0883	0.2396
50	ABC	0.4994	0.4985	0.1852
	AG	0.4932	0.4962	0.6123
	BC	0.4984	0.4970	0.2671
	BCG	0.4990	0.4983	0.1489
90	ABC	0.9249	0.9226	0.2461
	AG	0.9590	0.9559	0.3244
	BC	0.9342	0.9331	0.1119
	BCG	0.9307	0.9294	0.1422

Table B.4.1.7: Application test – PMU F at S and PMU C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0958	0.0965	0.7333
	AG	0.0569	0.0599	5.2724
	BC	0.0914	0.0847	7.3255
	BCG	0.0933	0.0898	3.7814
50	ABC	0.5007	0.5008	0.0138
	AG	0.5200	0.4991	4.0210
	BC	0.5060	0.5005	1.0806
	BCG	0.5041	0.5010	0.6236
90	ABC	0.9258	0.9695	4.7144
	AG	0.9847	0.9597	2.5409
	BC	0.9413	0.9364	0.5148
	BCG	0.9352	0.9331	0.2331

Table B.4.1.8: Application test – PMU F at S and PMU A-1 at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0947	0.0968	2.1965
	AG	0.0603	0.0605	0.4034
	BC	0.0853	0.0862	0.9521
	BCG	0.0890	0.0891	0.2085
50	ABC	0.5006	0.5005	0.0099
	AG	0.5045	0.5012	0.6398
	BC	0.5005	0.5005	0.0125
	BCG	0.5005	0.5006	0.0997
90	ABC	0.9257	0.9244	0.1436
	AG	0.9705	0.9608	0.9994
	BC	0.9364	0.9363	0.0074
	BCG	0.9317	0.9318	0.0091

Table B.4.1.9: Application test – PMU F at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0943	0.0955	1.3067
	AG	0.0547	0.0594	8.3727
	BC	0.0840	0.0846	0.6802
	BCG	0.0882	0.0887	0.6188
50	ABC	0.4997	0.4997	0.0002
	AG	0.4988	0.4998	0.1907
	BC	0.4994	0.4985	0.1855
	BCG	0.4996	0.4998	0.0554
90	ABC	0.9256	0.9245	0.1292
	AG	0.9650	0.9593	0.5883
	BC	0.9356	0.9350	0.0648
	BCG	0.9315	0.9313	0.0296

B.2.2: PMUs and Time Synchronization Clocks

The estimated locations under different fault scenarios using reference phasors and DUT's phasors respectively, and the location errors for each configuration of PMUs and time synchronization clocks at two ends are given in the following tables.

Table B.4.2.1: Application test – PMU C: Clock A at S and Clock C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0953	0.0946	0.7135
	AG	0.0561	0.0578	2.9858
	BC	0.0853	0.0820	3.8954
	BCG	0.0895	0.0867	3.0787
50	ABC	0.4995	0.4986	0.1587
	AG	0.4991	0.4951	0.8065
	BC	0.4994	0.4972	0.4385
	BCG	0.4996	0.4979	0.3317
90	ABC	0.9243	0.9672	4.6419
	AG	0.9644	0.9551	0.9675
	BC	0.9342	0.9323	0.2020
	BCG	0.9300	0.9297	0.0250

Table B.4.2.2: Application test – PMU C: Clock A at S and Clock D at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0954	0.0947	0.7100
	AG	0.0564	0.0581	3.0470
	BC	0.0855	0.0819	4.1868
	BCG	0.0899	0.0868	3.3942
50	ABC	0.4996	0.4986	0.1879
	AG	0.4993	0.4952	0.8236
	BC	0.4995	0.4975	0.3787
	BCG	0.4996	0.4980	0.3319
90	ABC	0.9243	0.9672	4.6390
	AG	0.9645	0.9551	0.9815
	BC	0.9342	0.9326	0.1699
	BCG	0.9300	0.9298	0.0216

Table B.4.2.3: Application test – PMU C: Clock C at S and Clock A at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0956	0.0945	1.1066
	AG	0.0569	0.0577	1.4202
	BC	0.0856	0.0816	4.6239
	BCG	0.0896	0.0870	2.9197
50	ABC	0.4998	0.4987	0.2338
	AG	0.4989	0.4948	0.8164
	BC	0.4994	0.4976	0.3570
	BCG	0.4996	0.4978	0.3545
90	ABC	0.9244	0.9672	4.6284
	AG	0.9640	0.9545	0.9526
	BC	0.9342	0.9318	0.2540
	BCG	0.9301	0.9296	0.0501

Table B.4.2.4: Application test – PMU C: Clock C at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0953	0.0946	0.8059
	AG	0.0561	0.0577	3.0363
	BC	0.0854	0.0819	3.9795
	BCG	0.0895	0.0867	3.0658
50	ABC	0.4997	0.4986	0.2062
	AG	0.4991	0.4949	0.8464
	BC	0.4994	0.4975	0.3888
	BCG	0.4996	0.4978	0.3501
90	ABC	0.9243	0.9672	4.6332
	AG	0.9642	0.9550	0.9645
	BC	0.9342	0.9318	0.2526
	BCG	0.9301	0.9296	0.0561

Table B.4.2.5: Application test – PMU C: Clock C at S and Clock D at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0954	0.0947	0.8024
	AG	0.0564	0.0581	3.0971
	BC	0.0855	0.0819	4.2705
	BCG	0.0899	0.0868	3.3814
50	ABC	0.4999	0.4987	0.2353
	AG	0.4993	0.4950	0.8635
	BC	0.4995	0.4978	0.3290
	BCG	0.4996	0.4978	0.3504
90	ABC	0.9243	0.9672	4.6303
	AG	0.9644	0.9550	0.9785
	BC	0.9343	0.9322	0.2205
	BCG	0.9302	0.9297	0.0527

Table B.4.2.6: Application test – PMU C: Clock D at S and Clock A at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0956	0.0946	1.0638
	AG	0.0566	0.0573	1.1666
	BC	0.0855	0.0815	4.6111
	BCG	0.0895	0.0869	2.9376
50	ABC	0.4998	0.4986	0.2466
	AG	0.4985	0.4947	0.7652
	BC	0.4994	0.4972	0.4288
	BCG	0.4995	0.4978	0.3434
90	ABC	0.9245	0.9673	4.6351
	AG	0.9635	0.9547	0.9104
	BC	0.9341	0.9324	0.1788
	BCG	0.9300	0.9296	0.0457

Table B.4.2.7: Application test – PMU C: Clock D at S and Clock C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0953	0.0946	0.7630
	AG	0.0558	0.0574	2.7870
	BC	0.0852	0.0819	3.9657
	BCG	0.0894	0.0866	3.0838
50	ABC	0.4997	0.4986	0.2190
	AG	0.4987	0.4947	0.7952
	BC	0.4994	0.4970	0.4606
	BCG	0.4996	0.4978	0.3391
90	ABC	0.9244	0.9673	4.6400
	AG	0.9636	0.9547	0.9222
	BC	0.9341	0.9324	0.1775
	BCG	0.9300	0.9295	0.0518

Table B.4.2.8: Application test – PMU C: Clock D at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0954	0.0947	0.7595
	AG	0.0561	0.0577	2.8493
	BC	0.0854	0.0818	4.2571
	BCG	0.0898	0.0867	3.3997
50	ABC	0.4998	0.4986	0.2481
	AG	0.4989	0.4949	0.8123
	BC	0.4995	0.4974	0.4009
	BCG	0.4996	0.4979	0.3394
90	ABC	0.9244	0.9673	4.6370
	AG	0.9638	0.9548	0.9363
	BC	0.9342	0.9328	0.1453
	BCG	0.9301	0.9296	0.0483

Table B.4.2.9: Application test – PMU A-1: Clock A at S and Clock C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0945	0.0964	1.9994
	AG	0.0547	0.0599	9.5322
	BC	0.0845	0.0772	8.6500
	BCG	0.0888	0.0888	0.0078
50	ABC	0.4998	0.4987	0.2086
	AG	0.4989	0.4966	0.4556
	BC	0.4995	0.4989	0.1060
	BCG	0.4995	0.4990	0.1083
90	ABC	0.9250	0.9231	0.2032
	AG	0.9645	0.9568	0.7934
	BC	0.9348	0.9342	0.0717
	BCG	0.9308	0.9299	0.0976

Table B.4.2.10: Application test – PMU A-1: Clock A at S and Clock D at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0946	0.0965	1.9532
	AG	0.0543	0.0604	11.098
	BC	0.0846	0.0847	0.0948
	BCG	0.0889	0.0887	0.2095
50	ABC	0.4997	0.4993	0.0732
	AG	0.4987	0.4977	0.1996
	BC	0.4994	0.4988	0.1108
	BCG	0.4995	0.4990	0.1030
90	ABC	0.9250	0.9226	0.2591
	AG	0.9645	0.9575	0.7279
	BC	0.9349	0.9343	0.0614
	BCG	0.9308	0.9299	0.0992

Table B.4.2.11: Application test – PMU A-1: Clock C at S and Clock A at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0938	0.0946	0.8528
	AG	0.0547	0.0633	15.669
	BC	0.0846	0.0850	0.3520
	BCG	0.0889	0.0881	0.8904
50	ABC	0.5002	0.4988	0.2762
	AG	0.4988	0.4983	0.1085
	BC	0.4993	0.4971	0.4525
	BCG	0.4995	0.4997	0.0416
90	ABC	0.9251	0.9224	0.2825
	AG	0.9654	0.9445	2.1641
	BC	0.9350	0.9357	0.0831
	BCG	0.9308	0.9305	0.0353

Table B.4.2.12: Application test – PMU A-1: Clock C at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0941	0.0958	1.8065
	AG	0.0547	0.0630	15.157
	BC	0.0846	0.0775	8.3449
	BCG	0.0888	0.0881	0.8575
50	ABC	0.4997	0.4983	0.2904
	AG	0.4988	0.4972	0.3352
	BC	0.4994	0.4970	0.4714
	BCG	0.4995	0.4997	0.0289
90	ABC	0.9251	0.9230	0.2283
	AG	0.9654	0.9438	2.2358
	BC	0.9349	0.9355	0.0637
	BCG	0.9307	0.9305	0.0299

Table B.4.2.13: Application test – PMU A-1: Clock C at S and Clock D at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0934	0.0942	0.8565
	AG	0.0543	0.0634	16.766
	BC	0.0847	0.0849	0.2297
	BCG	0.0889	0.0881	0.9400
50	ABC	0.4997	0.4989	0.1552
	AG	0.4987	0.4983	0.0755
	BC	0.4993	0.4970	0.4611
	BCG	0.4995	0.4997	0.0397
90	ABC	0.9250	0.9224	0.2802
	AG	0.9654	0.9447	2.1482
	BC	0.9350	0.9356	0.0763
	BCG	0.9308	0.9305	0.0308

Table B.4.2.14: Application test – PMU A-1: Clock D at S and Clock A at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0946	0.0964	1.8502
	AG	0.0547	0.0601	9.8725
	BC	0.0846	0.0848	0.1693
	BCG	0.0888	0.0887	0.1934
50	ABC	0.5002	0.4993	0.1844
	AG	0.4988	0.4976	0.2366
	BC	0.4994	0.4991	0.0678
	BCG	0.4995	0.4990	0.1158
90	ABC	0.9251	0.9224	0.2973
	AG	0.9652	0.9573	0.8207
	BC	0.9350	0.9343	0.0712
	BCG	0.9308	0.9298	0.1123

Table B.4.2.15: Application test – PMU A-1: Clock D at S and Clock C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0945	0.0964	1.9533
	AG	0.0547	0.0598	9.3826
	BC	0.0846	0.0772	8.6880
	BCG	0.0888	0.0887	0.0399
50	ABC	0.4997	0.4987	0.1953
	AG	0.4989	0.4966	0.4604
	BC	0.4995	0.4991	0.0805
	BCG	0.4996	0.4990	0.1232
90	ABC	0.9251	0.9230	0.2350
	AG	0.9651	0.9567	0.8732
	BC	0.9349	0.9341	0.0881
	BCG	0.9308	0.9298	0.1053

Table B.4.2.16: Application test – PMU A-1: Clock D at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0946	0.0965	1.9073
	AG	0.0543	0.0602	10.947
	BC	0.0847	0.0847	0.0461
	BCG	0.0889	0.0887	0.2441
50	ABC	0.4997	0.4994	0.0631
	AG	0.4987	0.4977	0.2039
	BC	0.4994	0.4990	0.0850
	BCG	0.4995	0.4989	0.1178
90	ABC	0.9251	0.9224	0.2951
	AG	0.9652	0.9574	0.8080
	BC	0.9350	0.9343	0.0778
	BCG	0.9308	0.9298	0.1068

Table B.4.2.17: Application test – PMU F: Clock A at S and Clock C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0942	0.0951	0.9772
	AG	0.0545	0.0581	6.7061
	BC	0.0842	0.0844	0.3254
	BCG	0.0883	0.0884	0.1211
50	ABC	0.4997	0.4998	0.0080
	AG	0.4988	0.4986	0.0370
	BC	0.4995	0.4985	0.1960
	BCG	0.4996	0.4993	0.0520
90	ABC	0.9256	0.9243	0.1511
	AG	0.9649	0.9595	0.5602
	BC	0.9356	0.9350	0.0694
	BCG	0.9315	0.9313	0.0212

Table B.4.2.18: Application test – PMU F: Clock A at S and Clock D at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0948	0.0955	0.7440
	AG	0.0549	0.0578	5.3845
	BC	0.0842	0.0845	0.3001
	BCG	0.0884	0.0883	0.0462
50	ABC	0.4999	0.4998	0.0080
	AG	0.4989	0.4988	0.0089
	BC	0.4995	0.4986	0.1852
	BCG	0.5000	0.4996	0.0726
90	ABC	0.9256	0.9244	0.1353
	AG	0.9649	0.9600	0.5085
	BC	0.9356	0.9342	0.1448
	BCG	0.9316	0.9311	0.0553

Table B.4.2.19: Application test – PMU F: Clock C at S and Clock A at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0942	0.0953	1.1100
	AG	0.0549	0.0598	8.9012
	BC	0.0841	0.0848	0.0871
	BCG	0.0882	0.0892	1.0826
50	ABC	0.4997	0.4996	0.0302
	AG	0.4993	0.4990	0.0619
	BC	0.4994	0.4993	0.0160
	BCG	0.4996	0.4995	0.0235
90	ABC	0.9247	0.9255	0.0943
	AG	0.9601	0.9648	0.4935
	BC	0.9349	0.9354	0.0477
	BCG	0.9309	0.9313	0.0433

Table B.4.2.20: Application test – PMU F: Clock C at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0942	0.0950	0.7804
	AG	0.0546	0.0586	7.2418
	BC	0.0847	0.0842	0.5162
	BCG	0.0888	0.0883	0.5845
50	ABC	0.4998	0.4997	0.0219
	AG	0.4990	0.4981	0.1658
	BC	0.4995	0.4993	0.0265
	BCG	0.4995	0.4991	0.0840
90	ABC	0.9245	0.9256	0.1162
	AG	0.9602	0.9647	0.4654
	BC	0.9353	0.9349	0.0523
	BCG	0.9310	0.9314	0.0350

Table B.4.2.21: Application test – PMU F: Clock C at S and Clock D at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0948	0.0954	0.5484
	AG	0.0551	0.0583	5.9182
	BC	0.0842	0.0847	0.4910
	BCG	0.0888	0.0884	0.4168
50	ABC	0.4998	0.4997	0.0220
	AG	0.4990	0.4983	0.1199
	BC	0.4995	0.4994	0.0158
	BCG	0.4998	0.4996	0.0407
90	ABC	0.9246	0.9255	0.1004
	AG	0.9647	0.9607	0.4135
	BC	0.9353	0.9342	0.1277
	BCG	0.9307	0.9314	0.0691

Table B.4.2.22: Application test – PMU F: Clock D at S and Clock A at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0942	0.0952	1.0212
	AG	0.0548	0.0607	10.601
	BC	0.0840	0.0844	0.5120
	BCG	0.0890	0.0882	0.9427
50	ABC	0.4997	0.4993	0.0765
	AG	0.4988	0.4987	0.0202
	BC	0.4994	0.4989	0.0897
	BCG	0.4995	0.4993	0.0260
90	ABC	0.9243	0.9255	0.1248
	AG	0.9598	0.9662	0.6598
	BC	0.9355	0.9356	0.0127
	BCG	0.9313	0.9311	0.0237

Table B.4.2.23: Application test – PMU F: Clock D at S and Clock C at R

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0942	0.0948	0.6915
	AG	0.0595	0.0546	8.9479
	BC	0.0842	0.0843	0.1575
	BCG	0.0883	0.0887	0.4447
50	ABC	0.4997	0.4994	0.0683
	AG	0.4988	0.4975	0.2481
	BC	0.4994	0.4989	0.1003
	BCG	0.4995	0.4988	0.1335
90	ABC	0.9255	0.9241	0.1467
	AG	0.9660	0.9600	0.6317
	BC	0.9355	0.9356	0.0081
	BCG	0.9313	0.9312	0.0154

Table B.4.2.24: Application test – PMU F: Clock D at both ends

Location (%)	Fault Type	Estimate by REF (%)	Estimate by DUT (%)	Error (%)
10	ABC	0.0948	0.0953	0.4602
	AG	0.0550	0.0592	7.6113
	BC	0.0842	0.0843	0.1322
	BCG	0.0884	0.0886	0.2770
50	ABC	0.4998	0.4994	0.0684
	AG	0.4988	0.4978	0.2021
	BC	0.4995	0.4990	0.0895
	BCG	0.4995	0.4995	0.0089
90	ABC	0.9242	0.9254	0.1310
	AG	0.9661	0.9605	0.5803
	BC	0.9348	0.9355	0.0673
	BCG	0.9309	0.9313	0.0495

Revision History

Date	Version	Description	By
04/02/2012	1.0	Original draft	M. Kezunovic Y. Guan
04/30/2012	2.0	Dr. Sprintson added his part section 3.5 “Interoperability of PMUs, PDCs and Communication Network”	A. Sprintson M. Yan
05/07/2012	2.1	Dr. Abur added his part section 4.2 “State Estimation”	A. Sprintson L. Zhang
06/01/2012	3.0	Merged all parts into one complete report	M. Kezunovic Y. Guan
07/01/2012	3.1	Add conclusion part	M. Kezunovic Y. Guan
07/07/2012	3.2	Modify the executive summary and conclusion	Y. Guan
07/19/2012	3.3	Updated Executive summary and publication list.	M. Kezunovic Y. Guan
07/20/2012	3.4	Updated Executive summary	M. Kezunovic Y. Guan
08/10/2012	4.0	Modified based on comments	M. Kezunovic Y. Guan