METHODOLOGY AND TOOLS FOR FIELD TESTING OF SYNCHROPHASOR SYSTEMS

A Thesis

by

CHRISTOPH SEIDL

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Chair of Committee,	Mladen Kezunovic
Committee Members,	Thomas Overbye
	Steve Liu
	Srinivas Shakkottai
Head of Department,	Miroslav Begovic

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ABSTRACT

The electrical power grid, as one of today's most critical infrastructures, requires constant monitoring by operators to be aware of and react to any threats to the system's condition. With control centers typically located far away from substations and other physical grid equipment, field measurement data forms the basis for a vast majority of control decisions in power system operation. For that reason, it is imperative to ensure the highest level of data integrity as erroneous data may lead to inappropriate control actions with potentially devastating consequences. Performance of one of the most advanced monitoring systems, the synchrophasor system, is the focus of this thesis.

This research will look at testing techniques used for performance assessment of synchrophasor system performance in the field. Existing methods will be reviewed and evaluated for deficiencies in capturing system performance regarding data quality. The focus of this work will be on improving synchrophasor data quality, by introducing new testing methodology that utilizes a nested testing approach for end-to-end testing in the field using a portable test set and associated software tools. The capability of such methods and these tools to fully characterize and evaluate the performance of synchrophasor systems in the field will be validated through implementation in a large-scale testbed.

The purpose of this research is to specify, develop and implement a methodology and associated tools for field-testing of synchrophasor systems. To this day, there is no dedicated standard for field-testing of synchrophasor systems. This resulted in an inability to define widely accepted procedures to detect deterioration of system performance due to poor data quality and caused communication failures, unacceptable device and subsystem accuracy, or loss of calibration. This work will demonstrate how the new approach addresses the mentioned performance assessment gap.

The feasibility of implementation of the proposed test procedures will be demonstrated using different test system configurations available in a large-scale testbed. The proposed method is fully leveraging the benefits of a portable device specifically developed for field-testing, which may be used for improvement of commissioning, maintenance and troubleshooting tests for existing installations. Use Cases resulting from this work will illustrate the practical benefits of the proposed methodology and associated tools.

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NOMENCLATURE

BPA	Bonneville Power Administration
DOE	Department of Energy
DUT	Device Under Test
EMS	Energy Management System
FTS	Field Test Set
GLONASS	GLObal NAvigation Satellite System
GPS	Global Positioning System
ICAP	IEEE Conformity Assessment Program
IRIG-B	Inter Range Instrumentation Group Time Code – Format B
IT	Instrument Transformer
NASPI	North American SynchroPhasor Initiative
NIST	National Institute of Standards and Technology
PDC	Phasor Data Concentrator
PMU	Phasor Measurement Unit
PNNL	Pacific Northwest National Laboratory
PPS	Pulse Per Second
PSTT	Performance and Standards Task Team
ROCOF	Rate Of Change Of Frequency
SCADA	Supervisory Control And Data Acquisition
TEES	Texas Engineering Experiment Station
THD	Total Harmonic Distortion

TI	Timing Intrusion
TTE	Total Time Error
TUR	Test Uncertainty Ratio
TVE	Total Vector Error

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1. INTRODUCTION

1.1. Overview of Power System Monitoring Importance

The electrical power grid, as one of today's most critical infrastructures, requires constant monitoring by operators to be aware of and react to any threats to the system's condition. With control centers located far from sub stations and other points of interest, data measured and monitored in the field conclude the basis for all control decisions in the power system. For that reason, it is imperative to ensure the highest level of data integrity as erroneous data may lead to inappropriate control actions with potentially devastating consequences.

As the power system is constantly exposed to different kinds of disturbances, it is important to capture data throughout the wide-ranging system to counteract the potentially severe impacts [1]. Monitoring not only aims at withstanding disturbances and providing reliable continuous operation, it also aims at protecting the power apparatus, whose failure has much more severe impacts than temporary outages [2].

Analysis of events such as the severe blackout in North America that affected parts of the US and Canada on August 14th, 2003 [3], has shown that the design of the Energy Management System (EMS) is inadequate for monitoring heavily dynamic power system behavior. This created a need for improved monitoring technology, which resulted in efforts to promote synchrophasor technology. The North American SynchroPhasor Initiative (NASPI) was the leading force in improving "power system reliability and visibility through wide area measurements and control" through synchrophasor technology [4].

1.2. SCADA vs. Synchrophasor Systems

According to [5] “the accurate time resolution of synchrophasor measurements allows unprecedented visibility into system conditions, including rapid identification of details such as oscillations and voltage instability that cannot be seen from SCADA measurements”. With reporting rates of up to 120 synchronized data frames per second, synchrophasor technology has a superior role in monitoring and analysis of Power Systems over the legacy SCADA system that only reports every 4-6 seconds. While the SCADA system also monitors other information, such as breaker states that do not require such frequent updating, synchrophasor technology has already redeemed SCADA for monitoring of voltage, current and frequency of the power system. Using synchrophasors not only helps improving the monitoring aspect of power systems, but also helps improving models through PMU data validation, as shown for a generator model in the Bonneville Power Administration [6].

1.3. Monitoring System Performance During Emergency in Power Systems

The merit of synchrophasor data certainly lies within the improved dynamic capabilities over the SCADA system. Especially its large-scale compatibility due to synchronization of the PMUs is incredibly helpful concerning analyzing dynamic events, such as faults. While some work has been done to analyze synchrophasors under fault conditions or power swing, the important issue of monitoring the actual system performance and therefore ensuring data integrity during such events has not been properly addressed so far. One of the few attempts to characterizing such behavior using replayed fault waveforms is described in this thesis with results presented in chapter 6.1.

1.4. Importance of Field Testing

Many previous efforts are focused on testing and evaluating synchrophasor systems or components in a controlled laboratory environment, which will be elaborated later in the review of prior work. While these efforts are very important to uphold and improve the design quality, the methods and tools are very often not feasible for field environments. Field-testing imposes special requirements on the testing methodology: tools portability, automation of test procedures, and ease of operation suited for technicians. It is very important to perform tests of a system in the field after being installed and fully capture any characteristics specific to the non-controlled field environment. For that reason, it is necessary to develop tools and methods that work around these constraints, such as the Field Test Set and the end-to-end methods presented and used in this thesis.

Another important aspect is the security and troubleshooting aspect of a setup that requires minimum impact and downtime for testing and troubleshooting purposes, while maintaining a great level of accuracy. Many issues like network and security constraints or compatibility of other substation equipment are likely to be different from what is found in a laboratory environment, which adds to the special needs when evaluating field equipment or installations.

1.5. Thesis Organization

Chapter 1 provides an introduction to the importance and general matter of power system monitoring. The new synchrophasor technology is put in comparison to the legacy SCADA system. It also elaborates on the field-testing importance for synchrophasor systems.

Chapter 2 gives an introduction to the background of synchrophasor systems and provides requirements for field testing techniques and evaluation criteria.

Chapter 3 looks at previous work and establishes the state-of-the-art, focusing on synchrophasor system development and analysis, and evaluating their impact on the testing requirements. Shortcomings are analyzed and outlined for evaluation in this thesis.

Chapter 4 describes the importance and key problems this thesis is trying to address and resolve. It poses a hypothesis that if type (design) and application tests, as well as commissioning, maintenance and troubleshooting tests are performed on synchrophasor systems in the field, then the synchrophasor stream and application output will be more accurate and reliable, which improves system quality and helps ensure continuous power system operation.

Chapter 5 gives a detailed explanation of synchrophasor system evaluation methods using type and application tests. Both existing and novel methods are presented. This chapter also presents testing tools developed for evaluating synchrophasor systems in the field.

Chapter 6 gives further input on how to apply the methods and tools introduced in chapter 5 by providing step-by-step instructions for end-to-end testing in the field.

Chapter 7 provides results to illustrate the feasibility and credibility of the proposed methods and tools.

Chapter 8 summarizes the work and contributions of this thesis and outlines open issues out of the scope of this thesis to be addressed in future work.

References quoted in the Thesis and list of papers published by the author are given at the end.

2. BACKGROUND

2.1. Synchrophasor Systems and Applications

According to the IEEE standard for synchrophasors [7] and its amendment [8], synchrophasors are time-synchronized measurements of so-called phasors. The units that are located in substations and perform these measurements are called Phasor Measurement Units (PMUs). They are using a reference time signal provided by a GPS/GNSS synchronized clock to sample voltage and current waveforms, and consequently calculate an estimate of the magnitude, frequency and phase angle from the waveform samples. They are used to create phasors that are then streamed to Phasor Data Concentrators (PDCs) located in the control center via specified protocols [9]. PDC performance requirements are specified in [10]. An example of an architecture of such a system is shown in Figure 1.

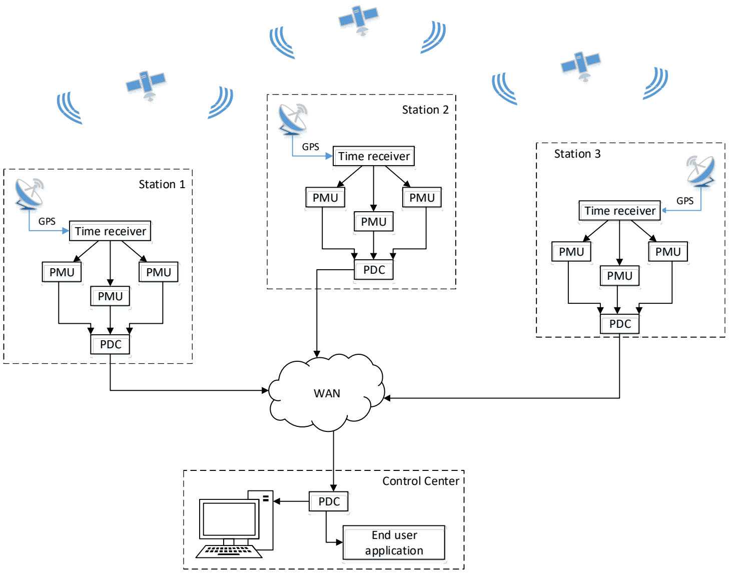

Figure 1: Synchrophasor System Example Architecture. Adapted with permission from [19].

Large deployment of interconnected PMUs provides phasor data streams as shown in Figure 2, which beneficially increases the observability as well as the visibility of Power System operations in the USA. The additional benefit of acquiring up to 120 data frames per second, as opposed to the existing Supervisory Control and Data Acquisition (SCADA) System that typically reports data every 4-6 seconds, gives synchrophasor technology a superior role in monitoring and analysis of Power Systems. This is one of the reasons for field deployment of PMUs in the USA increasing by a factor of 10 within the last 10 years, reaching well over 2,500 units installed so far [11]. Its functionality covers a wide range of applications that encompass, among others, Phase Angle Monitoring [12], Fault Location [13], Oscillation Detection [14], Wide Area Monitoring and Control [15], as well as Modeling Improvements [16]. Other applications for current and future uses are listed in [17].

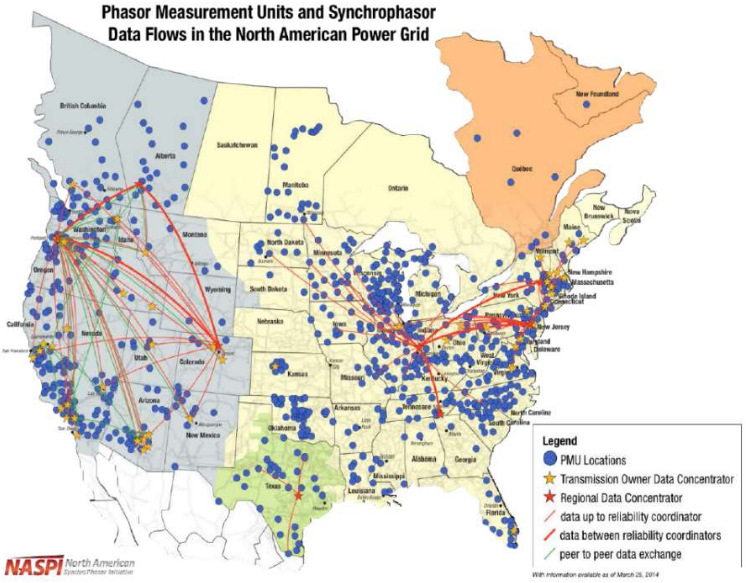

Figure 2: Synchrophasor Data Flow in the North American Power Grid. Reprinted from [11]

2.2. Phasor Representation

Phasor representation of waveforms is very commonly used in power systems to represent node voltages and line currents under the assumption of constant frequency or steady state for the time frame under consideration. A sinusoidal waveform is defined as follows [7]:

$$x(t) = Re\left(\sqrt{2}Xe^{j\omega t+\varphi}\right) = X_m \cos(\omega t + \varphi),$$

where the phasor X is a complex number:

$$X = |X|e^{j\varphi} = |X|\angle\varphi = |X|\cos(\varphi) + j|X|\sin(\varphi)$$

$$|X| = X_m/\sqrt{2}$$

The magnitude of a phasor is the RMS value of the waveform. The value of φ depends on the time scale, particularly where $t = 0$. It is important to note this phasor is defined for the angular frequency ω; evaluations with other phasors must be done with the same time scale and frequency.

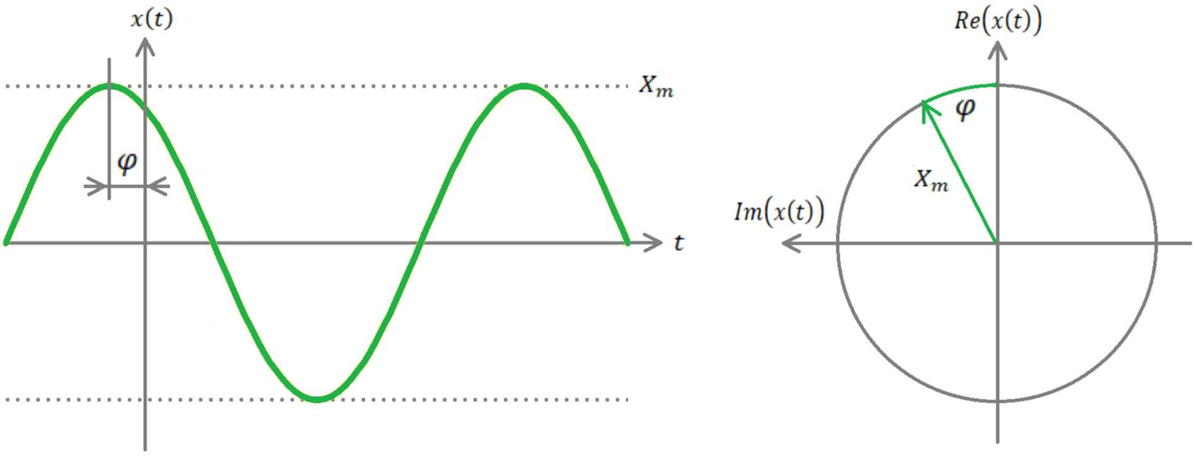

Figure 3: Waveform to phasor correlation

2.3. Sychrophasor Reference for PMU Characterization

According to the IEEE standard C37.118.1 [7], a reference system or calibration device for PMUs needs to meet national standards and perform with a *test uncertainty ratio* of four or better in comparison to the test requirements. The defined evaluation of Phasor Measurement Units (PMUs) uses a metric called Total Vector Error (TVE) that uses a ratio of the output synchrophasor stream to an expected reference. This reference consists of the test signals described in the standard, which defines the composition of generated analog input waveforms provided to the input of the PMU under test. An IEEE working group worked on the *Definition of Accurate Reference Synchrophasors for Static and Dynamic Characterization of PMUs* [18]. In a laboratory environment, this can be achieved by establishing a calibrated reference system capable of providing highly accurate results for comparison. In the field where establishing and maintaining such a reference system is not feasible, this may be accomplished by using a portable test set featuring such capability. However, this functionality is currently not commercially available, which creates a need for such testing tools.

In this thesis, this concept of a reference will also be adopted for application tests. Application tests use signal replaying based on simulated or measured waveform data to recreate pre-defined waveform scenarios for testing the synchrophasor systems and respective applications. While there is no standard available for application tests, the prior knowledge of the waveform data will be leveraged and used as a reference for evaluation purposes. This requires synchronization with an accurate timing source to align the replayed waveforms with the reference data. Establishing a reference for application tests creates even bigger challenges based on the dynamic input data of certain applications. A reference system calibrated according to the standards [7]-[9] might not be able to capture the full range of input signals, which strengthens the call for new testing tools. This issue is addressed in this thesis by proposing methodology and tools novel to field-testing of synchrophasor systems.

2.4. Field Testing of PMUs and Synchrophasor Systems

While acceptance tests are typically performed in a controlled lab environment to ensure reproducible results when evaluating performance requirements of a device or module, field-testing aims at addressing the constraints and needs of setups in the field. Field-testing comprises commissioning, calibration, periodic maintenance, and troubleshooting tests. As mentioned in chapter 2.3, establishing a reference for testing in the field is extremely challenging and has not been properly addressed so far. This leaves current testing practices and tools with a limited ability to fully characterize and evaluate a synchrophasor system in the field, which is addressed in this thesis.

The status of field equipment and all its components when installed or after continued service for an extended period of time is typically unknown. In addition, some updates to the system may include adding new components or reconfiguring existing ones, causing slightly different base performance. For that reason, the field-testing methodology covers several different aspects:

- Commissioning Test

This test verifies the proper installation of a system and characterizes all its components to determine the connection status, detect anomalies in device and system behavior, and consequently establish a working environment for operation and future testing by addressing erratic behavior.

- Calibration

This form of testing is used to calibrate a system and its components to assert characteristic behavior, adjust variable control factors, and establish a reference for operation and future testing to optimize a systems performance. This test is typically performed after commissioning and before the system goes into production mode, and then again in regular intervals to ensure consistent system operation. It usually consists of a full suite of type and possibly application tests, and is performed in a controlled non-attack environment.

- In-field Test

Also referred to as a periodic maintenance test, it may be performed during normal operation or periodically recurring system maintenance sessions to ensure safe and reliable operation. This test is be used to re-evaluate a systems calibration status and detect any hidden anomalies by replaying and evaluating selected test scenarios, as well as comparing results with the initial calibration test results. This test predominantly uses type test waveforms to check for intrusions and system health but may entail application tests if needed.

- Troubleshooting Test

Being aware of a certain problem in the system, either by performing an In-field test or through another detection approach requires troubleshooting to resolve the problem. Using the same tools as for commissioning, calibration and periodic maintenance, the methodology and especially the replayed waveforms can be tailored to pinpoint the source and extent of erratic behavior. This aims to assess the problem and determine potential counter measures. The tests may entail both type and application signals.

2.5. Field Implementation of End-to-end and Nested Testing

To evaluate the end-to-end integrity of a synchrophasor system in the field, this thesis introduces the concept of nested testing for synchrophasor applications [19] and [20]. The idea of this testing methodology is to evaluate all components of a system layer by layer with a bottom up approach, as shown in Figure 4, using a portable test set.

Starting with the timing reference, i.e. GNSS clock receiver, the span of the test loop is gradually increased to include PMUs, PDCs, communications network and finally an end-user application. The mentioned papers [19] and [20] not only describe the development of a test methodology, but also the implementation of the portable modules as well as a calibration laboratory to determine the impact of erroneous behavior on a synchrophasor system using nested testing.

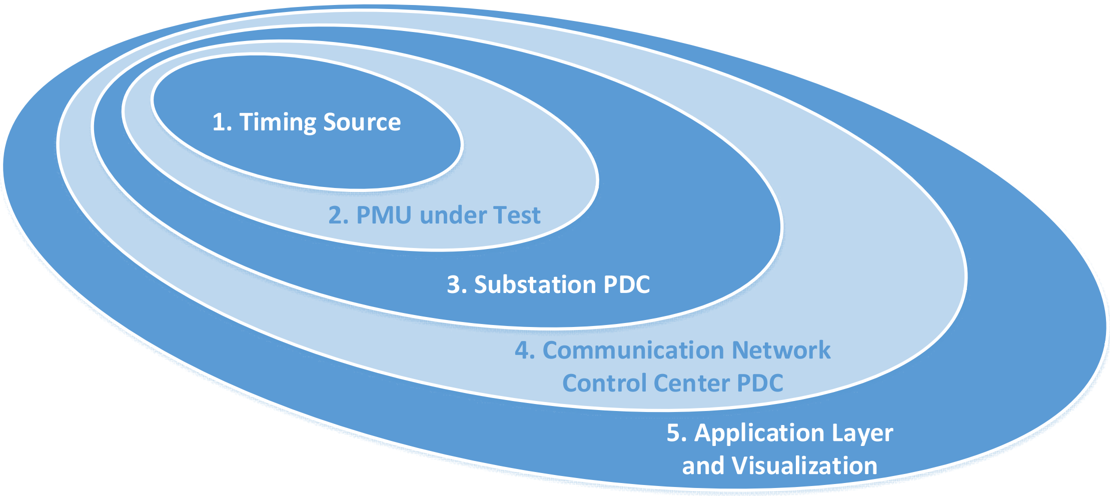

Figure 4: Nested testing strategy enabling End-to-End testing of synchrophasor system

2.6. Indicators of Irregular Synchrophasor Data

The goal of synchrophasor system testing procedures is to evaluate system's performance including its components, and to reveal potential indicators of irregular behavior. Some of the most common reasons for irregular behavior are as follows [19], [21]:

- Calibration: One or more modules in the system are poorly calibrated.
- Measurement: Erroneous PMU filter design or issues due to measurement channel.
- Communication: Latency, network congestion, or failure of communication nodes.
- Malfunctions: One or more modules in the system fails and show unexpected behavior.
- Synchronization Error: PMU is not properly synchronized with a timing source.
- Intrusion: Malicious attacks may affect system behavior.
- Clock Drift: Drifting of the internal clock may lead to loss of synchronization.

3. PRIOR WORK

3.1.Standardization

Over the years, a lot of standardization work was done to accelerate the development and use of synchrophasor systems. In 2005, an IEEE working group released the first version of the standard C37.118-2005 [22] specifying requirements for the use of synchrophasors for power systems and introducing the concepts of compliance tests, Total Vector Error and the "Absolute Phasor" referenced to UTC. This document replaced the original standard IEEE Std. 1344-1995, that was reaffirmed in 2001. In 2011, the C37.118-2005 standard evolved into the two standards C37.118.1 [7] and C37.118.2 [9], covering measurement provisions and data communication, respectively. Further test methodology clarification was provided, the testing concepts were expanded, and dynamic tests have been introduced. Furthermore, two performance classes were introduced: 1) P-class (Protection), intended for applications requiring fast response and no explicit filtering requirements, and 2) M-class (Measurement), intended for less time-sensitive applications that may be affected by aliasing, which implies specific filtering performance. This often affects specification of a desirable PMUs dynamic response. In 2013, efforts to improve synchrophasor performance resulted in a *Guide for Phasor Data Concentrator Requirements for Power Systems* [10]. In 2014, the standard C37.118.1 was amended with C37.118.1a [8] to modify selected performance requirements. This relaxed some constraints that were deemed unrealistic, especially regarding Rate Of Change Of Frequency (ROCOF) errors, as computational methods for interaction between phasor, frequency and ROCOF were not developed well enough at the time of publication.

3.2. Lab Implementation of Standardized Tests

Based on the requirements of the aforementioned standards, there have been some developments of calibration laboratories, incorporating the standardized form of testing. In a joint effort, the Bonneville Power Administration (BPA) and Pacific Northwest National Laboratory (PNNL) published their work on standardized testing in 2006 [17]. The used standardized testing approach for PMUs was creating waveform data in COMTRADE format from simulation data and replaying it synchronously to a PMU using a commercial test set. With that method, the used test set was not able to generate the analog waveforms accurate enough to fully characterize the PMU under test. In 2007, G. Stenbakken, working for the National Institute of Standards and Technology (NIST), developed a dynamic PMU performance measurement system [24]. Furthermore, an analysis model was proposed. The system demonstrated the necessary accuracy to determine dynamic errors in PMU measurement quantities, such as TVE and *Rate of Change of Frequency* (ROCOF). In the same year the North American Synchrophasor Initiative (NASPI) Performance and Standards Task Team (PSTT) published two integral documents, [25] and [26], with the intent to cover instrument transformers used by PMUs, which improved the team's earlier work [27] and [28], as elaborated in [29]. The first document being a guide for *PMU System Testing and Calibration*, featuring a multitude of test descriptions to be performed on PMUs, such as conformance, performance, interoperability and acceptance tests. The second document elaborates on impacts on phasor measurements caused by instrumentation channels. While this work has provided some good suggestions and insights to PMU testing, it does not address comprehensive testing of the entire synchrophasor system and its operation in the field. In a separate effort, a working group provided a *Definition of Accurate*

Reference Synchrophasors for Static and Dynamic Characterization of PMUs [18], which helped create a better understanding of synchrophasor references for testing.

In 2012 and 2013 NIST published papers [30] and [31], featuring the development of a PMU calibration system with an estimated uncertainty of 0.05%, which was a major improvement to the setup used in 2007. Early efforts to create test environments for assessing the dynamic test requirements of the standard amendment [8] were presented in [32], but failed to fully exploit the level of anticipated accuracy required by the standard in their tests. A joint effort of NIST with the IEEE Conformity Assessment Program (ICAP) later published the Synchrophasor Measurement Test Suite Specification Guide [33], which developed a thorough procedure and guidelines for performing PMU certification tests. That document provided requirements for equipment used for PMU testing, measurements made by PMU test equipment and reporting of measurements in a controlled laboratory environment. It still does not address the use and calibration of equipment in a field environment. The greater level of detail than the standard for PMU performance, and the specification of test procedures, as well as calculation and test implementation are targeting potential ambiguities in the standard. These guidelines were followed in an effort to develop a PMU calibrator at the Texas Engineering Experiment Station (TEES) at Texas A&M University. The TEES calibration system was evaluated and calibrated by NIST in 2018 and will serve as a reference for the measurements and tests performed throughout this Thesis. The importance of the impact of Instrument Transformers (IT) on the calibration of synchronized measurement systems was emphasized in [34], which claimed to be a benchmark for the IT+PMU chain characterization. While this part focuses on including ITs into the test loop, the impact of the PMU design on the synchrophasor output would be represented better by bypassing both instrument and auxiliary transformers for calibrating PMU systems through creation of low-level test signals, as mentioned in [19].

3.3. Guidelines for Non-Standardized Tests

Other work focused on providing guidelines and sharing early experiences accumulated by practitioners. The IEEE Guide for Synchronization, Calibration, Testing, and Installation of PMUs for Power System Protection and Control C37.242 [35] gathers helpful information on installing and testing PMUs and provides a practical guide for that purpose. The same topics have also been addressed in earlier published documents such as NASPIs' *A Guide for PMU Installation, Commissioning and Maintenance* (2006) [36] and [37], or the *PMU System Testing and Calibration Guide* (2007) [38]. In an effort to verify interoperability and application performance of PMUs, PMU-enabled IEDs and PDCs, different groups tested devices from multiple vendors and in collaboration with industry helped improve detected interoperability issues [33], [34].

The work referenced above is based on the assumption that the signals observed by the PMU are sinusoidal. It specifies accuracy thresholds that need to be met under, at least near-sinusoidal conditions. These assumptions may not always be correct under power system transients such as the ones generated during power system fault conditions. NASPI's document titled *A report on Using PMU Data Under Fault Conditions* that is currently under a revision, elaborates on the use of PMU data under fault conditions and provides insights into the applicability of the standardized requirements imposed on the PMUs. According to that report, a large factor in the PMUs ability to characterize the input waveforms under fault conditions is the length of the data window of the sampled data considered by the PMU algorithm. While longer windows, i.e. 2-10 cycles, were less susceptible to noise and performed better for near steady state signals, the expected values deviated more from the estimated values than for smaller window size. In the report, this was demonstrated by comparing analog waveform data captured by a DFR to waveform signals reconstructed from PMU phasors corresponding to the same input. Decreasing the data window size, however, seemed to result in a lack of meaning for anything other than waveform reconstruction, which makes the accuracy measures imposed by the standard irrelevant for PMU operation under fault conditions. This knowledge can be used for fault detection purposes by leveraging information about the "Goodness of Fit" metric and shows the importance of such evaluations in the field. The general issue of having a trade-off between phasor estimation quality and dynamic is recognized but not fully addressed in the C37.118.1 standard by introducing performance classes, as mentioned at the beginning of this chapter. This discussion provides valuable considerations as to how a system can be tuned to an application, which is especially useful for application tests corresponding to dynamic behavior. The transfer and application of these insights in field-testing has not been addressed so far.

3.4. Tools and Methodologies for Synchrophasor System Performance Assessment

A practical approach to PMU testing using a real time simulator for large-scale power system simulation was introduced in [41]. The development of a smart grid test bed, as well as applications in PMU and PDC testing using real time simulators is further discussed in [42]. A more recent publication [43] analyzed and characterized uncertainty contributions in a high-accuracy PMU validation system that used a similar methodology and hardware setup as earlier work [30]-[33]. This identified potential uncertainty contributors to be considered when establishing laboratory setups for synchrophasor calibration, but also confirmed the effectiveness of the used hardware and setup.

The work presented in [44] uses multilevel end-to-end testing to asses synchrophasor measurements during faults. The presented test framework was developed to incorporate type tests, application tests and end-to-end tests. This first step towards comprehensive testing of synchrophasor systems was designed for laboratory environments and validated based on real time simulator data. However, this work is not directly applicable to field applications, which is a critical issue that needs to be addressed.

3.5. Conclusions

To summarize the analysis in this chapter, there are standards available to define PMU design, PDC behavior, and synchrophasor data transfer but these standards only focus on their respective areas of operation. Previous work has mainly focused on type test waveforms that were defined to evaluate PMU design performance. First advances towards more comprehensive testing methods, including end-to-end testing, were limited to controlled laboratory environments. The analysis has also shown that testing tools for more comprehensive tests are not readily available, nor feasible for field-testing since they rely heavily on simulated waveforms rather than actual field data. This creates a need for end-to-end testing methods and tools to evaluate the overall system performance of interconnected synchrophasor systems in the field environment. Additionally, new methods and tools for application testing in the field are needed to evaluate the performance of existing systems up to the end-user application level more accurately and realistically.

4. PROBLEM STATEMENT

4.1. State of the Art

4.1.1. Performance issues

With synchrophasor systems constituting an integral part of power system monitoring and control, the goal is to provide highly accurate phasor data to system operators. Besides making sure the PMUs meet necessary accuracy requirements, this entails ensuring the highest level of data quality and integrity for all relevant operational data received in the control center.

Based on the nature of phasor estimation techniques it is not possible to capture power system dynamic behavior in full. With the right test methodology, however, it can be determined how well dynamic behavior is represented in a specific setup and what impact it imposes on an application. Unfortunately, the available standards and guides associated with synchrophasor systems are not yet formulated to characterize such impacts, which causes a lack of commercially available testing tools appropriate for field-testing.

4.1.2. Existing standards

The existing standards and guides are aimed at defining the design performance requirements for Phasor Measurement Units (PMUs), Phasor Data Concentrators (PDCs), and associated communications [7]-[10]. These standards are introducing design tests also called type test aimed at characterizing components of the synchrophasor system according to the design requirements stated in the standards. For PMUs, this is done by defining a suite of steady state and dynamic test waveforms, as shown in Table 1, and evaluating the PMUs ability to replicate the characteristics of these replayed waveforms.

Table 1: Listing of defined type tests. Adapted from [7]

	Influence Quantity	Influence Range		Reference Condition
		M-Class	P-Class	
Steady State Tests	Frequency Range	± 2.0 Hz for $F_S < 10$ $\pm {F_S}/{5}$ for $10 \leq F_S < 25$ ± 5.0 Hz for $F_S \geq 25$	± 2.0 Hz	$F_{nominal}$
	Voltage Magnitude	10% to 120% rated	80% to 120% rated	100% rated
	Current Magnitude	10% to 200% rated	10% to 200% rated	100% rated
	Phase Angle	$\pm\pi$ radians	$\pm\pi$ radians	Const.
	Harmonic Distortion	10%, each harmonic up to 50th	1%, each harmonic up to 50th	<0.2% THD[1]
	Out-of-Band Interference	10% of signal magnitude for $F_S \geq 10$, No requirement for $F_S < 10$	N/A	<0.2% of signal magnitude
Dynamic Tests	Measurement Bandwidth	Modulation Frequency 0.1 to min(${F_S}/{5}$,5Hz)	Modulation Frequency 0.1 to min(${F_S}/{10}$,2Hz)	100% rated magnitude
	Frequency Ramp	±MIN(${F_S}/{5}$,5Hz) @ ± 1.0 Hz/s	± 2.0 Hz @ ± 1.0 Hz/s	100% rated magnitude
	Magnitude Step Change	± 10 %		All nominal
	Angle Step Change	$\pm {\pi}/{18}$		All nominal

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[1] THD – Total Harmonic Distortion

4.1.3. Performance Issues not Covered by Existing Standards

The impact on end-user applications caused by design performance shortcomings is not covered by the standards and no methodology or testing tools exists to asses such impacts. Design test waveforms are not directly associated with any application but rather with an ability of PMUs to calculate phasors accurately under some know waveform imperfections. Introducing application tests consequently increases the ability to assess the application's performance.

4.2. Hypothesis

Analysis of state-of-the-art developments has shown that tools and methods specifically designed for evaluation of synchrophasor systems in the field are not readily available on the market. To address the restrictions of available equipment, combining the capabilities of a portable test set with improved test methods will revolutionize the aspect of field-testing.

The hypothesis posed in this thesis is that if type (design) and application tests, as well as commissioning, maintenance and troubleshooting tests are performed on synchrophasor systems in the field, then the synchrophasor stream and application output will be more accurate and reliable, which improves system quality and helps ensure continuous power system operation. This can be achieved using improved methodology and a portable test set, and features several different aspects:

- Using a portable Field Test Set (FTS), described in this thesis, makes field-testing of synchrophasor systems accessible by addressing the feasibility issues of established laboratory methods. Its use of small signal testing is expected to achieve more accurate results while also making it feasible to deploy in a field environment.
- The prevailing need for enhanced end-to-end testing methods can be addressed with a nested end-to-end testing scheme presented in this thesis. This Thesis poses a

Hypothesis that performing nested end-to-end tests enables calibration of individual modules in the field system while evaluating the end-to-end system performance. It is also expected to detect and locate potential anomalies from the timing source to the end-user application, which increases its functionality over existing methods.

- A network based nested testing approach will further improve the concept of field testing by enabling parallel evaluation of all nested levels, which will improve the critical aspect of down-time for testing and usability. If proven feasible, this concept may be adopted as a new standardized framework for field testing and monitoring.
- Including both type and application tests into the field-test sequence allows evaluation of the entire synchrophasor system more accurately. It can differentiate between impacts on the synchrophasor quality and the application output. Using specific grid models and field measurements helps tune the setup towards individual applications.

4.3. Focus of the Thesis

This thesis provides insights on methodology and tools for field-testing of synchrophasor systems. Existing testing practices and methods are analyzed, tested, and described in regard to field testing. The thesis develops a methodology and testing techniques, as well as tools to address the issues found with existing practice mostly defined for laboratory testing. The focus of this thesis is to provide instructions on how to use these tools and techniques to perform end-to-end evaluations of synchrophasor systems using a portable test set. This will improve the overall performance of synchrophasor systems in the field and help make power system calibration, commissioning, and maintenance more accessible and reliable.

4.4.Demonstration Approach

The concepts and methods presented in this thesis are demonstrated using a large-scale test bed at the Texas Engineering Experiment Station (TEES) at Texas A&M. The developed tools are evaluated and verified against a synchrophasor reference calibration laboratory that was developed, tested, and evaluated in collaboration with NIST at Texas A&M. The tools are then implemented in the respective setups described in chapter 5 and used for performing tests following the step-by-step description provided. The results obtained from performing the full test sequences are then analyzed and presented in chapter 6, which is expected to confirm the developed hypothesis.

4.5. Conclusions

In conclusion, enhancing the scope of testing from so-called *type tests* defined in the standard to include *application tests* developed for end-to-end assessment helps in assessing application performance more accurately. In order to utilize these tests in non-controlled field environments, not only the methodology, but also testing tools need to focus on constraints imposed by field-testing. Current testing practices and tools do not fully cover these issues, which is addressed in this thesis.

Some of the proposed solutions to address these issues include: implementation of a nested end-to-end testing approach using a portable FTS, using specific grid models and field measurements to tune the setup towards individual applications, and a proposed network based nested testing approach will further improve the concept of field testing and enable parallel evaluation. The presented tools and methods are expected to improve the overall performance of synchrophasor field systems and make system calibration, commissioning, and maintenance more accessible and reliable, which will be demonstrated using a large-scale testbed.

5. END-TO-END SYNCHROPHASOR SYSTEM EVALUATION*

5.1. Background

End-to-end testing is a very common approach for testing power system protection solutions. Starting in the late 1980’, this method has continuously gained popularity as more and more devices in the protection chain became digital. It transforms the complex functions of individual modules into a black box and uses only the necessary inputs and outputs, as mentioned in [46]. With the recent introduction of synchrophasor modules, it is necessary to adopt the end-to-end testing approach to explicitly evaluate the performance of synchrophasor systems.

For synchrophasor systems, end-to-end testing includes evaluation from the timing source to the end-user application. This chapter addresses requirements imposed on a synchrophasor system and how these can be tested for using type and application tests. A test set with unique functionality specifically developed for testing in field environments is described and its distinguishing features are highlighted. Testing methods such as nested end-to-end testing leveraging the specialized features of the Field Test Set are described for evaluation of synchrophasor systems in the field. The individual stages of such tests are thoroughly explained and improved techniques such as network-based nested testing are presented.

5.2. Standard Requirements

The standards associated with synchrophasor systems [7]-[10] not only define the various ways a system should be tested, but also imposes requirements on the outcome of the respective

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* Parts of this section are reprinted with permission from from C. Seidl and M. Kezunovic, "Tools for End-to-end Analysis, Calibration and Troubleshooting of Synchrophasor Systems", ISGT Europe 2019, Bucharest, Romania, 2019, pp. 1-5. Copyright 2019, IEEE

testing procedures. A commonly used metric introduced and specified in the standard [7] is the so-called *Total Vector Error* (TVE). It is defined as follows:

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

“where $\hat{X}_r(n)$ and $\hat{X}_i(n)$ are the sequence values estimated by the unit under test. $X_r(n)$ and $X_i(n)$ are the theoretical sequence values of the input signal at time (*n*) assigned by the unit to those values”. PMUs in compliance with the standard [7] and its amendment [8] are therefore known to fall within a certain range of accuracy defined by TVE values when being compared to the expected reference value of the defined input. The respective TVE thresholds requirement for each test is listed in Table 2.

Table 2: C37.118.1(a) TVE thresholds. Adapted from [7].

	Influence Quantity	**TVE Threshold**		**Reference Condition**
		M-Class	**P-Class**	
Steady State Tests	Frequency Range	1	1	$F_{nominal}$
	Voltage Magnitude	1	1	100% rated
	Current Magnitude	1	1	100% rated
	Phase Angle	1	1	Const.
	Harmonic Distortion	1	1	<0.2% THD[2]
	Out-of-Band Interference	1.3	None	<0.2% of signal magnitude
Dynamic Tests	Measurement Bandwidth	3	3	100% rated magnitude
	Frequency Ramp	1	1	100% rated magnitude
	Magnitude Step Change	Defined in table as function of reporting rate [7]	Defined as response time: $1.7/f_0$	All nominal
	Angle Step Change	Defined in table as function of reporting rate [7]	Defined as response time: $1.7/f_0$	All nominal

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[2] THD – Total Harmonic Distortion

5.3. Type Testing

Type test waveforms were developed to standardize PMU performance, which in return means any PMU complying with the standard will have no more than a pre-defined uncertainty error when measuring these waveforms and computing the corresponding phasor. For the purpose of evaluation, the TVE is used as a threshold metric, see chapter 5.2. Any PMU exceeding those thresholds is therefore expected to indicate a malfunction or intrusion. Deviations of performance that stay within the specified limits may not always be detected when solely observing the standard's limits. More precise thresholds for this evaluation can be determined by performing lab tests for device characterization and calibration tests for field installation evaluation. For calibration, this can be formulated as follows:

> *"The systems response can be characterized to get a more accurate analysis of the system to be used later on during troubleshooting. If initial testing shows elevated TVE errors for certain type tests after being installed, such errors will not be classified as a malfunction at a later point in time. By detecting and locating such issues early on, the corresponding error threshold can be adjusted not to create alarms during in-service system operation, for such levels of error."*

Establishing a calibration threshold is especially useful for detection of gradual performance deterioration, as shown in Figure 5. This graph shows an example of performance results of a system with TVE values increasing over time, i.e. the performance is deteriorating. The TVE values throughout periodic follow-up maintenance measurements are continuously increasing. Following this trend would suggest that the next measurement could be outside of the specified limits. This information can be used to issue work tasks to counteract this trend, such as re-calibration or replacement of a device. Monitoring the status of a system and comparing it to its calibration state can therefore help to take preemptive actions to avoid that a system falls outside of the limits required by the standard.

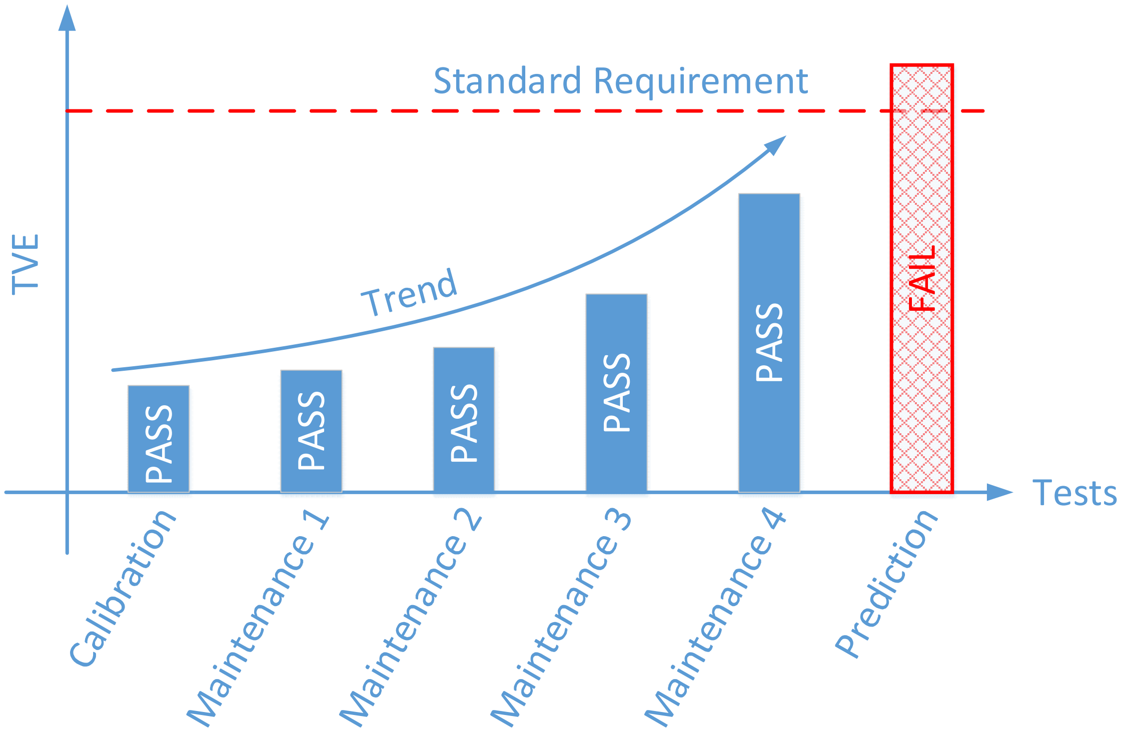

Figure 5: Benefit of Establishing a Calibration Threshold

5.3.1. Type Testing Setup

To observe and enforce a systems conformance with the standardized guidelines, a test setup that can implement the corresponding testing and calibration techniques is needed. The IEEE

Test Suite Specification [24] gives recommendations and guidance to achieve a calibration setup capable of classifying and calibrating PMUs and/or synchrophasor systems, as shown in Figure 6. Using proper testing methodology the setup's capability can be expanded to serve entire synchrophasor systems, which is explained in chapter 5.6.

The most critical part in the calibration is to ensure an accurate timing source to be able to precisely determine systems' performance. This can be achieved in various ways, but always requires a reference known to be accurate enough to test and calibrate the devices and setup under consideration. While this thesis uses the approach outlined in chapter 5.6.1.1 to ensure the necessary timing integrity, [45] presents a more sophisticated approach including a hardware design specifically developed to detect any anomalies in the timing system. Coincidentally, this timing module was developed, tested and deployed for a DOE project called "TIMER" that combines the timing integrity check with the end-to-end testing methodology presented in chapter 5.6. Test results are be presented in chapter 6.2.

A basic setup to test and calibrate a PMU typically consists of a synchronized signal generator, a PMU under test and a controller comparing the output data stream to the generated waveforms. It may be expanded with additional equipment such as external GPS receivers or PDCs to enhance the scope of the calibration. A commonly used test setup, as introduced in [24], [30], and [31], is shown in Figure 6. The setup shows a GPS clock receiver providing timing signals, i.e. 1PPS, IRIG-B, 10MHz clock signal, to a generation and sampling unit (GSU). The GSU serves two purposes 1) synchronized generation of type test waveforms, 2) sampling of analog signals and synchrophasor stream.

1. Synchronized generation refers to the generation of analog signals under consideration of an absolute time reference. This is a key factor for making

synchrophasor experiments (type-tests) reproducible and compare the output of the Device Under Test (DUT), which is typically a PMU, to an expected reference value.

2. The sampling of input signals to the DUT is a suggested measure for compensating potential amplifier deviation. By measuring the generated output signal and comparing it to the expected output value using calibrated attenuators and transformers, the GSU can automatically correct magnitude and phase deviations.

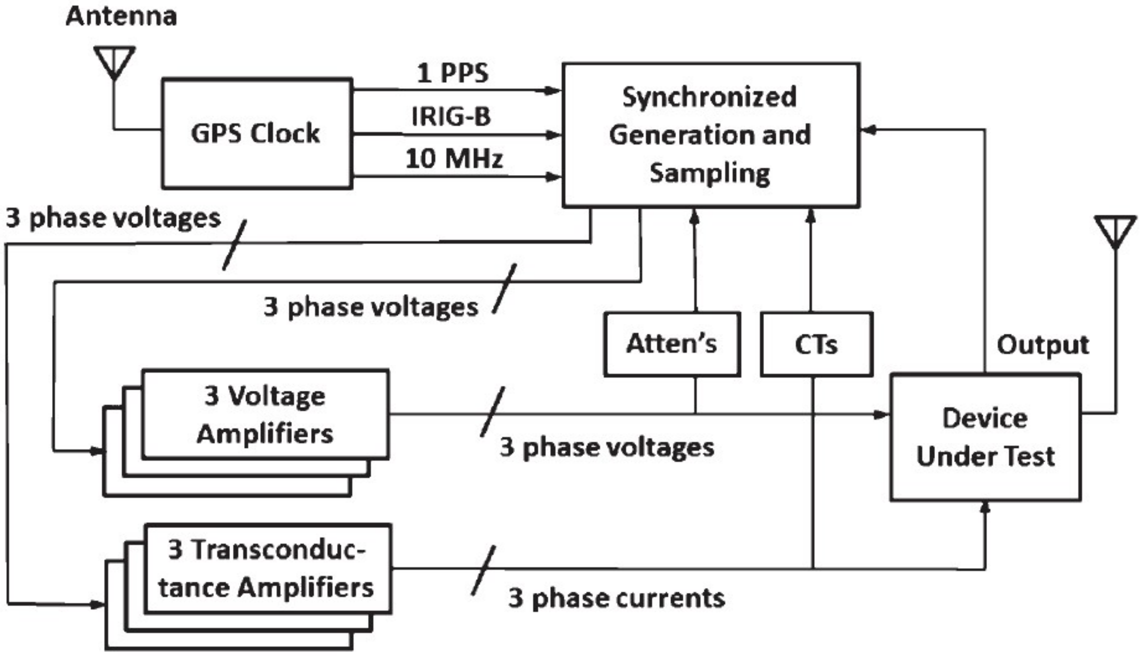

Figure 6: Block diagram of a NIST PMU test system. IRIG-B stands for the Inter-Range Instrumentation Group time code B. CT refers to current transformer. Reprinted from [24].

The work presented in [24], [30], and [31] suggests the use of National Instruments PXI and/or compact RIO modules to act as the waveform generator and control unit to evaluate synchrophasor systems, based on their high reliability and accuracy. According to these papers, a PMU calibration setup established at the National Institute of Standards and Technology (NIST) has an estimated uncertainty of 0.01% TVE. This value is roughly two orders of magnitude better than the threshold used in the PMU standard and can therefore considered sufficient to calibrate PMUs and synchrophasor systems. Most commercial GPS clock receivers provide an accurate enough signal to the controller via IRIG-B or other protocols to exceed the timestamp accuracy of the PMU output stream. Some setups as mentioned in [30] may use GPS receivers that are directly integrated into the controller and/or signal generator. In any case, it is important to consider and compensate for any time delays that may arise due to the nature of the setup. This is especially important when amplifiers are in the test loop to achieve nominal values for the PMU's inputs. The test setup developed and used for the work presented in this thesis is described in chapter 5.6.

5.3.2. Type Testing Methodology

The test plan for each individual type test defined in the standard [7] is clarified in the IEEE Test Suite Specification [33]. The test sequence is illustrated in Figure 7 and always includes the following steps:

1) Applying analog signals to PMU under test,
2) Waiting for system to initialize
3) Capturing PMU output stream for fixed timeframe (typically 5 seconds)
4) Calculating errors relative to respective type test reference
5) Comparing error calculations to class limits in standard
6) Creating report based on test results

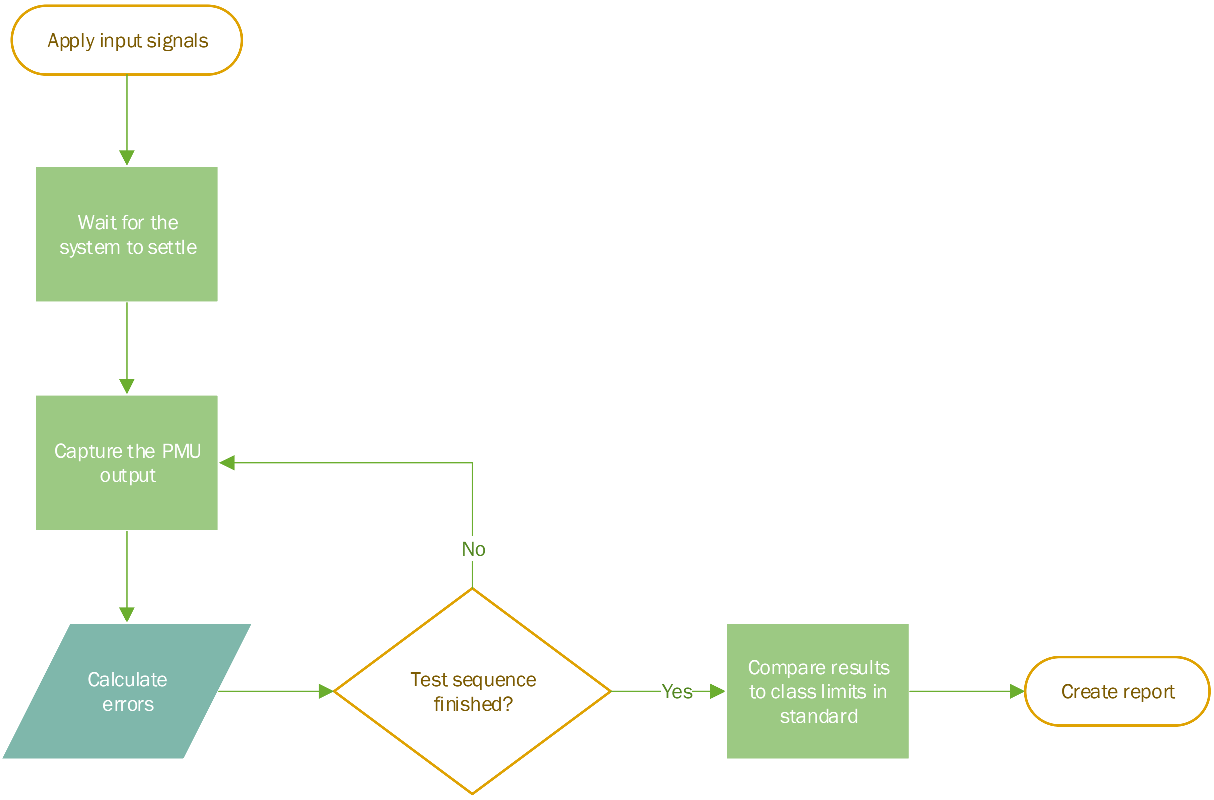

Figure 7: Individual Test Sequence Flow Chart

The methodology also entails the definition of evaluation thresholds for setup accuracy and uncertainty. The standard [7] requires a Test Uncertainty Ratio (TUR) for PMU calibration systems of 4 or higher compared to the test requirements. Factoring in the uncertainty of such setups, this limits the area of guaranteed pass or fail decisions to 75% of the actual requirement. For that reason, the TSS [33] requires a TUR of 10. The effect of uncertainty on testing evaluation is illustrated in Figure 8. Figure 8.a) shows the uncertainty of a phasor with TUR 4. It can be seen that the area of guaranteed evaluation for pass/fail decision is decreased by 25%. Even though a measured phasor would be within the specified limits, indicated by the black circle, the measurement uncertainty does not allow confident judgment. With TUR 10, shown in

Figure 8.b), the judgement uncertainty is decreased to 10%, which allows more accurate assessment of a synchrophasor system. The issue is especially apparent towards the end of a PMUs frequency spectrum, where the TVE could be expected to fall within 75%-100% of the limit. In such cases, the setup would not be able to differentiate between a pass and a fail and would need to flag the measurement as *indeterminate*.

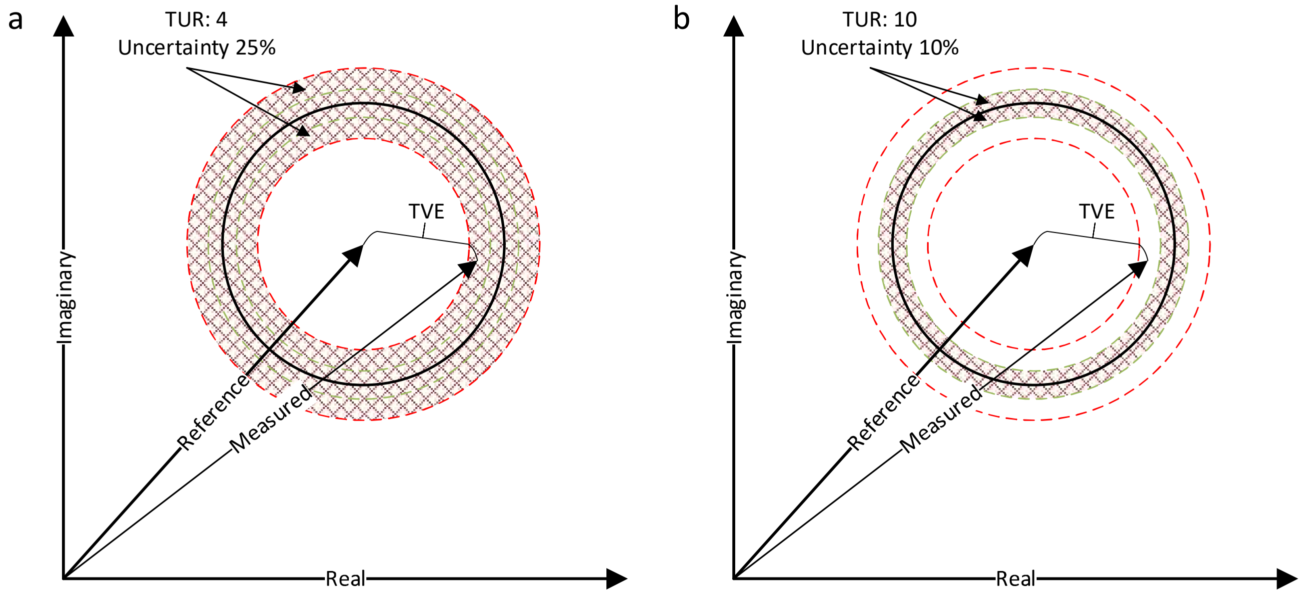

Figure 8: Effect of uncertainty on testing evaluation with a) TUR 4, b) TUR 10. Adapted with permission from [7].

5.4. Application Testing

This testing procedure is based on replaying waveforms of either recorded or simulated events, where the outcome of the application is known or can be predicted. Applications tests, as opposed to type tests, are mainly used for impact analysis of end-user applications, such as fault location [13], small signal stability [14], voltage stability [15], or model validation [16] to name a few. The test setup is similar to type testing, except that the waveform generator needs a waveform replaying capability that is not commercially available for synchrophasor system evaluation equipment. This feature is implemented in the FTS, which is explained in chapter 5.5.3.

5.4.1. Application Test Methodology

Pre-defined analog waveforms corresponding to a known recorded or simulated event in a power system are replayed to a PMU under test. The output synchrophasor stream is then computed by an end-user application, which then provides the applications output to the user. Using pre-defined waveforms in a calibrated system, the output of the application is expected to have a known response. This can be verified by performing this test in a laboratory environment. In case of any form of perturbation, malfunction, or intrusion in the system, the application will likely deviate from its expected response. The underlying test signals for the application tests are stored as analog waveform samples that are capable of capturing many unfolding time domain details of measured or simulated power system conditions. That can profoundly affect the phasor calculation, including DC offset subharmonic, harmonics and high frequency transients. This unlocks a whole new potential of dynamic testing capable of revealing insufficient ability of PMUs to capture complex waveform changes as phasors on much more realistic signal interaction time-scale than conventional type tests. The waveform replaying for evaluation of synchrophasor systems using a portable test set is explained in chapter 5.5.3.

The goal of application testing is to evaluate the impact of deviation in system behavior from a reference state on the end-user application. One benefit of including application tests into system testing is to acquire knowledge about the impact of a specific system event on an end-user application performance. Another advantage is to get a more in-depth understanding of the dynamic behavior of a synchrophasor system, which allows tuning the system parameters towards an improved application. To illustrate the concept of application testing, this thesis uses a fault location application as an example, as demonstrated in chapter 6.1.

5.4.2. Fault Location Application

The fault location application used in this thesis [13], [47] is evaluating phasor data provided by three station PMUs corresponding to faults in a 5-bus system, as shown in Figure 9. The model for the 5-bus system is calculated from real system parameters of a larger system provided by a utility company.

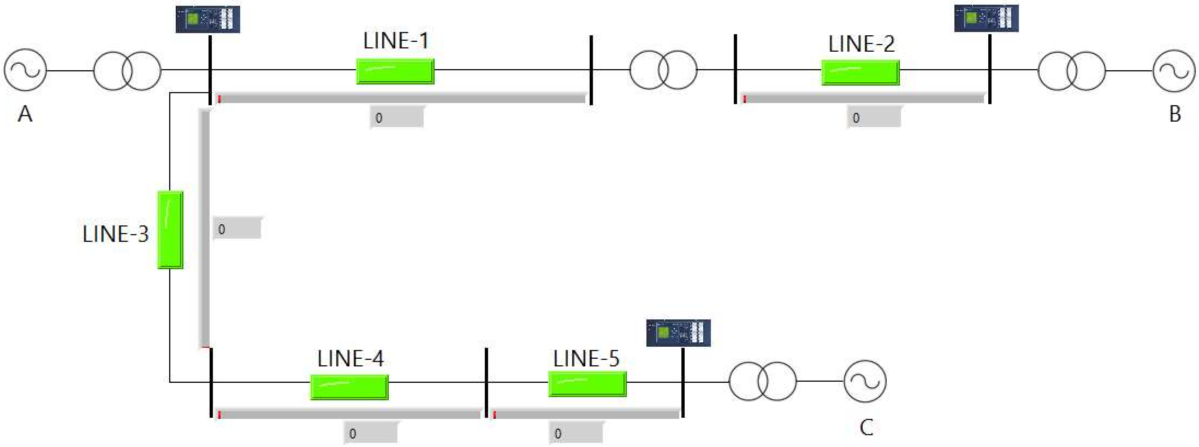

Figure 9: 5-bus Fault Location Test System

The fault location algorithm is trained with phasor data from real time simulations in PSSE based on the 5-bus system model. The same simulated phasor data is used to calculate the analog waveforms corresponding to the respective fault scenarios. The analog data is calculated based on the assumption that the nominal frequency f_{nom} stays constant throughout the duration of the fault as follows:

$$v(t) = \sqrt{2} * V(t_n) * \cos\left(2\pi f_{nom} t + \varphi_{rad}(t_n)\right)$$

$$i(t) = \sqrt{2} * I(t_n) * \cos\left(2\pi f_{nom} t + \varphi_{rad}(t_n)\right)$$

where

$$t_n \in const. \forall: t_0 + n * \Delta t \leq \ t < t_0 + (n+1) * \Delta t$$

$$\bar{V}(t_n) = V(t_n) < \varphi_{rad}(t_n)$$

$$\bar{I}(t_n) = I(t_n) < \varphi_{rad}(t_n)$$

$$\Delta t = {}^{1}\!/_{f_{nom}}$$

An example for this correlation is shown in Figure 10. For a fault in the system shown in Figure 9 on line 2 at 66% of the line from the left, the simulated magnitude and phase are shown in the first and second plot in Figure 10, respectively. The plots show a 3s long simulation, with a fault occurring at 1s and being cleared 2 cycles later. The third plot in Figure 10 shows the corresponding analog data calculated with the formulas above. This data is stored and used for replaying to a synchrophasor system under test, as explained in chapter 5.5.3.2 and evaluated in chapter 6.1.

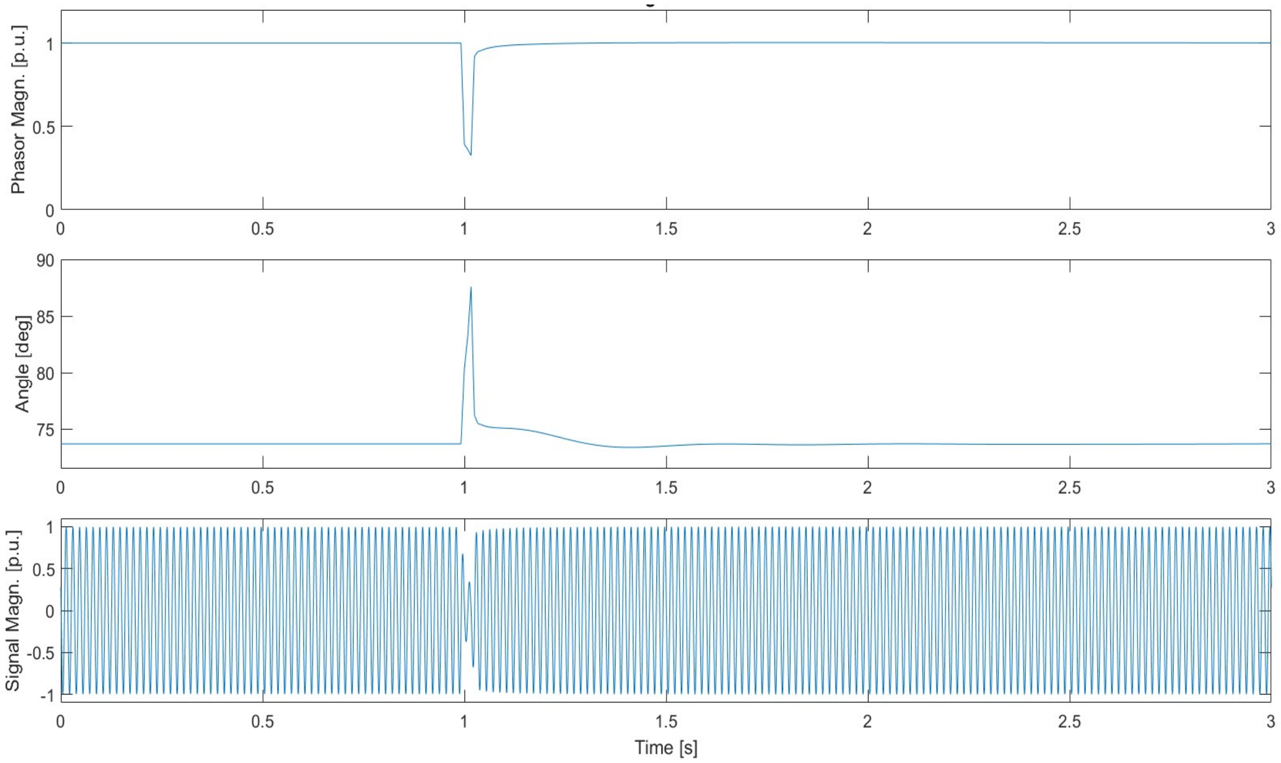

Figure 10: Fault Location - Phasor to Signal Correlation for Line 2 Fault at 66%

5.4.2.1. Application Test - Impact Evaluation

In order to comprehensively reflect the impact of any system event on the application, the evaluation needs to consider two aspects:

- Synchrophasor stream comparison: Comparing the synchrophasor stream of the PMU and/or PDC output to the expected phasor values based on time stamp alignment shows how the setup affects the phasor stream and its values.
- Application output comparison: Comparing the actual output of the application to the expected result shows how the setup affects the application itself, which typically does not directly correlate to the impacts determined in the phasor comparison.

Multiple ways of evaluation are important to establish a full assessment not only how the setup affects the quality of the synchrophasor and application output, but also how well an application responds to deviations from the expected input. While phasor stream or value deviation might be small, the impact on the application result may already be severe due to very sensitive application algorithms, as shown in Figure 11. On the shown correlation between application accuracy and input deviation, it can be observed that time-stamp misalignment causes very strong non-linear deviation of the FL detection accuracy. This confirms the need for application tests to fully capture the impact of system behavior on an end-user application, as small deviations in phasor data may cause severe degradation in application accuracy.

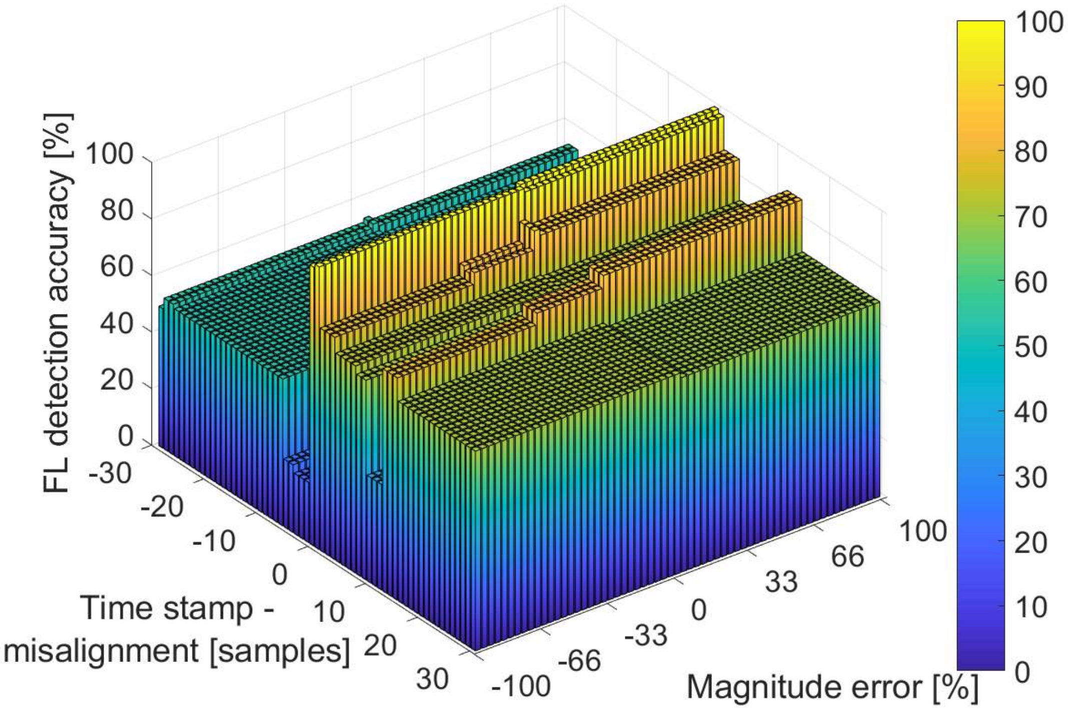

Figure 11: Impact Evaluation on Fault Location Application. Reprinted with permission from [19].

5.5. Field Test Set - FTS

The FTS is a portable test set specifically designed for performing type and application tests in synchrophasor systems in the field. The test set uses low power signal testing to eliminate the need for the use of heavy amplifiers in the field by bypassing the PMUs auxiliary transformers and thereby eliminating the impact of amplifier and transformer behavior.

5.5.1. FTS – Functional Description

The FTS is based on a National Instruments real time controller, which has proven to be a very high-precision platform and has been recognized as a commonly used tool for similar applications, as demonstrated in [24], [28], [30], [31], and [44]. It is embedded in an enclosure that fits into 5U rack space and can therefore easily be installed in any substation or field environment, as shown in Figure 12. The main capabilities include:

- Processing of time synchronization protocols: IRIG-B, GPS
- Synchronized generation of analog reference waveforms
    - Playback of type test waveforms specified in synchrophasor standard [7]
    - Playback of stored application test waveforms
    - Distribution of small signal waveforms via ribbon cables
- Evaluation of PMU performance
    - Comparison of synchrophasor stream to known reference
    - Computation of error metrics
    - Report generation based on PMU performance
- Support end-to-end calibration of synchrophasor systems: Details provided in chapter 5.6
- In-service testing of timing receivers, PMUs, PDCs, end-user applications, and synchrophasor systems end-to-end
- Provides a synchronized reference phasor stream corresponding to generated analog waveforms

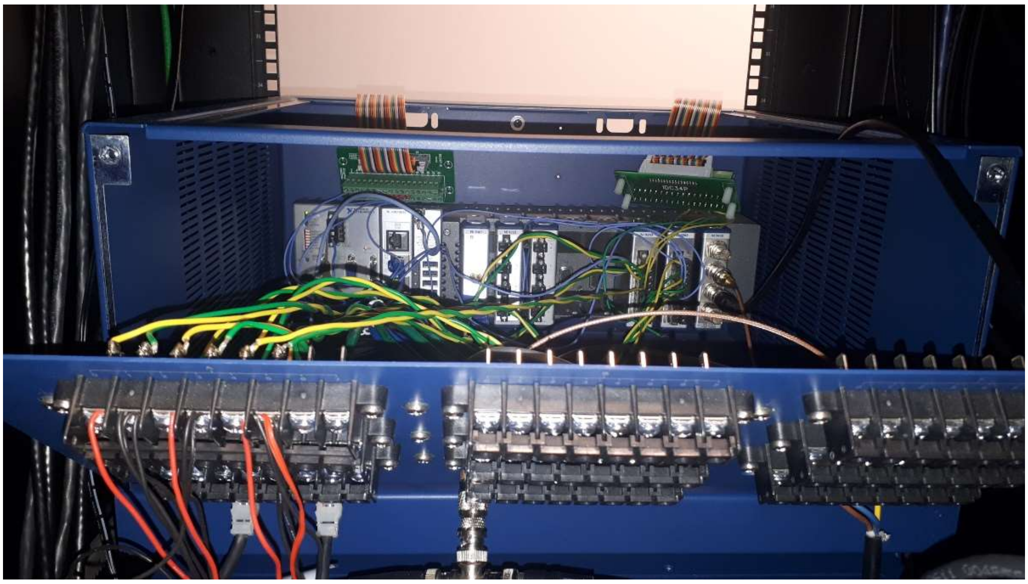

Figure 12: Field Test Set Hardware

The capability to provide reference type-test signals was confirmed using a calibration laboratory at TEES, which was established in 2018 in an effort to obtain the IEEE ICAP certification. In collaboration with NIST, whose staff had developed a calibration device for PMU calibrators using an NI platform, the laboratory setup was thoroughly tested and calibrated. Proper generation of all type test variations was confirmed. This calibration laboratory was used to establish the type testing conformity of the FTS and confirm its status as a reference device.

5.5.2. Use of FTS in Field-Testing

The setup to use the FTS for field-testing is shown in Figure 13. The FTS is connected to the GPS antenna and the timing receiver providing an IRIG-B signal, which enables both evaluation of the timing receiver and generation of synchronized analog waveforms as well as generation of a synchrophasor reference stream (both chapter 5.6.1.1). The FTS provides small signal analog waveforms to the PMU via ribbon cables, bypassing the auxiliary transformers. The synchrophasor stream from the PMU is distributed to the FTS and the PDC that connects to the communication network. From there both the end-user application and the FTS have access to the synchrophasor stream, which closes the loop of testing, as explained in chapter 5.6. With the FTS being connected to all the synchrophasor data feedback loops, the system can be evaluated using the synchrophasor comparison logic, see chapter 5.5.3.

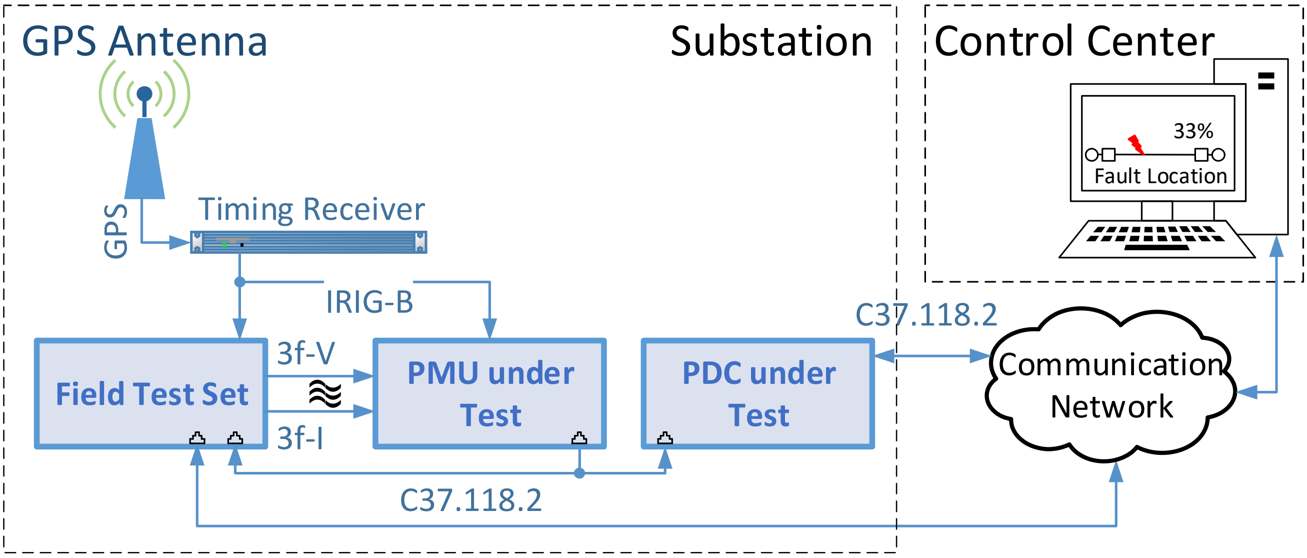

Figure 13: Implementation of Field Test Set for Evaluation of Synchrophasor System. Adapted with permission from [19].

5.5.3. FTS – Signal Replaying

The FTS is able to generate a multitude of reference signals:

- Synchronized Analog Type Test Waveforms
- Synchronized Analog Application Test Waveforms

- Reference Synchrophasor Stream (based on generated analog waveforms)

The generation of analog signals, such as type and application test waveforms happens in the FGPA portion of the cRIO hardware to assure controlled and synchronized replaying.

5.5.3.1. Type Test Waveform Generation

Type test waveforms are generated “on demand” based on the timing information provided by the timing source. The FPGA uses an internal counter to calculate the fractional second and consequently the current time, which is the base for calculating the analog value depending on the chosen standardized test, defined in [7]. The internal process is illustrated in Figure 14.

5.5.3.2. Application Test Waveform Generation

Application Test Waveforms are generated based on a look-up table. For pre-defined scenarios, the analog data corresponding to specific events is stored in the FPGA. Based on a timer, the stored waveforms are continuously replayed to the PMU under test. The internal process is illustrated in Figure 15.

5.5.3.3. Reference Synchrophasor Stream Generation

Based on the chosen analog test, i.e. type or application test waveforms, the FTS will also output a reference synchrophasor stream. Since the generated waveforms are known to the FTS, this information is used to calculate the expected phasor at a specific moment in time. This phasor is then combined with the timing information and packaged into a phasor stream synchronized with the analog output. This provides a reference to the expected output of the PMU under test, which can be used for evaluation of the system design and testing of the end-user application. This process is visualized for type and application test in Figure 14 and Figure 15, respectively.

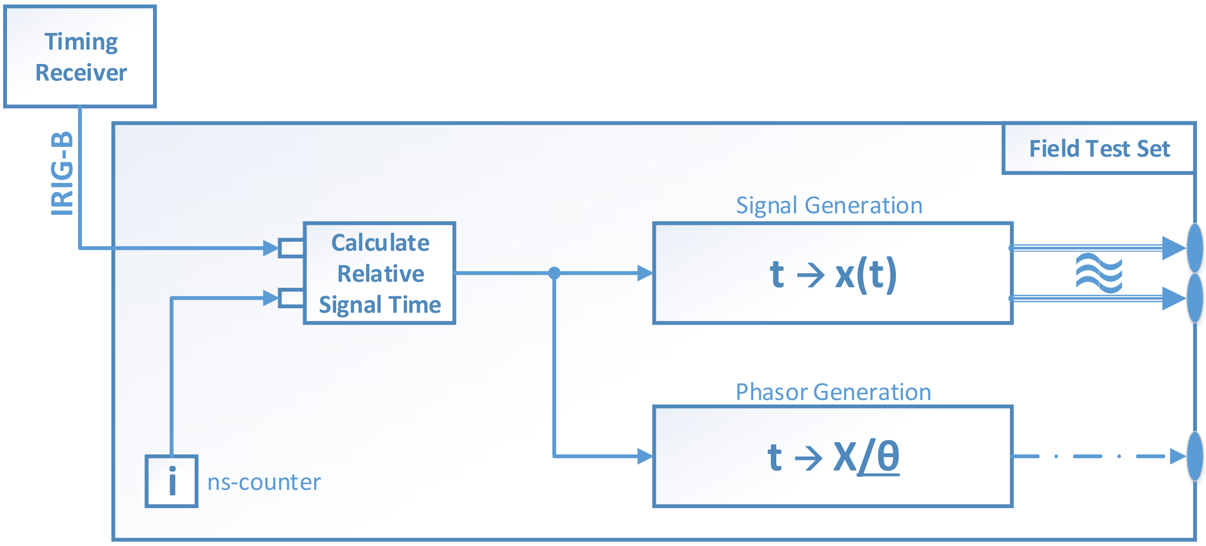

Figure 14: Type Test Signal Generation with Reference Phasor Stream

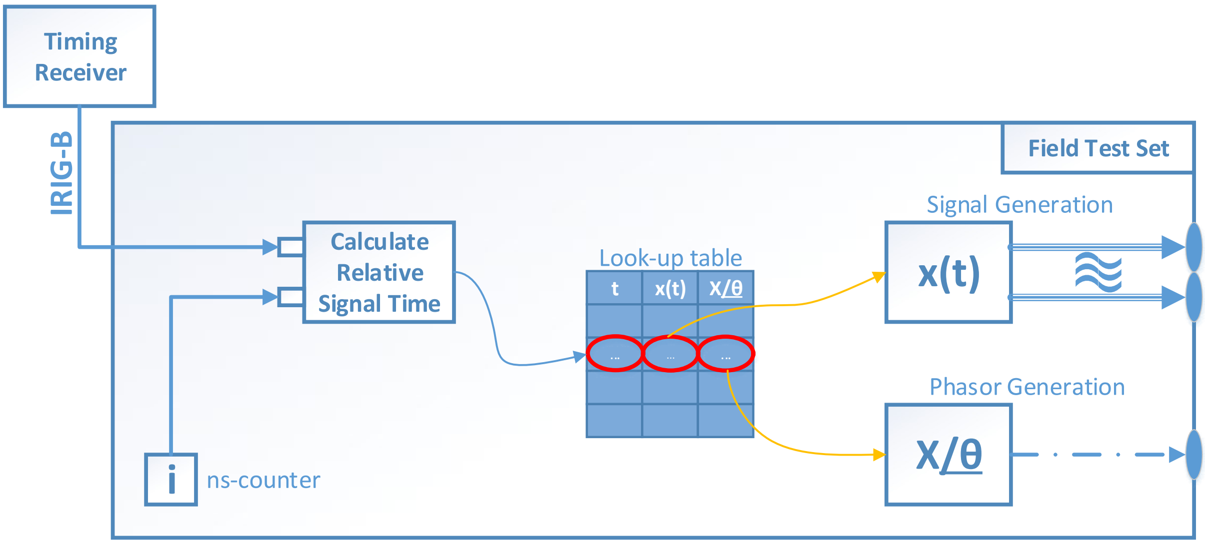

Figure 15: Application Test Signal Generation with Reference Phasor Stream

5.5.4. Synchrophasor Comparison Logic

The synchrophasor comparison logic is used to monitor and evaluate the integrity and performance of a synchrophasor system. The logic continuously calculates error metrics like TVE throughout the duration of any test. In case of any unexpected behavior or malfunction, the TVE value will exceed the thresholds specified in the standard, see chapter 5.2. As soon as a threshold violation is detected, the logic generates an alarm based on the problem source and reports a message to the end-user. The comparison logic evaluation using the FTS consists of multiple steps:

- Check #1: FTS pulls synchrophasor data from the device under test and aligns the data frames in terms of timestamp between *received stream* and *reference stream*. Misalignment may be caused by missing data packet or tampered timestamp.

  $$|T^{REF}(n) - T^{DUT}(n)| \leq \frac{\Delta t}{2}$$

  where

  $$\Delta t = \frac{1}{F_S}$$

  and F_S is the PMU reporting rate.

  Aligned → Succeeded; Misaligned → Failed.

- Check #2: Estimate the accuracy of the phasor data under evaluation in terms of TVE. TVE is within pre-defined threshold → Succeeded: TVE is greater than pre-defined threshold → Failed.

Note: Check #2 is performed ONLY when Check #1 is succeeded.

The flow chart for comparison is shown in Figure 16.

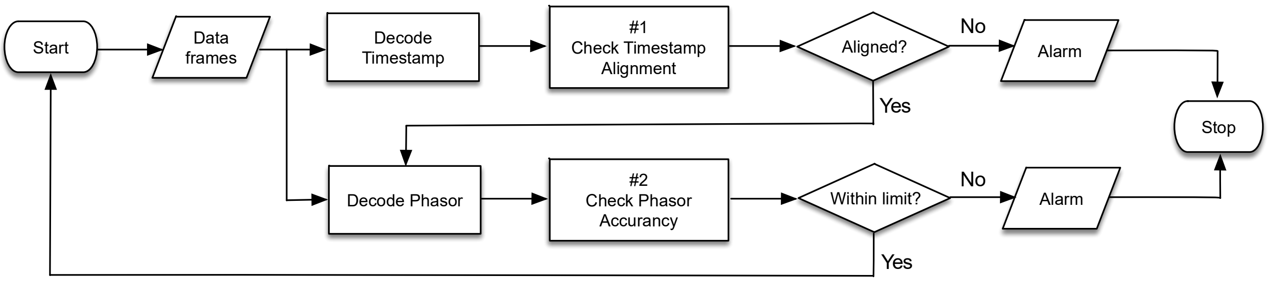

Figure 16: Synchrophasor Comparison Logic - Flow Chart

5.6. Nested End-to-end Testing Using a Portable Test Set

As briefly outlined in chapter 2.5, nested testing for synchrophasor systems is a bottom-up approach to evaluate a systems integrity and performance in a systematic procedure. This method evaluates a synchrophasor system in the following order, as illustrated in Figure 4:

- Timing Source: Integrity and accuracy of timing receiver or clock
- PMU under Test: Evaluation of PMU performance
- Substation PDC: Evaluation of PDC performance
- Communication Network and Control Center PDC
- Application Layer and Visualization: Performance and impact on application, as described in chapter 5.4

5.6.1. Levels of Nested Testing

Following this approach, the performance of each level is evaluated and can be used as a basis for including the next level into the test loop. Testing all levels establishes a much more comprehensive evaluation than simple end-to-end tests that only consider output of the entire system as opposed to sub-levels. The entirety of sequences of these tests is called *nested testing.*

5.6.1.1. Timing Integrity Check

The timing module is evaluated comparing the incoming GPS signal to the IRIG-B signal processed by the timing receiver. This functionality was specifically developed for the FTS at Texas A&M and is not readily available in commercial products. GPS intrusions cannot be detected with this method, unless a time reference signal can be provided to the FTS, as is utilized in the TIMER project and described in [45].

The FTS processes the GPS signal and extracts a 1PPS signal that is compared to the IRIG-B or 1PPS output stream of the commercial timing receiver, as shown in Figure 17.a). In case of an anomaly or intrusion, the discrepancy can be evaluated through comparison, as shown in Figure 17.b).

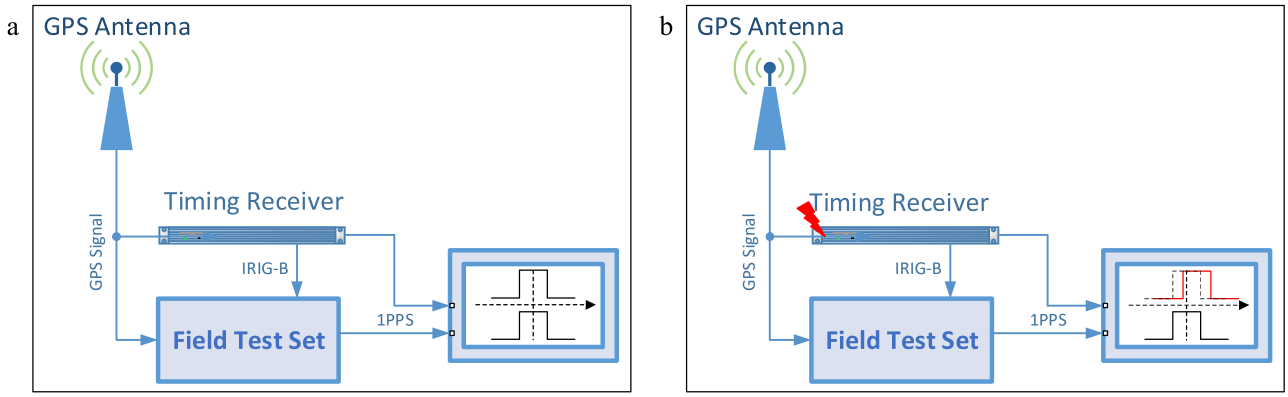

Figure 17: Time module test setup a) without intrusion, b) with intrusion. Adapted with permission from [19].

An example of the methodology for this evaluation is shown in Figure 18. The timing information of the GPS signal and the IRIG-B signal received from the clock is converted into a synchronized 1PPS step. The time difference between the rising edges of the signals is equal to the difference between the two timing signals. If this difference exceeds a pre-defined threshold, the system is compromised.

Figure 18: Example for Timing Signal Comparison

Since the method aims at a time or angle difference to evaluate the GPS against the IRIG-B signal, a conversion is needed to enable direct comparison to the TVE values from type or application tests. For evaluation purposes, this thesis introduces a metric called *Total Time Error (TTE)* that is defined as follows:

$$TTE = \sqrt{2 - 2\cos(\Delta t * 2\pi * 60)} = \sqrt{2 - 2\cos(\Delta\theta)}$$

where

$$\Delta t \in time\ difference\ between\ two\ time\ signals$$

$$\Delta\theta \;\in angle\ difference\ between\ two\ phasors$$

Suggested thresholds for evaluating the timing system are as follows:

$$\begin{cases} TTE < 0.01\% \ldots Good\ Condition \\ 0.01\% \leq TTE \leq 0.1\% \ldots Poor\ Quality \\ TTE > 0.1\% \ldots\ FAIL \end{cases}$$

5.6.1.2. PMU Level Check

After ensuring the credibility of the timing module, the PMU under test will be included into the test setup. The FTS will now take on a different role and evaluate the measured PMU data in addition to providing analog test signals to the PMU, as shown in Figure 19.a).

The FTS is connected to a timing source of choice that has been verified as intact. Based on that, the test waveforms are synchronized and replayed to the PMU. The output data stream is then looped back to the FTS to be compared to a reference. The comparison utilizes the knowledge of the generated waveforms and establishes a reference against which the PMU synchrophasor is compared. As mentioned before, these waveforms are standardized, which not only provides knowledge about the expected output data, but also defines in what range of TVE the output data can be considered non-erroneous. This threshold is defined in the standard but may be narrowed down further if a laboratory evaluation report for given device is available, making the detection process more accurate. This is especially useful if the DUT performance by far exceeds the standard requirements.

Whenever the TVE in regard to the expected output does not comply with the standard, an intrusion or malfunction of some sort can be assumed at the PMU level, as shown in Figure

19.b). Running different sets of standardized waveforms may be capable of exposing details about design specific anomalies.

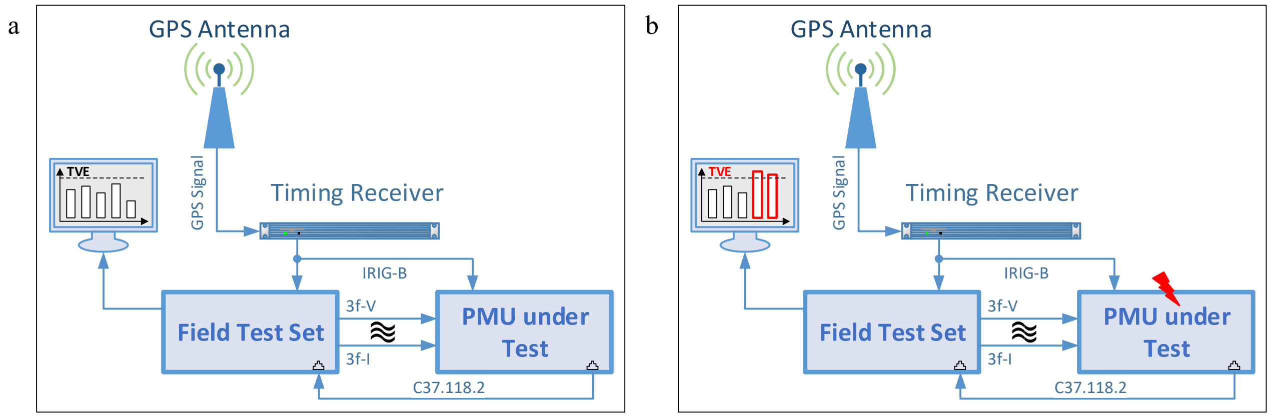

Figure 19: PMU test setup a) without intrusion, b) with intrusion. Adapted with permission from [19].

5.6.1.3.PDC Level Check

Assuming the PMU has been cleared successfully, i.e. showing no signs of malfunction, the PDC is included into the test loop next. Again, analog signals are being replayed to the PMU under test similar to the PMU layer check, but this time the output data is being read from the PDC output instead of the PMU, as shown in Figure 20.a). In case of a malfunction, the TVE values evaluated from the PDC data should indicate such behavior by exceeding the prescribed limits, as shown in Figure 20.b). A natural delay may be inevitably caused by the nature of the network setup. This needs to be established during the calibration stage when an unperturbed system can be guaranteed.

The accuracy of the evaluation can be improved if the output data from the PMU level test is being used as a reference to the PDC level test. Due to the fact that the FTS is generating waveforms synchronized with a global time source, the results are reproducible in reference to the starting point of each set of tests. Performing a test twice should, within a very small range of uncertainty, give the same synchrophasor value at a fixed time after the starting point.

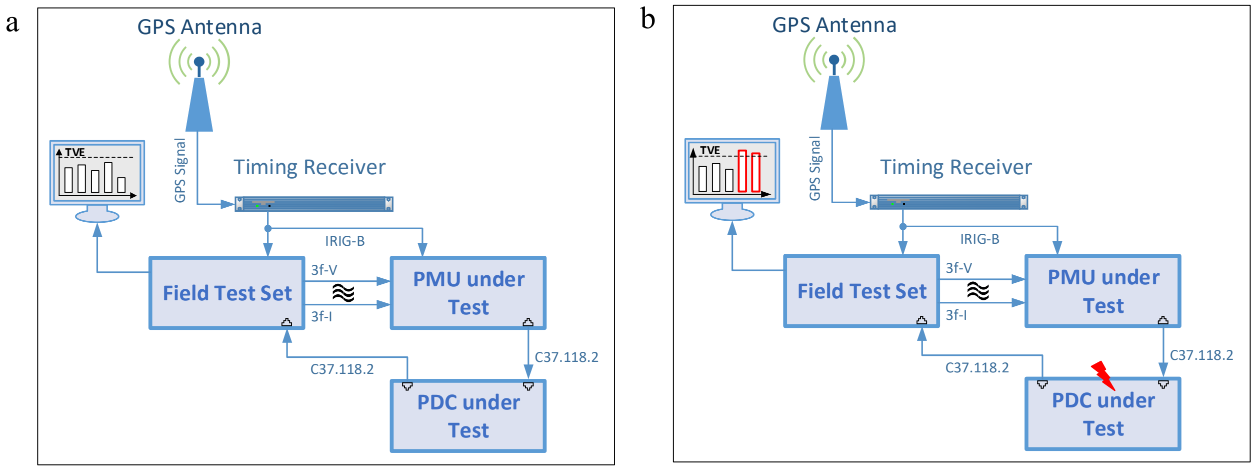

Figure 20: PDC test setup a) without intrusion, b) with intrusion. Adapted with permission from [19].

5.6.1.4. Network and Control Center Check

This step is already testing the system up to the end-user application, as shown in Figure 21, and aims at evaluating the potential impact of the network setup and control center PDC. The FTS is used to send a reference phasor stream containing the phasor information corresponding to an application reference case through the substation PDC. The only factors potentially affecting the application outcome are therefore network related, such as packet loss or packet misalignment. Since the application algorithm is trained on the reference data, the synchrophasor stream should always produce the same known output. Any deviation indicates an error.

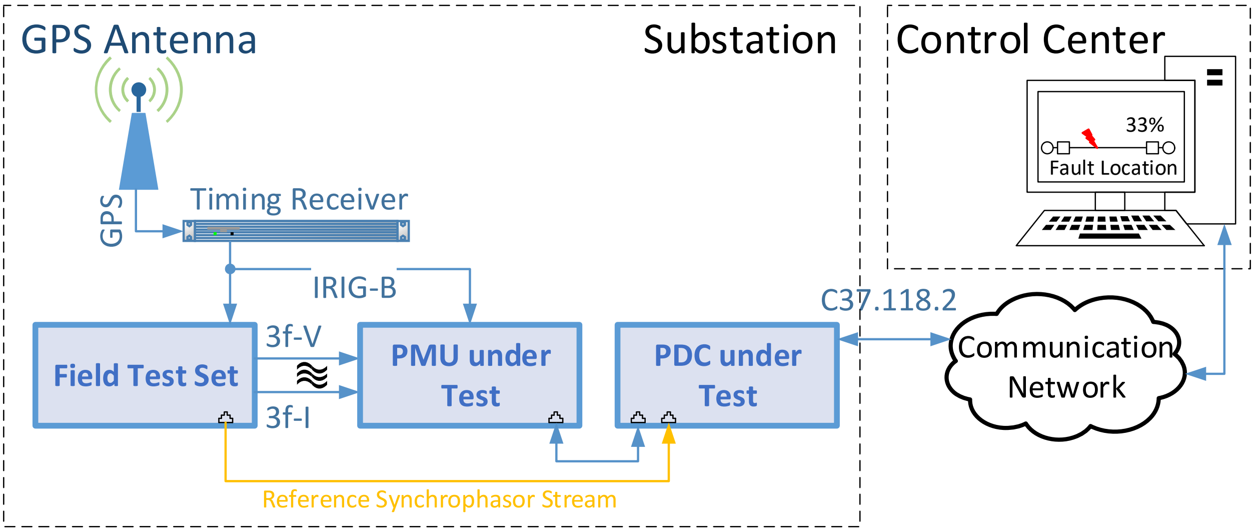

Figure 21: Application Level Evaluation. Adapted with permission from [19].

5.6.1.5.End-User Application Check

For the evaluation of impact on the end-user application, the FTS is replaying analog waveforms in the setup shown in Figure 21. Monitoring and comparing the application output to the expected outcome, as explained in detail in chapter 5.4, reveals if the output is within an acceptable margin of the expected outcome. The margin is dependent on the used application.

5.6.2. Network-Based Nested Testing

In larger systems, the process of performing nested testing one step at a time may be very time consuming and costly, especially considering the hardware connections to the FTS needs to be changed for each test step. For such cases, the process can be automated and implemented as a parallel communication network based nested testing scheme. This method requires the addition of network taps in the system to monitor the network streams and make them available to a central computing unit, as shown in Figure 22.

For this scheme to work, the FTS is now both replaying analog waveforms to the PMU, and sending a reference synchrophasor stream containing the phasor information of the replayed waveforms. This functionality is not commercially available and was developed at Texas A&M as part of the DOE TIMER project. Consolidating the three synchrophasor streams from FTS, PMU, and PDC in the server enables direct comparison. By using a database to process and store the incoming phasor streams, the tapped packets can be aligned according to their respective time-stamps and consequently evaluated by the synchrophasor comparison logic. The comparison logic for the simplest case shown in Figure 22 has two steps:

1. FTS reference stream vs. PMU stream
2. FTS reference stream vs. PDC stream

The result of each comparison is similar to the non-network based testing, expressed as a TVE value that determines whether or not an anomaly is present in the system. The process of comparing data packets is similar to the concept explained in chapter 5.5.4.

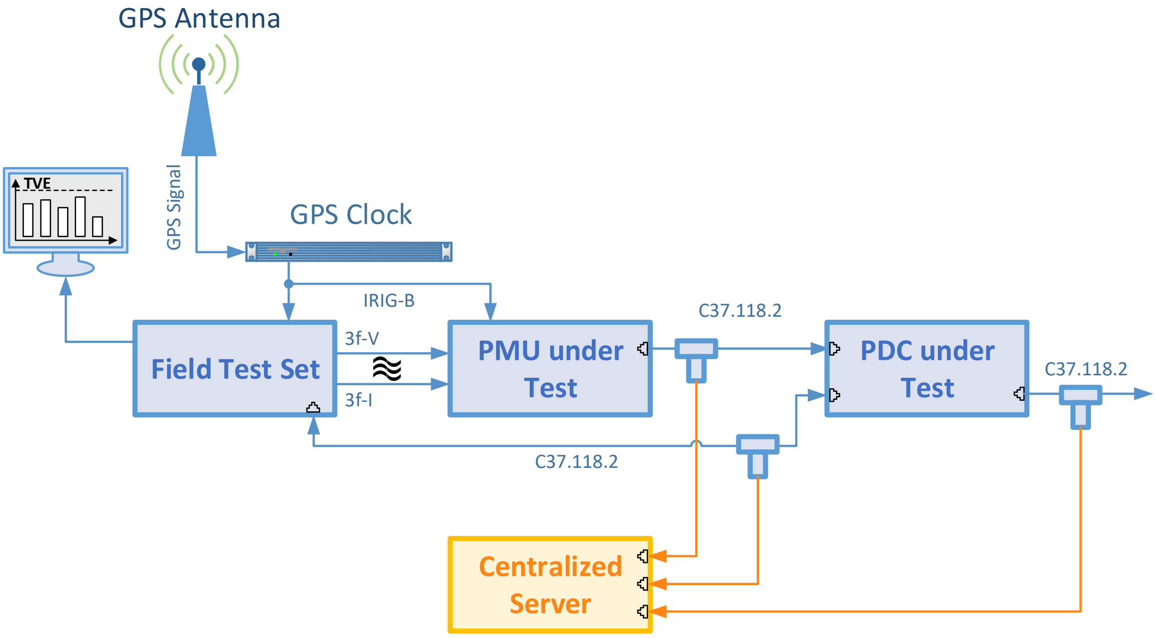

Figure 22: Network Based Nested Testing Setup

The benefit of the network-based method is that the comparison can not only be run on demand, but also run as a live monitoring process. Especially when paired with a reference system, this method can be implemented as an operation integrity control system that instantaneously generates alarms based on live observations. This enables continuous monitoring of performance degradation over time as well as instantaneous events. Figure 23 shows the more sophisticated setup needed for live comparison to a reference system in normal operation. The orange connections show the synchrophasor data flow to the centralized server where the synchrophasor comparison logic evaluates the stream in real time. Figure 24 shows the synchrophasor logic comparison steps in the server listed below indicated by numbers.

1. FTS Reference Phasor vs. Reference PMU Phasor (evaluation of Reference PMU performance)

2. FTS Reference Phasor vs. Test PMU Phasor (evaluation of Test PMU performance)
3. Reference PMU Phasor vs. Reference PDC Phasor (evaluation of Reference PDC performance)
4. Test PMU Phasor vs. Test PDC Phasor (evaluation of Test PDC performance)
5. Reference PMU Phasor vs. Test PMU Phasor (relative comparison between Reference and Test PMU)
6. Reference PDC Phasor vs. Test PDC Phasor (relative comparison between Reference and Test PDC)

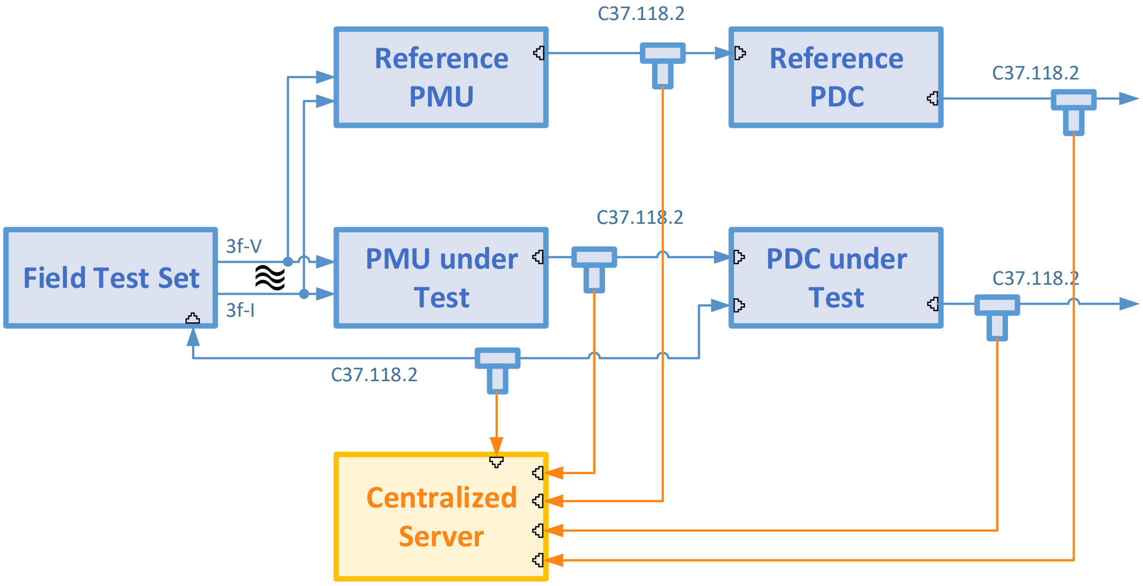

Figure 23: Advanced Network Based Nested Testing System

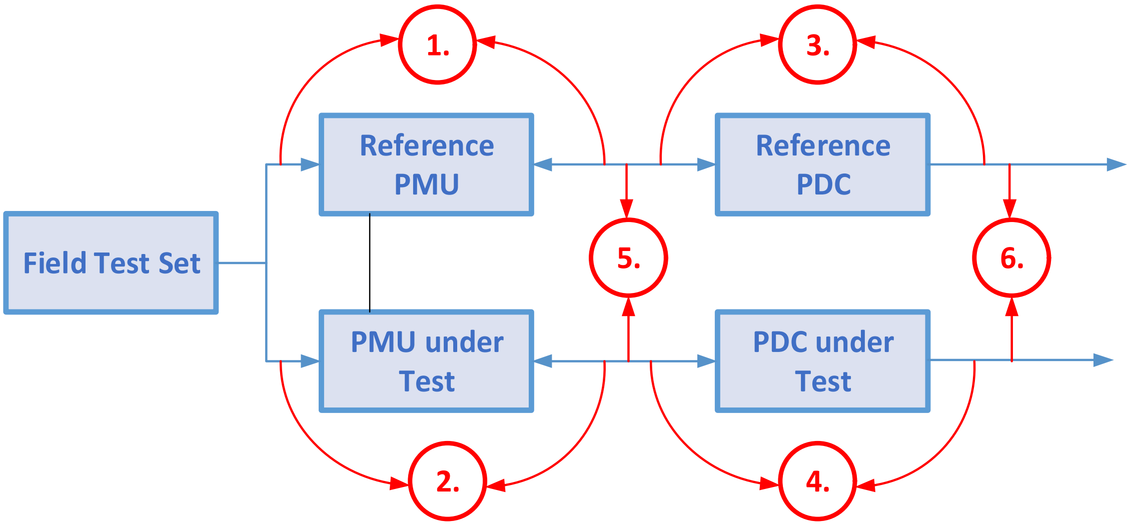

Figure 24: Advanced Network Based Nested Testing Logic

5.6.3. Life-Cycle Testing Stages

The nested end-to-end testing approach can be applied and modified in various ways to meet different objectives. The status of field equipment and all its components when installed or after continued service for an extended period of time is typically unknown. In addition, some updates to the system may include adding new components or reconfiguring existing ones, causing slightly different base performance. For that reason, the field-testing methodology covers several different aspects that utilize different test compositions, as shown in Table 3.

5.6.3.1. Calibration Tests

This form of testing is used to calibrate a system and its components to assert characteristic behavior, adjust variable control factors, and establish a reference for operation and future testing to optimize a systems performance. This test is typically performed before commissioning, before the system goes online and then again in regular intervals to ensure consistent system operation. It usually consists of a full suite of type and application tests, i.e. all tests listed in chapter 5.6.1. The tests are typically performed in a controlled non-attack environment and the results are stored for comparison during later test runs. This test aims at assuring the accuracy of a system is intact.

5.6.3.2. Commissioning Tests

This test verifies the proper installation of a system and characterizes all its components to determine the status, detect anomalies, and consequently establish a working environment for operation and future testing by addressing erratic behavior. This test may, depending on the user’s preferences, only contain a subset of the tests performed during calibration. It aims at verifying the proper installation and operation of the system under consideration and assure the functionality is intact.

5.6.3.3. Periodic Maintenance Tests

The periodic maintenance test or in-field test, it may be performed during normal operation or periodically recurring system maintenance sessions to ensure accurate and reliable operation. This test is be used to re-evaluate systems calibration status and detect any hidden anomalies by replaying and evaluating selected test scenarios, as well as comparing results with the initial calibration test results. This test predominantly uses type test waveforms to check for intrusions and system health but may entail application tests if needed. This test differentiates from commissioning in a way that its objective is to evaluate the status integrity of a system that is unknown after operating for an extended period of time, as opposed to determining proper operation for the first time after being put into service.

The calibration results may be used as reference values to evaluate how the system has deteriorated, if at all. Even if the system passes all maintenance tests according to the established thresholds, large deviation from the initial calibration results may indicate a trend that may need further analysis.

5.6.3.4.Troubleshooting Tests

Being aware of a certain problem in the system, either by performing an in-field test or through another detection approach requires troubleshooting to resolve the problem. Using the same tools as for commissioning, calibration and periodic maintenance, the methodology and especially the replayed waveforms can be tailored to pinpoint the source and extent of erratic behavior. This aims to assess the problem and determine potential counter measures. The tests may entail both type and application signals. The nested testing approach presented in this chapter is the preferred approach to determining the location of a specific issue, once it was concluded that the system is compromised. It lets the user pinpoint the location by checking each level of the synchrophasor system and stopping whenever an anomaly is detected.

Table 3: Proposed Test Mode Use-Cases

	Test-type	**Calibration**	**Commissioning**	**Maintenance**	**Troubleshooting**
Type Test	Frequency Range	✓	✓	✓	
	Voltage Magnitude	✓	✓	✓	✓
	Current Magnitude	✓	✓	✓	✓
	Phase Angle	✓		✓	✓
	Harmonic Distortion	✓	✓	✓	✓
	Out-of-Band Interference	✓		✓	
	Measurement Bandwidth	✓		✓	
	Frequency Ramp	✓	✓	✓	
	Magnitude Step Change	✓	✓	✓	✓
	Angle Step Change	✓		✓	
Application Test	Reference Test	✓	✓		✓
	Waveform Test	✓		✓	✓

5.7. Conclusions

To summarize the outcome of this chapter, the standard’s requirements on type testing including evaluation metrics were explained. The concept of type testing and its use in lab and field environments was elaborated by showing testing techniques, methodologies and tools used and developed during the thesis work, as well as prior work. Flow-charts and diagrams for the purpose of describing the evaluation of synchrophasor systems are provided. The concept of application testing is explained with a focus on field-testing, including the use of a fault location application to establish an application for demonstration in the results section.

A main contribution in this chapter is the introduction of a portable Field Test Set and its use in field-testing. It features additional functionality like providing a synchrophasor reference stream corresponding to the replaying of analog type and application test waveforms that are not commercially available in this form. The constraints of field-testing that make existing methods and techniques infeasible are addressed, which results in major improvement over prior testing techniques.

The state of a system after installation, maintenance, or extended time of operation is typically unknown, which is why the system needs to be evaluated end-to-end on a regular basis. For that, the concept of nested end-to-end testing in the field is explained in detail and backed up with instructions on how to evaluate a synchrophasor system level by level by running a comparison logic on the FTS. A timing integrity check was included, which has not been done before in the context for field-testing.

Another contribution is the proposed network-based approach to nested testing that is utilized for monitoring and evaluation of synchrophasor systems. This method aims at further improving the prevailing problem of hardware constraints imposed on testing in the field environment, by improving operability and test duration of such tests. Additionally, after commissioning and calibration, the network-based testing hardware can be utilized for continuous monitoring of system integrity during normal operation.

6. RESULTS

6.1. Implementation of Application Tests in the Field Environment

The experiment presented in this section shows and evaluates the implementation of applications tests in the field environment following the instructions in chapter 5.4. The impact of the PMU settings on the application output are of particular interest. Multiple test runs were performed using different settings of the PMU. Especially the distinction between P and M-class phasor estimation is expected to significantly affect the application performance.

6.1.1. Analysis of Application Test Implementation

In this thesis, only three phase faults are considered for evaluation of the fault location application. The system is therefore balanced and only one of the phase voltages and currents, respectively, is needed for analysis of the fault. To effectively represent all three stations of this model, the three phase A voltages and currents of each individual station are replayed at phase A, B, and C of the FTS output, respectively. With this method, the application cannot only be evaluated using a single PMU, but also the synchronization of the replayed data is easier to replicate.

Analyzing the measured phasor data clearly shows that the PMU phasor estimates deviate with the PMU setting. Looking at it more closely, the real difference lies within the response dynamic of the PMU algorithm. As expected, the phasor fault condition for the M-class setting lasted longer than the actual event, which was significantly less severe in the P-class setting. This behavior was observed for both phasor magnitude and phase, as shown in Figure 25 and Figure 26, respectively. While the difference in the phasor values between the M and P class PMU may seem small, the results in Table 4 show how big the impact on the end-user application is. This can be explained with the more accurate dynamic representation of the P-class PMU setting, which in this case is an important factor of the application algorithm. Other applications may respond better to other settings of the synchrophasor system. This can be determined by performing application tests accordingly.

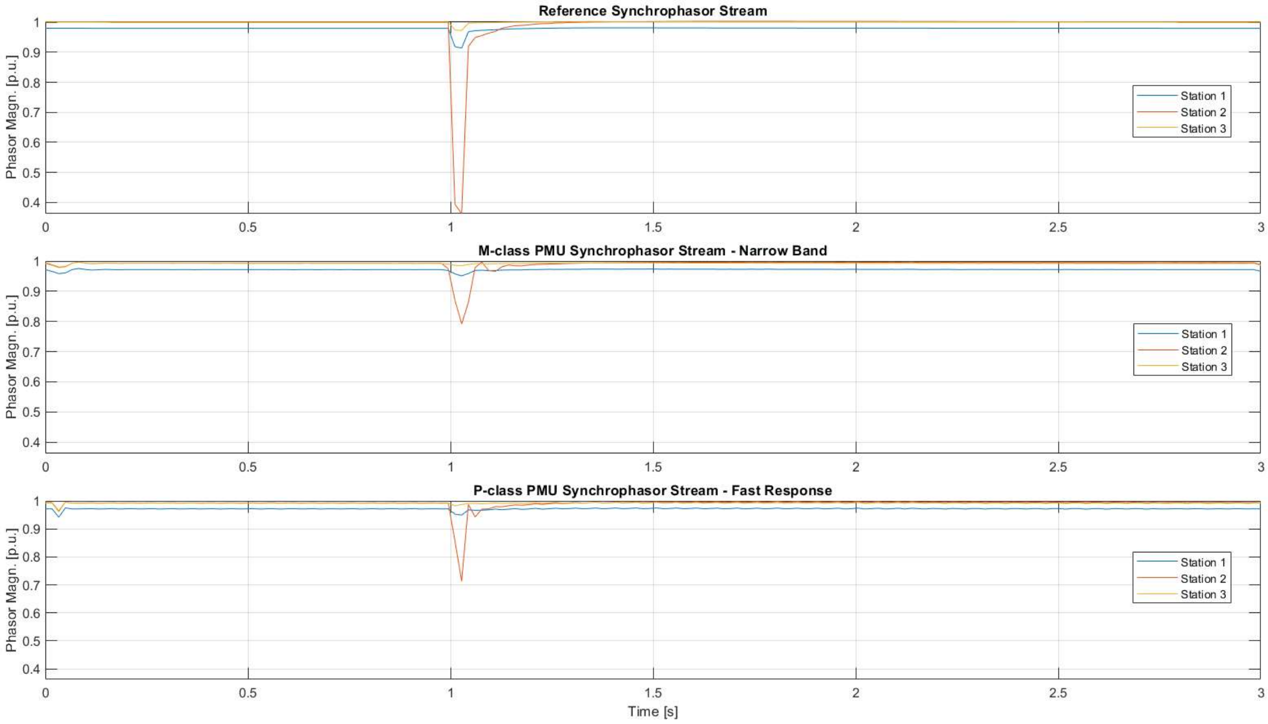

Figure 25: Fault Location – Phasor Magnitude Evaluation for Line 2 Fault at 66%

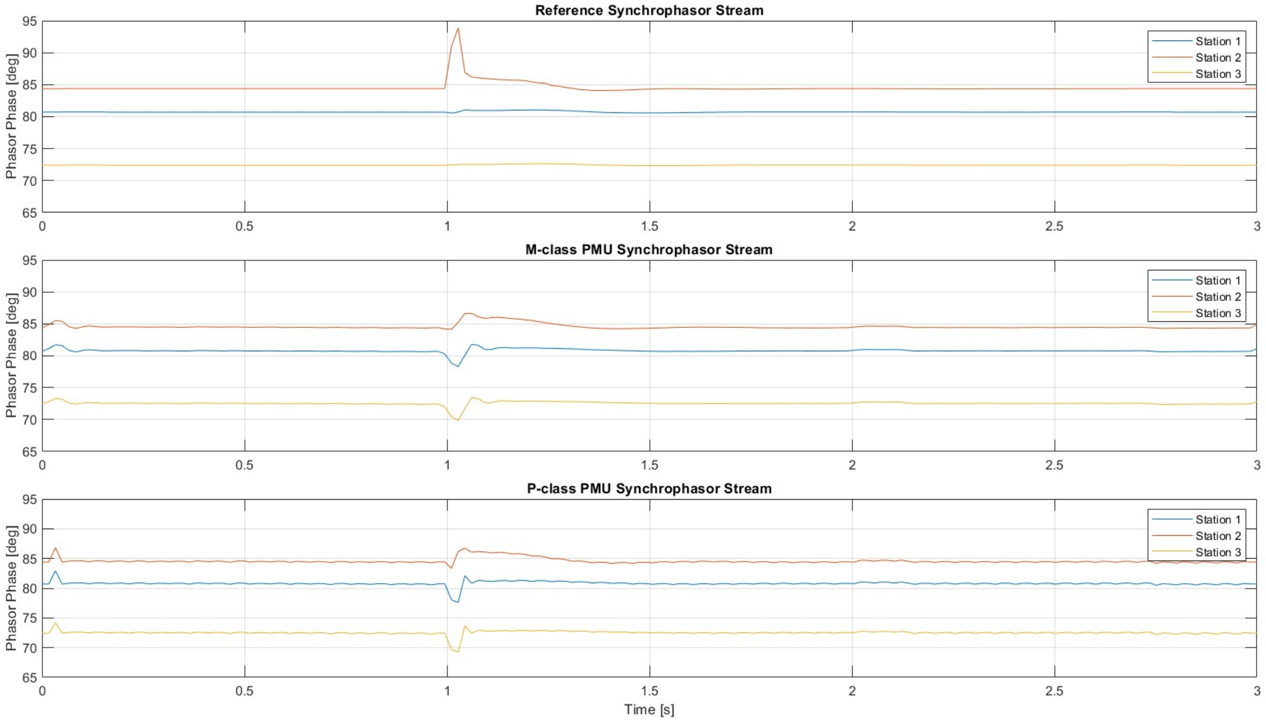

Figure 26: Fault Location – Phasor Angle Evaluation for Line 2 Fault at 66%

Table 4: Application Test Evaluation - Phasor vs. Application Output Error

	Phasor Comparison Error at PDC [%]			Application Output Error [%]
	Station 1	Station 2	Station 3	
Reference Stream	0%	0%	0%	6
M-class PMU	Max: 5.975 Median: 0.8495	Max: 122.62 Median: 0.7299	Max: 4.811 Median: 0.92	174
P-class PMU	Max: 6.774 Median: 0.851	Max: 119.53 Median: 0.727	Max: 5.874 Median: 0.9225	6

6.1.2. Result Assessment

The test presented in this section showed how changes like adjusting the performance class of the PMU have major impact on the application performance. With end-user applications being used very differently, each application has individual characteristics in reacting to variations in the input data. For that reason, each setup needs to be tuned individually to achieve the application's best possible performance. The use of specific grid models and field measurements can help to assess potential deviations from the expected outcome, tune the setup towards individual applications, and minimize errors.

6.2. Nested End-to-end Calibration Using A Portable Test Set

This section demonstrates the nested end-to-end testing approach presented in chapter 5.6. By utilizing the capabilities of the portable FTS, small analog voltage signals are generated and provided to the PMU under test. In a first step, the integrity of the timing source is evaluated. The synchrophasor streams from the PMU and PDC respectively are then evaluated by the FTS. In a final step, the output of the end-user application is evaluated.

6.2.1. Test Plan for Nested End-to-end Test Demonstration

To demonstrate the merit and effectiveness of the proposed methodology and use of tools, this chapter presents results from multiple test cases:

- Calibration Test in Controlled Environment: The system is in a controlled state with no expected erroneous behavior. This test is used to evaluate the systems performance, ensure proper operation, and calibrate system components.
- Maintenance Test with Error Detection: The PMU settings are purposely meddled with, which is expected to adversely affect the system's accuracy. Performing a

maintenance test using the nested end-to-end testing approach is expected to detect this behavior and quantify the impact on the overall system performance.

- Troubleshooting Test with Multiple Error Sources: In addition to erroneous PMU settings, a timing offset is introduced to the reference stream. The PDC is then set up to merge and distribute the phasor streams through a single port, which requires alignment of the incoming data and may cause packet loss in case of large timing variation.

6.2.2. Calibration Test in Controlled Environment

This section shows the implementation of a nested end-to-end testing scheme to evaluate a synchrophasor system in a controlled field environment, as explained in chapter 5.6. All equipment is expected to operate as intended and is not exposed to any attack vectors.

Evaluation of the timing source, as shown in Figure 27, demonstrates compliance with the pre-defined thresholds and confirms the timing integrity. The deviation between the signals was recorded as $\Delta t = 26ns$, which equates to $9.8 * 10^{-4}\ \%\ TTE$ and has therefore negligible impact on the synchrophasor system performance. This conclusion is reflected in Table 5 with a “PASS” as the timing system meets the anticipated criteria.

Figure 27: Timing Integrity Evaluation through Comparison of Extracted PPS Signal of Commercial Clock (blue) and GPS Signal (yellow)

The evaluation of PMU and PDC , respectively, was done by looping back the synchrophasor stream from the device outputs and comparing it to the expected phasors corresponding to the replayed waveforms at the input, as explained in chapter 5.6.1. In this scenario, the PMU and PDC operated as expected within the specified limits, which is reflected in Table 5 with a “PASS”.

The application level was evaluated using both a reference synchrophasor stream and fault waveform replaying:

- By using a reference synchrophasor stream, as explained in chapter 5.5.3.3, the output of the application under normal conditions is known. Since there is no PMU involved, only network components, such as PDCs, switches, and links can add to uncertainties that lead to packet loss or misalignment and consequently to application errors. The evaluated error is shown as “Application (reference)” in Table 5. No significant errors were found, which resulted in a “PASS” conclusion.

- Using analog waveforms replayed to the test PMU, the full system impact is reflected in the application output, with the PMU being the most likely contributor for uncertainties. With the PMU being tuned to the application, which was evaluated in chapter 6.1, the systems impact on the application was low, shown in Table 5 as “Application (waveforms)”.

Table 5 distinguishes the evaluated error as maximum, median, and relative error to reflect the overall performance in one table:

- Max and Median show large deviation: A single phase or phasor component shows exceptionally unexpected behavior.
- Relative Error: Shows whether the error contribution is actually from this level or “handed down” from a previous level, as shown in chapter 6.2.4 in a case with multiple error sources.

The test scenario and the pass/fail result are visualized in Figure 28.

Table 5: Nested End-to-end Test in Controlled Environment - Results

	Error (max)	Error (median)	Relative Error to lower level	PASS / FAIL
Timing level	$9.8 * 10^{-4}$ %	$9.8 * 10^{-4}$ %	$9.8 * 10^{-4}$ %	PASS
PMU level (Type Test)	0.5669 %	0.5594 %	0.5584 %	PASS
PDC level (Type Test)	0.5669 %	0.5594 %	0 %	PASS
Application (reference)	6 %	6 %	6 %	PASS
Application (waveforms)	6 %	6 %	6 %	PASS
End-to-end Performance			6 %	PASS

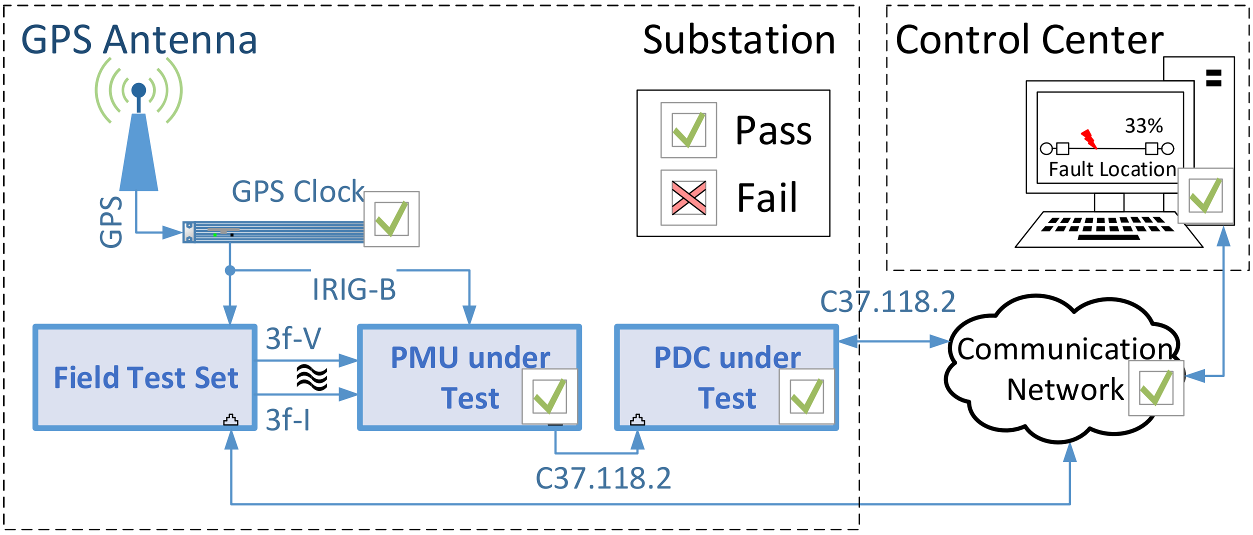

Figure 28: Test Result Visualization of Calibration Test. Adapted with permission from [19].

6.2.3. Maintenance Test with Error Detection

In this scenario the nested end-to-end testing methodology establishes an overview over the systems current state, detects anomalies, and quantifies their impact. The evaluation shown in Table 6 follows the same concept explained above in chapter 6.2.2. As expected, applying incorrect settings to the PMU has severe impact on the system's accuracy. The relative error of the evaluation also shows that the sole source of the error is caused by the PMU. Conventional end-to-end testing would only show the maximum relative system error of at least 100%, which indicates only the system's failure, but bears no further information. The impact on the synchrophasor system captured in this test is visualized in Figure 29.

Table 6: Maintenance Test Result Overview

	Error (max)	Error (median)	Relative Error to lower level	PASS / FAIL
Timing level	$9.8 * 10^{-4}$ %	$9.8 * 10^{-4}$ %	$9.8 * 10^{-4}$ %	PASS
PMU level (Type Test)	100 %	67.65 %	67.65 %	FAIL
PDC level (Type Test)	100 %	67.65 %	0 %	PASS
Application (reference)	6 %	6 %	6 %	PASS
Application (waveforms)	100 %	100 %	100 %	FAIL
End-to-end Performance			100 %	FAIL

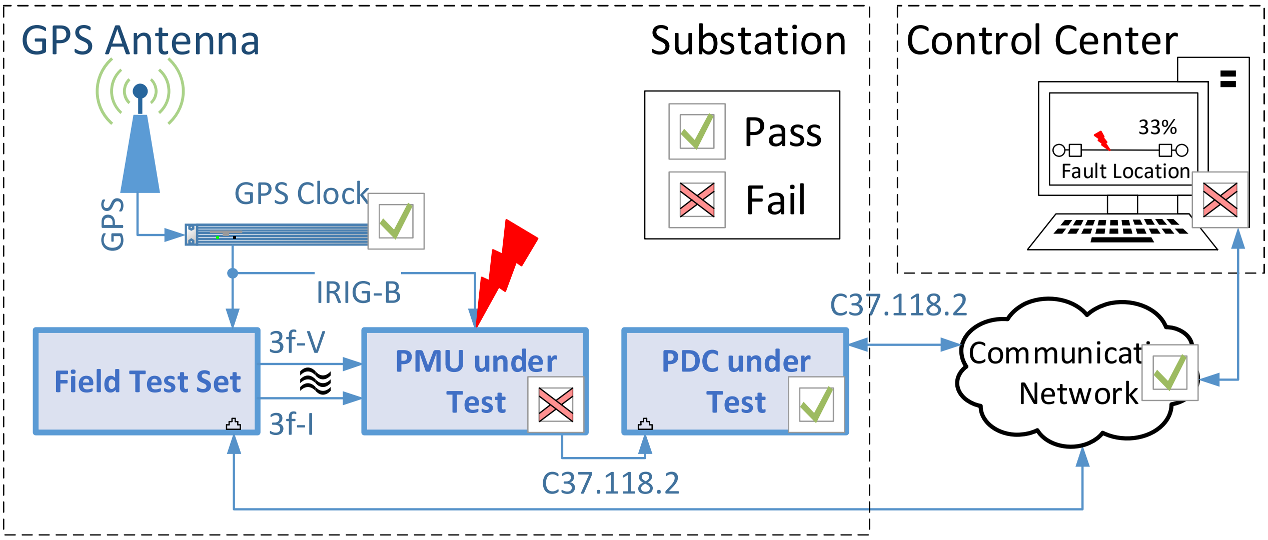

Figure 29: Maintenance Test Result Visualization. Adapted with permission from [19].

6.2.4. Troubleshooting Test with Multiple Error Sources

In this test, two forms of errors were introduced into the system. While the erroneous PMU behavior causes major deviation from the expected outcome, the error contribution from the PDC level causes all consequent levels to exceed the maximum thresholds and fail. While the PMU presumes normal operation with incorrect output, the PDC suffers packet loss because the incoming phasor data cannot be aligned due to their large deviation in respective time stamps. The test results are summarized in Table 7 and visualized in Figure 30.

Table 7: Troubleshooting Test Results Overview

	Error (max)	Error (median)	Relative Error to lower level	PASS / FAIL
Timing level	$9.8 * 10^{-4}$ %	$9.8 * 10^{-4}$ %	$9.8 * 10^{-4}$ %	PASS
PMU level (Type Test)	100 %	67.65 %	67.65 %	FAIL
PDC level (Type Test)	100 %	100 %	100 %	FAIL
Application (reference)	100 %	100 %	100 %	FAIL
Application (waveforms)	100 %	100 %	100 %	FAIL
End-to-end Performance			100%	FAIL

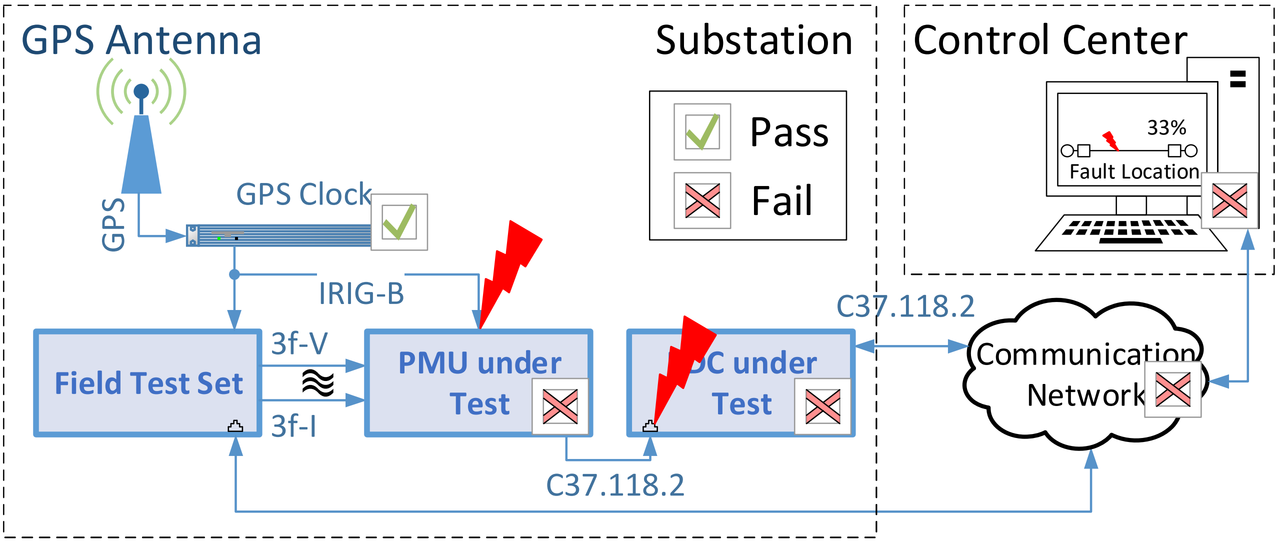

Figure 30: Test Result Visualization of Troubleshooting Test. Adapted with permission from [19].

6.2.5. Result Assessment

The results presented in this section provide insights into the process of nested end-to-end testing for field environments using a portable test set. The correct application of different variations of nested end-to-end testing, i.e. calibration, maintenance, and troubleshooting, is demonstrated by evaluating the status of the system under test and correctly locating erroneous behavior through nested testing. The applied methodology was able to:

- Characterize the performance of the field system under test using type and application tests generated by a portable test set (FTS)
- Detect and locate anomalies in the system under test using type and application tests generated by a portable test set (FTS)
- Confirming the quality of the communication channel from the PMU to the end-user application using a reference synchrophasor stream provided by the FTS
- Perform better than conventional end-to-end testing methods by providing more detailed evaluation of the synchrophasor system under test.

The objective of providing a test methodology using a portable test set to evaluate synchrophasor systems in a field environment was met, which was confirmed by successful execution of all test scenarios mentioned in this chapter. The level of detail of the acquired test results not only supersedes the assessment of existing techniques, but also enables the anticipated comprehensive testing in field environments.

6.3. Evaluation of a Network-Based Nested Testing Approach

The network based nested testing approach was implemented at a large-scale test-bed at Texas A&M University. It is an improved version of the nested testing approach demonstrated in chapter 6.2 that uses distributed network taps and runs the synchrophasor comparison logic on a centralized server. The setup schematic is shown in Figure 31. It features three parallel synchrophasor systems, i.e. a production system (green), a reference system (blue), and a test system (red), each having a timing source, a PMU, and a PDC. The network taps (ET), marked in orange, collect all network traffic in the field including the synchrophasor streams between the PMUs and the PDCs, and at the output of the PDCs. The logical flow of data is from the top down, with all data being merged in the switch before being forwarded through the network to the application located in the control center.

The basic nature of the tests is performed the same way as the non-network-based nested testing, i.e. the FTS is replaying test waveforms to the PMU. In addition to the analog waveforms, the FTS is providing a reference synchrophasor stream (marked in red) that is used for evaluation by the comparison logic located in the server, as described in chapter 5.6.2. To assess the merit of this testing scheme, the evaluation tests included the following steps:

- Assessment of timing signal: Is the timing signal received and ready to use for evaluation in the server? Comparison of PTP time (tapped by ET1 and ET2) to time reference provided to server.
- Assessment of synchrophasor streams: Are all streams gathered by the network taps and received by the server? Evaluation of network streams from ET3, ET4, ET5, ET6, ET7, ET8.

- Manual assessment of system performance: Can synchrophasor streams be compared manually to make a judgement about the system state? Read synchrophasor reference stream and compare to ET8, ET6, ET4, and ET7 to evaluate Reference PMU, Reference PDC, Test PMU, and Test PDC, respectively.
- Automated assessment of system performance: Can synchrophasor streams be compared automatically using the synchrophasor comparison logic. The comparison points as explained in Figure 24 in chapter 5.6.2 are as follows:

Table 8: Network Based Synchrophasor Comparison Points

Point	A	B
1	Synchrophasor Ref.	ET8
2	Synchrophasor Ref.	ET4
3	ET8	ET6
4	ET4	ET7
5	ET8	ET4
6	ET6	ET7

- System state judgment: What is judgement about the system state, i.e. is the system integrity intact? PASS/FAIL decision needs to be established based on the network based evaluation method.

The observations of this test are summarized in Table 9.

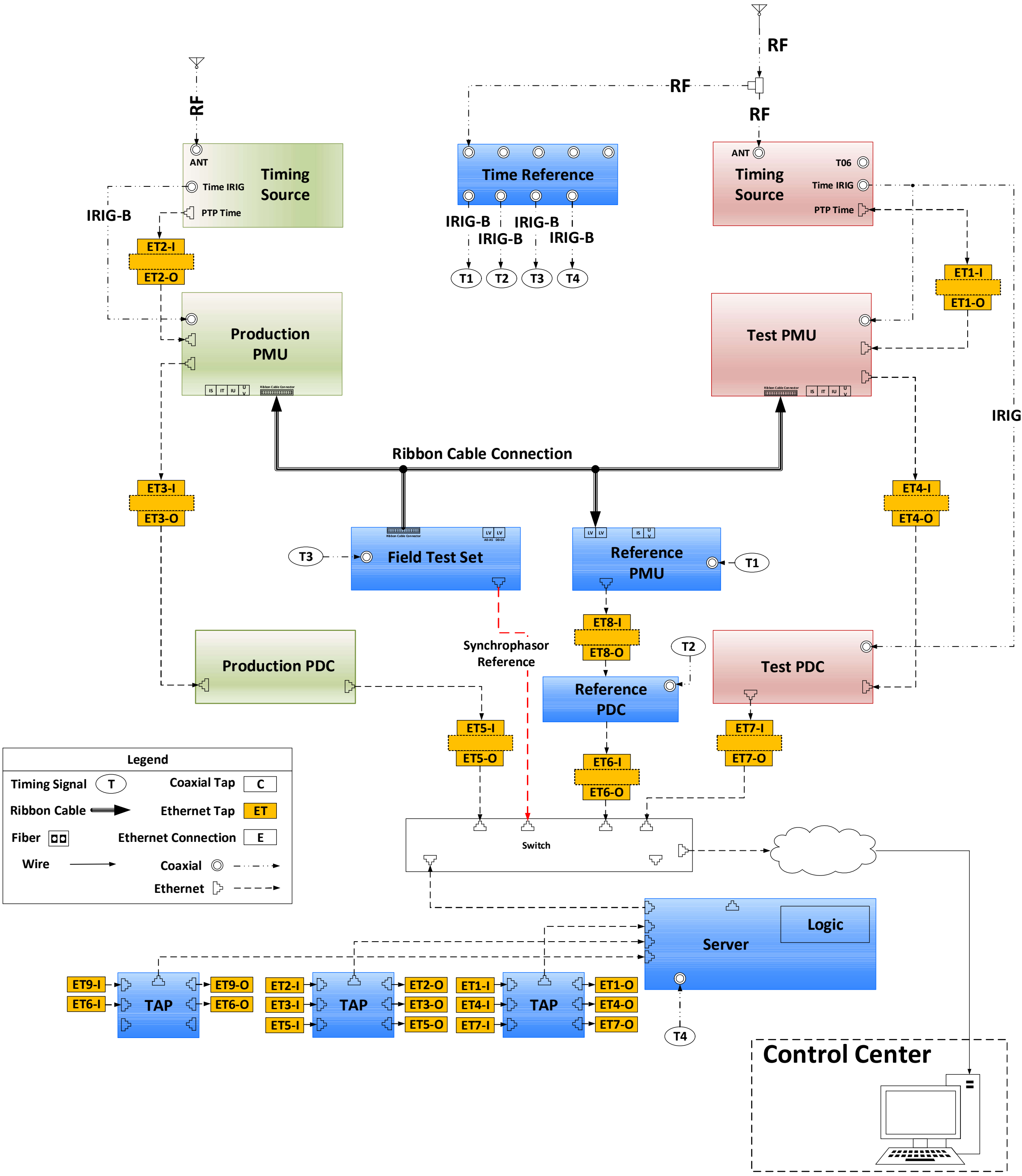

Figure 31: Network Based Nested Testing Setup

Table 9: Assessment of Network Based Nested Testing Scheme

		Type Test – Normal	Application Test – Normal	Type Test – Intrusion
Timing Source	IRIG-B	✓	✓	✓
	PTP	✓	✓	✓
	GPS	**X**	**X**	**X**
Synchrophasor Streams	Reference PMU	✓	✓	✓
	Test PMU	✓	✓	✓
	Reference PDC	✓	✓	✓
	Test PDC	✓	✓	**X**
	FTS Reference	✓	✓	✓
Assessment Decision	Manual	PASS	PASS	FAIL
	Automated	FAIL	FAIL	FAIL

The data in Table 9 can be interpreted as follows:

- IRIG-B and PTP timing signals were successfully tracked by the server, but GPS data was not processed and therefore no standalone judgement about the timing integrity can be made. The FTS or another form of timing evaluation tool is needed.
- The synchrophasor streams of all network taps were available for evaluation at the centralized server, except for the intrusion case replicated as presented in chapter 6.2.4 where the PDC stream suffers packet loss.
- Manually analyzing the network monitored data packets leads to the same assessment as obtained in the non-network based approach, which confirms the feasibility of the network based approach.
- The automated assessment of the system state delivers fail states, which can be traced back to potential implementation errors of the automation process. This may be further investigated in future work, further improving this testing scheme.

Comparison to the non-network based method tested in chapter 6.2 yields the following insights:

- The timing evaluation is only possible with FTS, as the server does not receive the input of the timing module (GPS).
- The network-based approach is good to evaluate a system from a control center or remote connection; no hardware change is needed. When controlling the FTS remotely, the entire test can be performed without physical presence at a station.
- The network-based approach is only feasible for comprehensive testing if it can be automated. Manual comparison and evaluation of phasor data is possible, but very tedious and takes much longer than “semi-automated” nested testing using the FTS.
- Both approaches yield the same results when implemented properly, which makes them equally valid for considerations of accuracy and performance trade-off.
- The network-based approach has hardwired network connections that do not need reconfiguration at each step. By using the small signal ports of separate channels on the PMU, the tests can be performed without disruption of the system operation. This helps maintaining the system’s integrity throughout the test and therefore increasing reliability.

6.3.1. Result Assessment

The network-based nested end-to-end testing approach presented in chapter 5.6.1.4 has proven to be a very helpful tool in improving the performance of synchrophasor system evaluation techniques. While the automated approach needs more work, the overall concept of network-based testing was successfully implemented and the expected merits were confirmed. At the expense of some network and database overhead, the test procedure is significantly faster and more efficient than the other approach. Some level of coordination with the FTS for type and application tests is needed. The method is especially useful to minimize disruption and downtime for any testing performed in a field environment by eliminating the need for physical access to substations for system testing. Combining the capabilities of the FTS with the benefits of network-based nested testing creates unprecedented availability of field tests. By addressing crucial restrictions imposed by the field environment, this scheme is superior to prevailing technology. The benefits and drawbacks of this method are summarized below.

Benefits

\+ Simultaneous evaluation at all network levels: No need for reconfiguration of network settings or hardware.

\+ Continuous monitoring of system operation beyond the scope of test mode.

\+ Test equipment can be permanently installed in substation and operated remotely: No physical access required.

\+ Significantly decreases down-time needed for comprehensive testing: Disruptions of operation are minimized.

\+ Simple maintenance or troubleshooting tests can be performed while system is operating: Continuous operation is maintained.

Drawbacks

− Large database and logic overhead.

− Requires additional equipment.

− Requires coordination with the FTS for testing, i.e. cannot run tests completely independent.

6.4. Conclusions

This chapter demonstrates the effectiveness and merit of the methods and tools presented in previous chapters by performing experiments in a large-scale synchrophasor system test bed. The experiments were segmented in three major parts:

- **Implementation of Application Tests in the Field Environment:** The test presented in this section showed how changes like adjusting the performance class of the PMU have major impact on the application performance. With end-user application performance being specified uniquely, each application reacts to the variations in the input data differently. It can be concluded that each setup needs to be tuned individually to achieve the application's best possible performance. The use of specific grid models and field measurements can help to assess potential deviations from the expected outcome, tune the setup towards individual applications, and minimize errors.
- **Nested End-to-end Calibration Using a Portable Test Set:** The results presented in this section provide insights into the process of nested end-to-end testing for field environments using a portable test set. The application of different variations of nested end-to-end testing, i.e. calibration, maintenance, and troubleshooting, is demonstrated by evaluating the status of the system under test and correctly locating erroneous behavior through nested testing. The objective of providing a test methodology using a portable test set to evaluate synchrophasor systems in a field environment was met, which was confirmed by successful execution of all the test scenarios mentioned in chapter 6.2. The benefits of this approach over existing

methods were demonstrated and highlighted. Especially the field-testing capability was of particular interest and has proven to be superior to prior methods.

- **Evaluation of a Network-Based Nested Testing Approach:** The network-based nested end-to-end testing approach presented in chapter 5.6.1.4 has proven to be a very helpful tool in improving the performance of synchrophasor system evaluation techniques. By enhancing the large-scale test bed to enable network-based evaluation of a synchrophasor system, the benefits and drawbacks of this approach were evaluated. The method is especially useful to minimize disruption and downtime for any testing performed in a field environment, by eliminating the need for physical access to substations for system testing. Combining the capabilities of the FTS with the benefits of network-based nested testing creates unprecedented availability of field tests. By addressing crucial restrictions imposed by the field environment, this scheme is superior to prevailing technology.

7. CONCLUSIONS AND CONTRIBUTIONS

7.1. Conclusions

7.1.1. Need for Improved Synchrophasor System Analysis

Review of prior work has shown that standards to define PMU design, PDC behavior, and synchrophasor data transfer, are available. However, these standards only focus on their respective areas of operation, which is the devices. Previous work has mainly focused on type test waveforms that were defined to evaluate PMU design performance. Initial advances towards more comprehensive testing methods, including end-to-end testing, were limited to controlled laboratory environments. The analysis has also shown that testing tools for more comprehensive tests are not readily available, nor feasible for field-testing since they rely heavily on simulated waveforms rather than actual field data. This creates a need for end-to-end testing methods and tools to evaluate the overall system performance of interconnected synchrophasor systems in the field environment. Additionally, new methods and tools for application testing in the field are needed to evaluate the performance of existing systems up to the end-user application level more accurately and realistically.

7.1.2. Overview of Proposed Concepts

This thesis addressed the open issues by analyzing the restrictions imposed by field-testing, exploring variations of existing methods, and proposing new test methods. The methodology proposed in chapter 5, uses a concept called nested end-to-end testing that allows thorough analysis of each individual level of a synchrophasor system. It leverages the capabilities of a Field Test Set (FTS) that is specifically designed for the use in field-testing, as described in chapter 5.5. The FTS enables evaluation of the timing source, PMU, PDC, communication network, and finally the end-user application in the field, by performing synchronized type and application tests.

Another concept proposed in this thesis, namely network based nested end-to-end testing (chapter 5.6.1.4), further enhances the performance of synchrophasor system assessment. By utilizing distributed network taps, the system evaluation can be performed on a centralized server running a synchrophasor comparison logic, see chapter 5.5.4. By establishing remote access to the server and FTS, the test procedure can be performed remotely. This can be done without physical access to the station, even during normal operation, which eliminates the need for disruption of power system operation.

7.1.3. Validation of Hypothesis

By implementing and evaluating the new test methods and tools in a large-scale test bed, which is demonstrated in chapter 6, the hypothesis posed in this thesis is that if type (design) and application tests, as well as commissioning, maintenance and troubleshooting tests are performed on synchrophasor systems in the field, then the synchrophasor stream and application output will be more accurate and reliable, was validated in all of its aspects. By providing results and insights into nested end-to-end testing, this thesis shows the effectiveness and merit of the proposed testing scheme.

The hypothesis aspect that "using a portable Field Test Set makes field-testing of synchrophasor systems accessible by addressing the feasibility of issues of established laboratory methods" could be confirmed. By utilizing a portable test set using small signal testing to evaluate synchrophasor systems, the feasibility issues of prior methods were addressed, which was confirmed by successful execution of all test scenarios presented in chapter 6.

Another aspect of the hypothesis stating that "the prevailing need for enhanced end-to-end testing methods can be addressed with a nested end-to-end testing scheme presented in this thesis" was evaluated in chapter 6.2. The results show that the applied methodology was able to:

- Characterize the performance of the field system under test using type and application tests generated by a portable test set (FTS)
- Calibrate and tune a system in the field to achieve the best possible performance
- Detect and locate anomalies in the system under test using type and application tests generated by a portable test set (FTS)
- Confirm the quality of the communication channel from the PMU to the end-user application using a reference synchrophasor stream provided by the FTS
- The used end-to-end testing methods provided a more detailed evaluation of the synchrophasor system under test than conventional methods

This validates the hypothesis that "performing nested end-to-end tests enables calibration of individual modules in the field system while evaluating the end-to-end system performance". It furthermore confirms the assumption that "it is also expected to detect and locate potential anomalies from the timing source to the end-user application, which increases its functionality over existing methods".

The network-based nested end-to-end testing approach presented in chapter 5.6.1.4 was successfully implemented and compared to the non-network approach. This showed the additional benefits that can be acquired at the expense of some network overhead, coordination, and additional equipment, which validates the hypothesis aspect that "this concept may be adopted as a new standardized framework for field testing and monitoring". Some of the benefits include:

- Simultaneous evaluation of all system levels.
- Continuous monitoring of system operation beyond the scope of test mode.
- Test equipment can be permanently installed in substation and operated remotely.
- Significant decrease in down-time needed for comprehensive testing.
- Simple tests can be performed while system is in operation.

This validates the hypothesis that “a network based nested testing approach will further improve the concept of field-testing by enabling parallel evaluation of all nested levels, which will improve the critical aspect of down-time for testing and usability”.

The entirety of all measurements, tests, and results presented in chapter 6, validates the hypothesis that “including both type and application tests into the field-test sequence allows evaluation of the entire synchrophasor system. It can differentiate between impacts on the synchrophasor quality and the application output”. Impact evaluation of the synchrophasor system performance on end-user application in chapter 6.1 showed how changes such as adjusting the performance class of the PMU has major impact on the application performance. This shows that each setup needs to be tuned individually to achieve an application’s best possible performance, which strengthens the aspect of the hypothesis that “using specific grid models and field measurements helps tune the setup better towards individual applications”.

The presented results confirm the expected importance of the testing tools developed and presented in this thesis. Performing the tests showed how the open issues for field-testing, such as inadequacy of existing methods or tools, could be addressed. Further improvements with suggestions like the network-based nested testing approach could be made. These efforts resulted in a methodology leveraging type and application tests that provides a more comprehensive and detailed synchrophasor performance assessment for field installations than today’s practice.

7.2. Summary of Contributions

- The development of a synchrophasor testing methodology using a single portable device, namely Field Test Set (FTS) [20] to implement field protocols for nested end-to-end and application tests [19].
- Specification of the performance analysis and error detection approaches for integrated synchrophasor systems that covers in-depth comprehensive system characterization and impact evaluation of system behavior on applications.
- The development of Use Cases for evaluating synchrophasor components, systems or applications, which are utilizing the portable test set and eliminate the need for any additional equipment while reducing cost, as well as personnel to implement and operate such tests.
- Verification of the effectiveness of the proposed nested testing scheme to detect and locate performance anomalies of the overall synchrophasor system and show the advantages and benefits by comparing it to existing test procedures [7], [37], and [44].
- An enhanced testing protocol using a network based nested testing approach was compared to the proposed non-network-based approach leading to a conclusion about the effectiveness of this elevated effort.
- A metric to evaluate the proposed end-to-end application tests in the field using a portable test set [19] and a fault location application based on a model developed from actual field measurements.
- Definition of a comprehensive test methodology for evaluation of synchrophasor systems in the field using both type and application tests to optimize testing procedures in terms of time and effectiveness to comprehensively analyze synchrophasor systems.

7.3. Future Work

While this thesis has laid out the foundation for new and improved synchrophasor system field testing methods and tools, the following aspects require further attention and improvement:

- Long-term monitoring of a synchrophasor system installation using the proposed techniques and tools were not addressed in this thesis. This would require life-cycle assessment of synchrophasor system behavior. Evaluating system degradation over time could yield better prediction methods for synchrophasor component failure and increase reliability.
- While the concept of network-based nested end-to-end testing was introduced and tested in this thesis, the method and especially physical implementation needs further improvement. Additionally, evaluation metrics leveraging the on-line monitoring capability during normal operation could further improve power system operation.
- The assessment and mitigation of cyber-attacks using the proposed methods and tools was not addressed in this thesis. While the tools and methods offer the capability to potentially detect and troubleshoot such intrusions, only little effort was made to thoroughly investigate this matter.

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